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THE LIMNOLOGY OF KAMLOOPS LAKE, B.C.

B.E. ST. JOHN, E.C. CARMACK, R.J. DALEY,
C.B.J. GRAY AND C.H. PHARO

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Inland Waters Directorate
Pacific and Yukon Region
Vancouver, B.C.

THE LIMNOLOGY OF KAMLOOPS LAKE, B.C.

by

B. E. St.John

E. C. Carmack

R. J. Daley

C. B. J. Gray

C. H. Pharo

DEPARTMENT OF ENVIRONMENT

Inland Waters Directorate

Pacific and Yukon Region

Vancouver

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PROGRAMME RESPONSIBILITIES

Project Design and Management	B. E. St.John
Geology	C. H. Pharo
Sediment Geochemistry	B. E. St.John
Chemistry	C. B. J. Gray
Biology	R. J. Daley
Physical Limnology	E. C. Carmack
Synthesis	All Authors
Report Co-ordination	R. J. Daley

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SUMMARY

A comprehensive, multi-disciplinary limnological study of Kamloops Lake was carried out between May 1974 and May 1975 as part of a Federal-Provincial Task Force examining the extent of environmental degradation in the Kamloops Lake-Thompson River watershed. From data on lake temperature and turbidity, sediment distribution and geochemistry, water chemistry, nutrient loadings and microbial activity, the current trophic status of the lake, its future pollution sensitivity, and its indirect effects on the water quality of the Lower Thompson River were evaluated.

Kamloops Lake is a long (25 km), narrow (mean width, 2.1 km), deep (mean depth, 71 m) lake situated in a dry glacial valley of the Thompson Plateau in south central British Columbia. The lake floor at the east end is smooth and deep with sandy sediments, becoming shallower and more rugged with increasingly silt- and clay-rich sediments toward the outlet. Grain size of the sediments decreased and most trace element concentrations increased linearly along an east-west gradient. Sediment phosphorus consisted primarily of mineral apatite. From indirect geochemical data, the apatite appeared to occur in both the sediments and the water column in a wide range of grain sizes (coarse silt to colloid). Sedimentation rates ranged from 0.92 g cm^{-2} yr^{-1} at the west end of the lake to 22 g cm^{-2} yr^{-1} at the Thompson River delta, which at present has an annual advance of *ca* 11 m.

The physical limnology of Kamloops Lake is dominated by the Thompson River, which has a mean annual inflow of 720 m^3 sec^{-1}. Over 60% of the discharge came in the early summer freshet period, with peak flows near 3400 m^3 sec^{-1} in June and minimum flows of 120 m^3 sec^{-1} in February. As a result of the large and variable discharge, bulk residence times were very short (20-340 days with a mean of 60 days).

Throughout summer (June-October), the inflowing highly turbid Thompson River water remained cooler than the surface lake water, thus interflowing through the epilimnion at depths of 10-30 m. Turbulence induced by this interflow effectively mixed the intermediate region of the epilimnion. Only in late summer, with declining river flows and deep convective mixing of the surface waters, did the lake establish a classical two-layer thermal structure. Throughout summer, the outflow river remained warmer and less turbid than the inflow. Direct stratification slowly broke down through November and December until complete convective overturn resulted. During this period, inflowing river water either sank to the bottom, or was confined to the eastern end of the lake. Hence the outflow was derived entirely from surface lake water remaining from the summer. The lake during winter (January-March) was characterized by weak, reverse temperature stratification and low turbidity; the inflowing river waters were less dense than the ambient lake water and, therefore, tended to remain at the surface. In spring (April-May), convective overturn again occurred, followed by direct thermal stratification. As with the autumn overturn, the spring mixing processes acted to retain all new inflow water within the lake. Thus, the outflow waters consisted of surface lake water reflecting winter conditions.

The concentrations of nutrients and major ions were low compared to other large southern B.C. lakes. Between the spring freshet and early autumn, epilimnion nutrient concentrations were generally determined by the concentrations of the inflowing Thompson River, except in late August when dissolved phosphate and nitrate concentrations were depressed slightly by biological uptake. However, in the hypolimnion during this period, and subsequently in the winter months, nitrate was regenerated by conversion from other nitrogen species, both natural and cultural in origin. During the winter, lower flows and hence reduced dilution of both wastewater and diffuse

inputs resulted in dissolved phosphorus levels as high as during the freshet. Annually, the lake retained the majority of the particulate phosphorus loading, but had little effect on the dissolved phosphorus. The total net phosphorus load to the lake was very high (22.8 g m^{-2} yr^{-1}). Pollution sources could only account for a small portion of the nitrate leaving the lake in the winter. However, the reverse was true for winter phosphorus, with an estimated 40-90% of the biologically available phosphorus in the outflowing river derived from point sources. Colour levels were lower and less variable in the outflow (5-15 units) than the inflow (5-45 units) due either to dilution or degradation within the lake. Oxygen levels were generally near saturation, with lowest values (8.3 mg l^{-1}) at the bottom in October.

All conventional microbiological and chemical criteria indicated that Kamloops Lake has undergone little, if any, eutrophication. Its oligotrophic status was apparent in the species composition and low activity of the phytoplankton. Mean annual chlorophyll *a* and C-14 primary production values were 3.3 mg m^{-2} and 32 g C m^{-2}, respectively, with both showing single maxima in the fall. Diatoms (*Fragillaria, Tabillaria*) dominated the phytoplankton (>50% by carbon) except during the fall maxima when two species of Cryptophytes, *Chroomonas* and *Cryptomonas*, were the principal genera. Blue-green algae only appeared as minor constituents in winter and consisted of non-bloom-forming genera. Total bacterial numbers were also low ($3\text{-}7 \times 10^5$ cells ml^{-1}), although on an areal basis heterotrophic biomass was five times the phytoplankton biomass.

Phosphorus loading data also indicated the unproductive nature of Kamloops Lake, although modifications to the conventional loading calculations were necessitated by two unusual features of the lake. The presence of up to 80% biologically inert apatite in the particulate phosphorus pool and the confinement of river water to the epilimnion in summer seriously

overestimates the available phosphorus load and the effective bulk residence time, respectively. When corrected for these effects, Kamloops Lake falls well within the oligotrophic category, based on the usual plot of phosphorus load versus the mean depth:flushing time ratio.

Cultural eutrophication of Kamloops Lake is expected to be slow, since future increases in summer nutrient levels and phytoplankton populations will be limited. The high flushing rates generally prevent long-term nutrient accumulation in the lake and most of the wastewater nutrients that do accumulate in the winter are flushed from the lake prior to the summer growing period. In addition, point source nutrients are insignificant in the summer epilimnion in comparison to natural loadings. Hence very large increases in pollution inputs will be required to elicit even a small algal response. Lastly, the summer growth rates of phytoplankton are largely limited not by nutrient availability but by their transport downwards out of the euphotic zone and their rapid subsequent removal from the lake. Both of these effects are a direct result of the unique interflow of the Thompson River through the lake.

Discolouration of Kamloops Lake by pulp mill effluent was primarily an aesthetic problem, having little effect *per se* on light-dependent biological processes. Long-term increases in colour are prevented by the rapid flushing rates of the lake. In addition, summer colour levels are reduced by dilution to insignificant levels compared to the light-limiting effects of river turbulence.

The high flushing rate that prevents eutrophication of the lake itself was, at the same time, indirectly responsible for the nuisance algal growths and enhanced pollution sensitivity of the Lower Thompson River. In general, incoming toxicants and nutrients are transferred into the lower river before they are utilized or degraded within the lake. Thus during the low-flow winter period, wastewater nutrients rapidly transit the lake and exit relatively undiluted into the Lower Thompson River. The relatively high nutrient levels, together with high transparency, low and constant water levels, and increasing light intensities result in rapid benthic algal growth in the river in late winter and early spring.

From indirect evidence, the cause of the river algal growths were ascribed to wastewater inputs of phosphorus from the Kamloops sewage system and the Weyerhaeuser Ltd. pulp mill. It is therefore recommended that the discharge of biologically utilizable phosphorus from both point sources should be reduced to as low a level as is technologically possible. A selective wastewater phosphorus release schedule that may reduce treatment costs is suggested.

RECOMMENDATIONS PROVIDED BY THE INLAND WATERS DIRECTORATE (CCIW)

to

THE FEDERAL-PROVINCIAL THOMPSON RIVER TASK FORCE

in

DECEMBER 1975

1. SEWAGE DISPOSAL FOR THE CITY OF KAMLOOPS:

a) *The sewage lagoons adjacent to the east end of Kamloops Lake should be modified to remove as much wastewater phosphorus as is technologically possible.* A selective wastewater phosphorus release schedule that may reduce treatment costs is recommended for consideration. Implementation of this recommendation along with recommendations 2(a) and 3(a) will minimize benthic algal growth in the Lower Thompson River in winter.

2. PULP MILL OF WEYERHAEUSER (CANADA) LTD.:

a) *The pollution control permit of the pulp mill of Weyerhaeuser (Canada) Ltd. at Kamloops should be revised to require the installation of equipment capable of removing as much of the phosphorus in the effluent as is technologically possible.* The selective release option also applies to the Weyerhaeuser effluent.

b) *An investigation of the effluent of the Weyerhaeuser (Canada) Ltd. mill should be undertaken to isolate and identify toxic substances which may be adversely affecting the biota of Kamloops Lake or the Lower Thompson River. Any such substances should subsequently be removed from the effluent.* Implementation of this recommendation will result in the elimination of pulp mill toxicants from the system.

c) *The pollution control permit of Weyerhaeuser (Canada) Ltd. should be modified to incorporate any suggestions of the Task Force regarding that company's ongoing lake monitor programme.* Implementation of this recommendation will permit surveillance of sensitive features such as phosphate and oxygen concentrations in the lake.

3. MINOR POLLUTION SOURCES:

a) *During the critical late winter period, phosphorus release from minor pollution sources such as Savona and rural settlements on the North and South Thompson Rivers should be minimized wherever this is possible at a reasonable cost.*

b) *Activities in the Thompson River Basin above Kamloops Lake (such as logging and feedlot operations) that will cause a major increase in the supply of particulate oxidizable organic matter should not be allowed until the effects of such an increase on the oxygen depletion area in front of the Thompson delta have been evaluated.*

4. IMPORTANT RESEARCH NEEDS:

a) *A research program should be undertaken on the physiology and nutrient energetics of benthic algae communities typical of British Columbia rivers.* Because of insufficient knowledge in this area, quantitative predictions of the changes in algal biomass to be expected in the Lower Thompson River as a result of phosphorus control are not possible.

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1. INTRODUCTION

In response to public expressions of concern over an apparent deterioration in the water quality of Kamloops Lake and the Thompson River, a short study was carried out by agencies of the Governments of British Columbia and Canada in 1973. One of the recommendations in the report from this study stated:

> "An immediate joint Federal-Provincial program of data collection and fact-finding be undertaken through establishment of additional monitoring stations to determine the source of nutrients and the type and source of foaming agents in the Thompson River system including the effects of nutrients and colour on the biological activities of Kamloops Lake and the Lower Thompson River over a minimum one-year period. This program will also include the effects upon recreation and fishery resources. All potential sources including logging, agricultural practices, and industrial and domestic discharges will be investigated."

The joint Federal-Provincial Task Force formed in 1973 in response to these recommendations requested the assistance of the Inland Waters Directorate (IWD) in the study. It was subsequently agreed that the Canada Centre for Inland Waters Branch of IWD in Vancouver would undertake an in-depth, multi-disciplinary study of Kamloops Lake. It was decided that assessments would be made not only of the effects of nutrients and colour on the lake's biological activity, but also of the underlying physical, chemical and biological processes that control the system's response to present and future cultural stresses. In addition, the lake was chosen as a site for certain basic research studies (operated mainly from the Canada Centre for Inland Waters, Burlington, Ontario) of only limited relevance to the immediate problems of the Thompson River system. These latter studies, it was hoped, would contribute new information on processes controlling rates of eutrophication and thus improve environmental management capabilities in other lakes and drainage basins. To this end, for example, the CCIW Kamloops Lake Study was included in the Lake Eutrophication Programme (Vollenweider 1973) of the Organization for Economic Co-operation and Development (OECD). Information gained on the lake was collected in a manner compatible with the OECD programme.

The scope and design of this study were determined in large part by two important characteristics of Kamloops Lake. Almost all of the water in the lake and almost all of the materials in the water enter from the combined flows of the North and South Thompson Rivers (the "Upper" Thompson River, Fig. 1). The high flow rates of this river result in water residence times that are very short for a lake of such large volume and depth. In addition, the 1973 data indicated that the lake itself was generally less polluted than the Thompson River downstream of the lake (the "Lower" Thompson River) even though the two largest potential pollution sources (the City of Kamloops sewage lagoons and the Weyerhaeuser Ltd. pulp mill) discharged into the Upper Thompson River above the lake. These facts together suggested that the various physical, chemical and biological processes operating within the lake were modifying the inflowing river water in unknown ways and were thereby determining the water quality of the Lower Thompson River. It thus seemed likely that a comprehensive analysis of the general limnological dynamics of the lake would be the key to understanding the tolerance of the Lower Thompson River to the pollution pressures originating upstream of the lake. Heavy emphasis was accordingly placed on three principal study areas: physical processes that distribute river water throughout the lake; spatial and temporal distributions and mass budgets of major nutrients and pollutants in the lake; and the response of pelagic microflora to these annual physical and chemical patterns.

The present report emphasizes these three major areas of study. Separate discussions of significant geological, physical, chemical and microbiological results are presented first. These sections (2 to 5) are intended as self-contained, descriptive summaries of all the major lake processes studied. The final discussion section contains a synthesis of our conclusions on the current trophic status and future pollution sensitivity of Kamloops Lake as well as the effects of the lake on the environmental tolerance of the Lower Thompson River. A number of specific recommendations made to the Task Force are also included in this section.

The report is intended as a data summary and synthesis to be used in corroborating the Summary Report of the Thompson River Task Force released in December 1975. Within this context it has been written (as far as possible) for the non-limnologist. Much of the data presented in somewhat simplified form here is also of basic research interest and will be reported later in the open limnological literature.

2. GEOLOGICAL LIMNOLOGY

2.1 Introduction

a) Geographic/Geologic Setting of Kamloops Lake

Kamloops Lake is situated on the Thompson Plateau (Holland, 1964) of British Columbia, a gently rolling upland of low relief lying between 1200 and 1500 m elevation, about 240 km northeast of Vancouver (Fig.1,2). Near Kamloops the uplands lie between 1400 and 1800 m and are dissected by steep valleys with floors 760 to 1500 m lower than the adjacent uplands. The hills are generally rounded, in contrast to the rugged Coast Mountains to the west. The area lies within the Interior dry belt where precipitation is low (25-28 cm yr^{-1}). The lower slopes of the valleys are generally covered with sagebrush, while open pine forest with little underbrush occurs higher on the adjacent hills.

Bedrock geology of the area around Kamloops is described by Cockfield (1948) and is summarized from this source in Figure 3. In many places in the Kamloops area bedrock is covered by deposits formed during and after the last glaciation. In the valleys, particularly those of the major rivers, the unconsolidated deposits reach 180 m in thickness (Fig.4, from Fulton 1963).

Mineral deposits around the lake include: placer gold on the lower Tranquille River and the Thompson River downstream from Deadman Creek; vein deposits with gold, silver, copper, lead and zinc which are or have been mined near Kamloops; and copper, generally together with molybdenite, in association with intrusive and volcanic rocks, particularly to the south of Kamloops Lake (eg. Afton Mine).

b) Post-Glacial History of Kamloops Lake

The post-glacial history of the Kamloops Lake basin has been described in detail by Mathews (1944) and Fulton (1969). A brief summary will suffice here.

At the maximum extent of the last glaciation, ice covered the entire

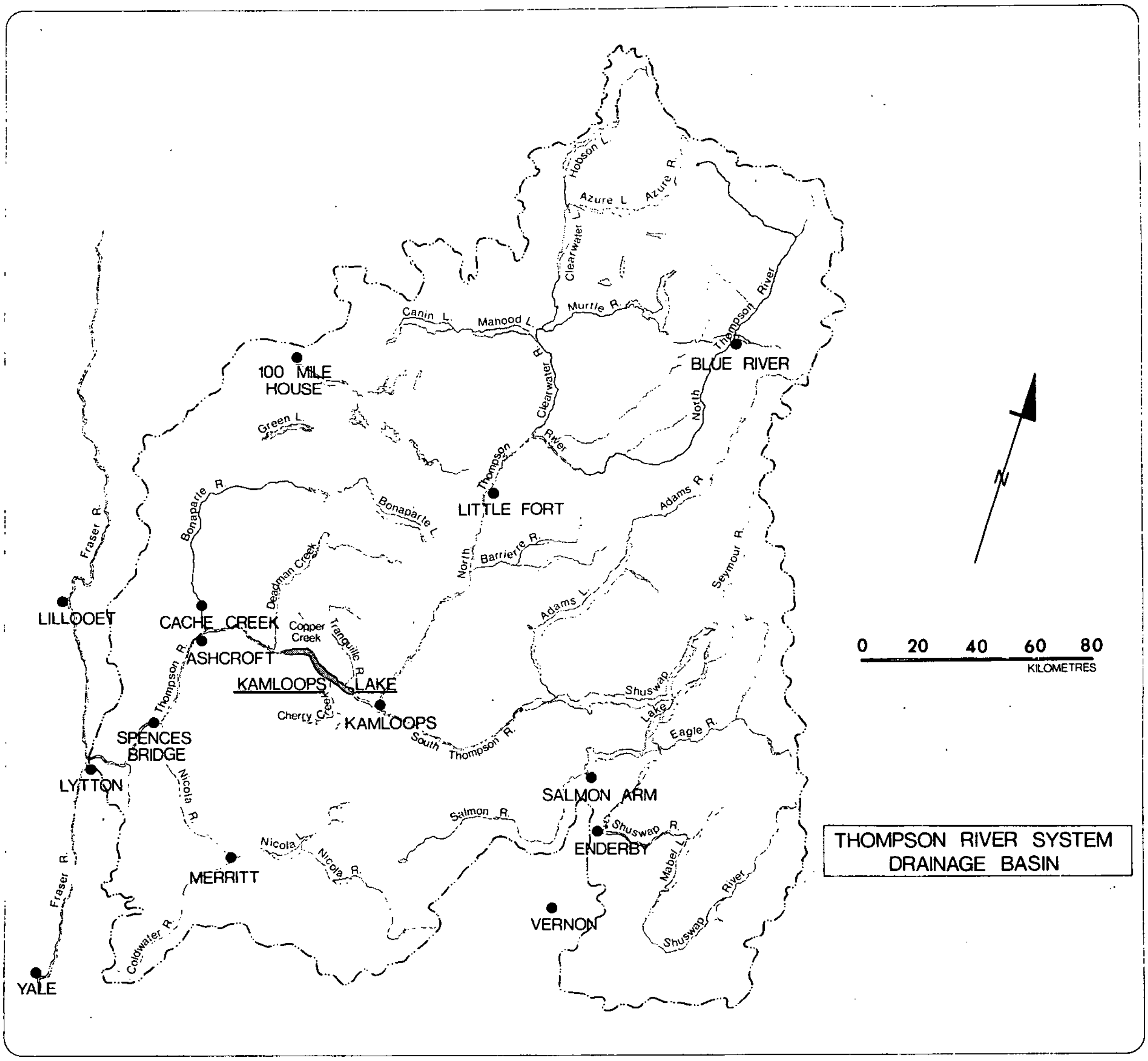


Figure 1. Outline of the Thompson River drainage basin showing the location of Kamloops Lake.

area to a thickness of 2500 m and flowed generally south and southeast. As the climate ameliorated, the ice sheet thinned by down-wasting, eventually leaving large "tongues" of ice in the major valleys. Glacial lakes, ponded by ice tongues, developed in the larger valleys and marginal lakes formed beside the ice tongues. Fine sediments such as the South Thompson Silts (Fulton 1965) were washed from the drift mantle and deposited in the glacial lakes. Drainage was to the east by way of marginal channels and eventually to the Pacific via the Okanagan Valley.

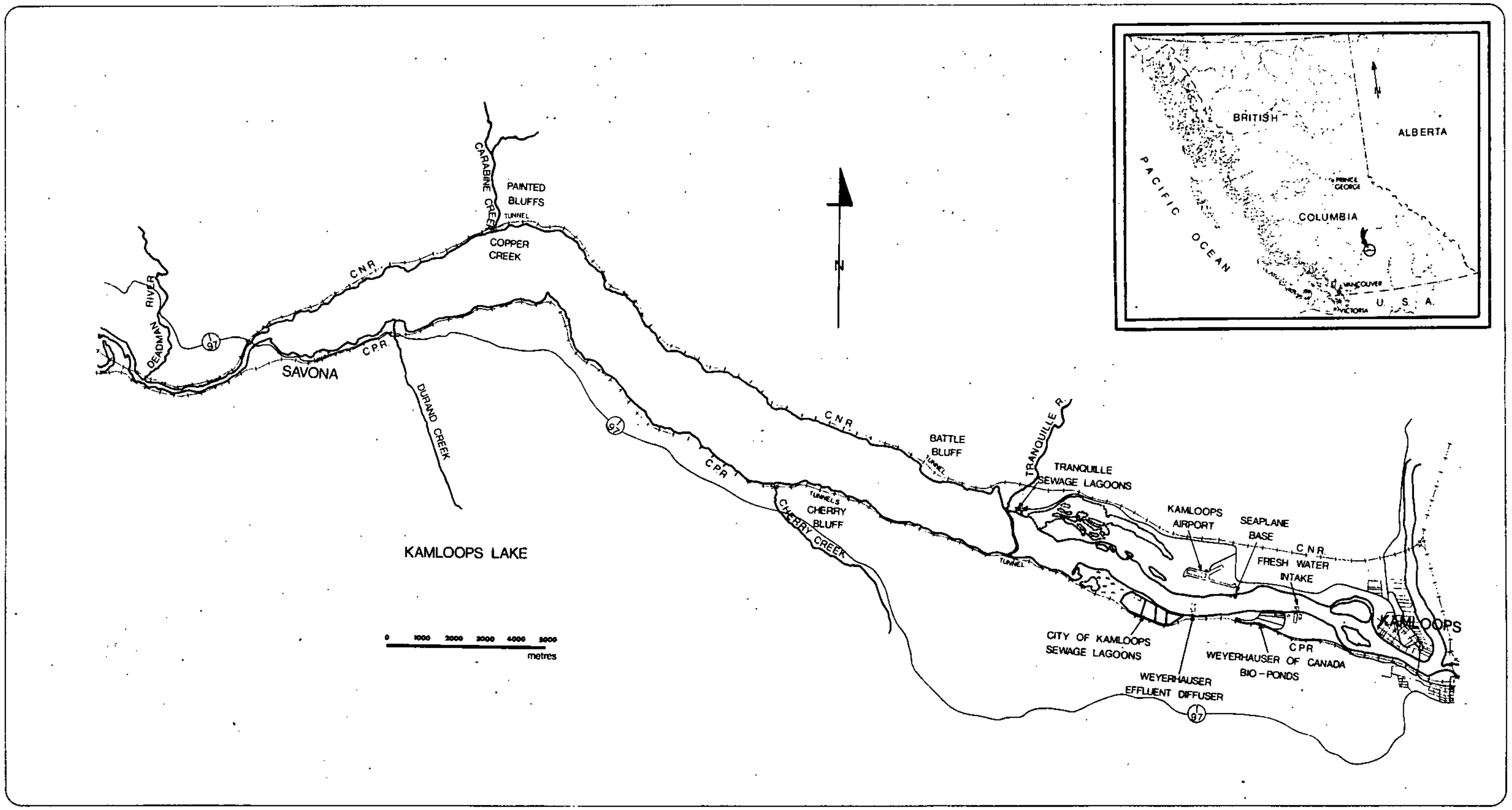


Figure 2. Kamloops Lake and major geographic, urban, and industrial features of the area.

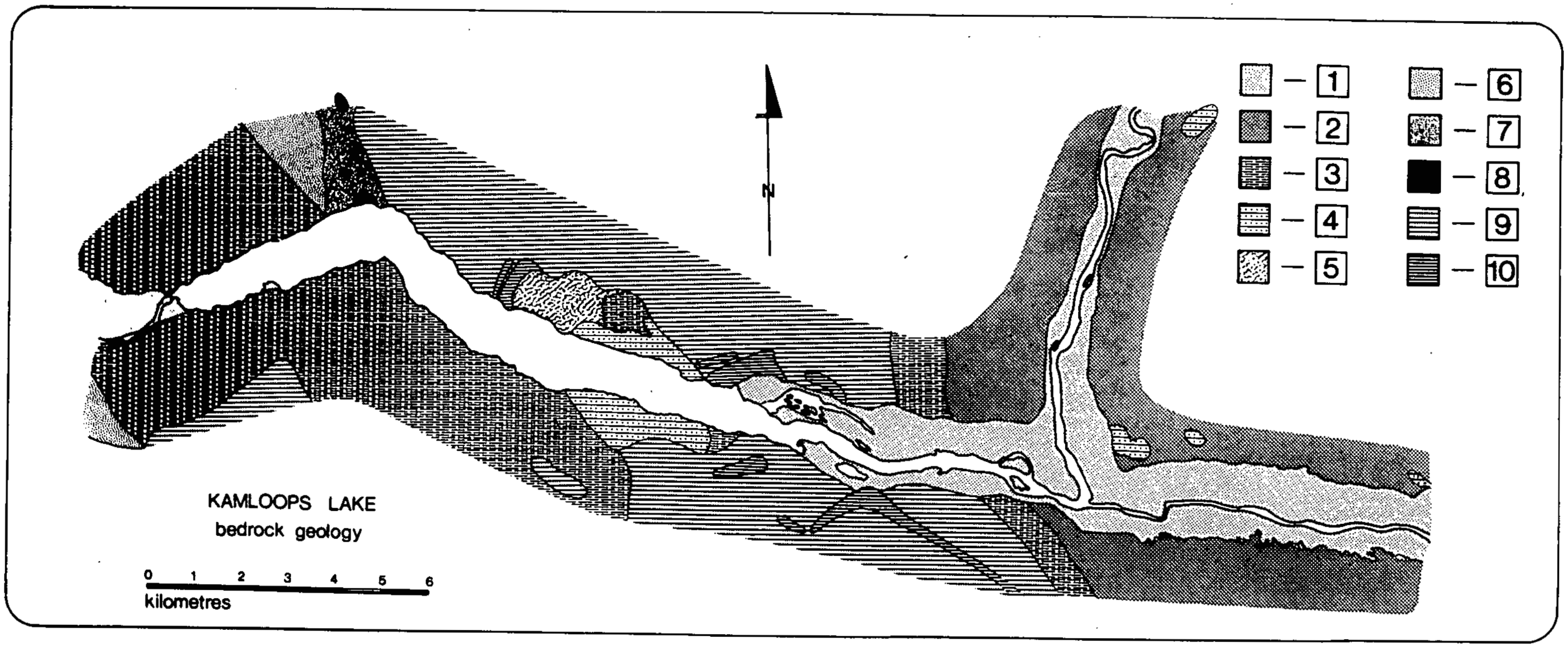


Figure 3. Generalized map of the bedrock geology in the vicinity of Kamloops Lake. $\boxed{1}$ Quaternary, mainly Holocene alluvium; $\boxed{2}$?Carboniferous Cache Creek Group; $\boxed{3}$ Upper Triasic Nicola Group (mainly volcanogenic); $\boxed{4}$ Jurassic and possibly later Coast Intrusions (granite, granodionite, gabbro); $\boxed{5}$ Lower Cretaceous Kingsvale Group (mainly volcanogenic); $\boxed{6}$, $\boxed{7}$, $\boxed{8}$ Cretaceous or Tertiary sedimentary rocks (6), volcanics (7), or intrusive rocks (8); $\boxed{9}$, $\boxed{10}$ Miocene or older Kamloops Group, volcanogenic (9) or sedimentary (10) rocks. (From Map 886A; Cockfield 1948).

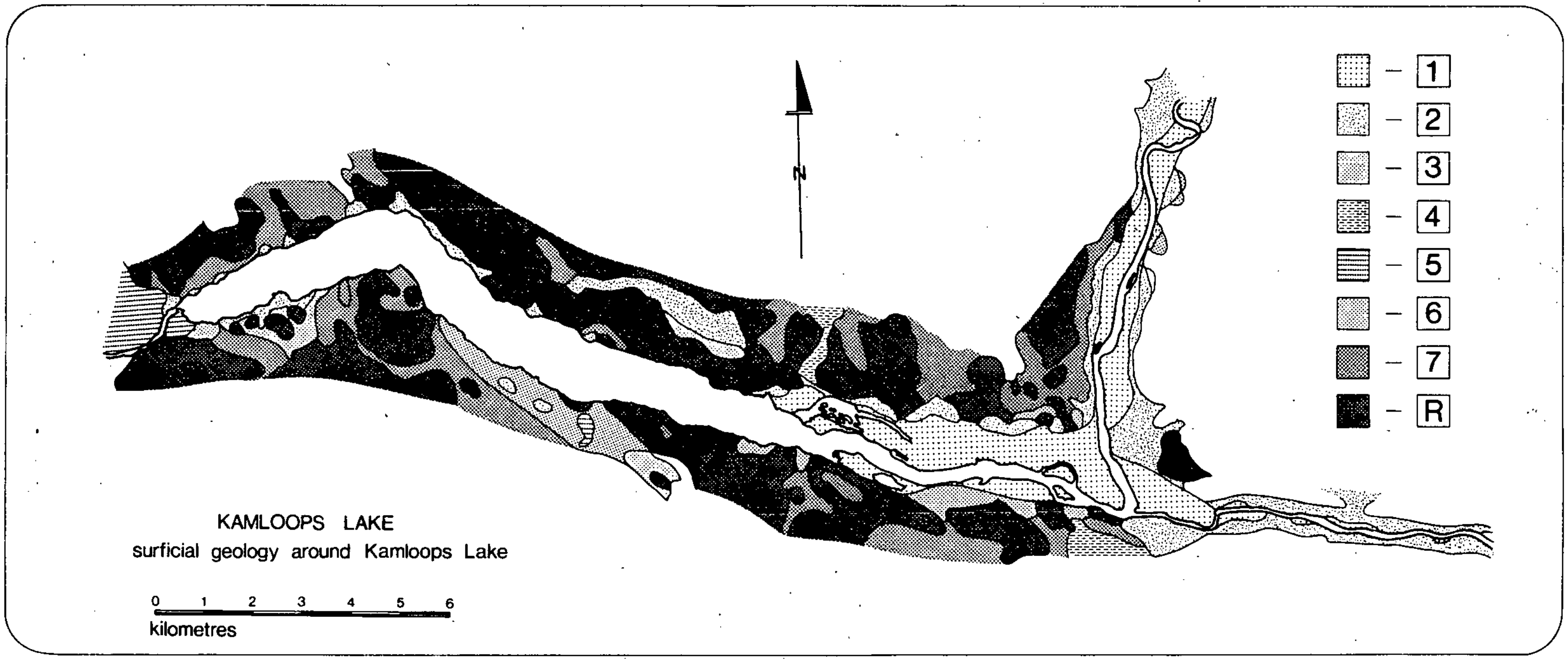


Figure 4. Distribution of surficial deposits around Kamloops Lake (from Fulton 1963). $\boxed{1}$ stream channel and flood-plain deposits; $\boxed{2}$ alluvial fan deposits; $\boxed{3}$ lacustrine and glacio-lacustrine deposits; $\boxed{4}$ morainal gravels of glacial and glacio-fluvial origin; $\boxed{5}$ kettled stream deposits of fluvial and glacio-fluvial origin; $\boxed{6}$ subtill stratified deposits of glacial and interglacial origin; $\boxed{7}$ undifferentiated glacial drift; $\boxed{R}$ bedrock. Generally Tertiary and older.

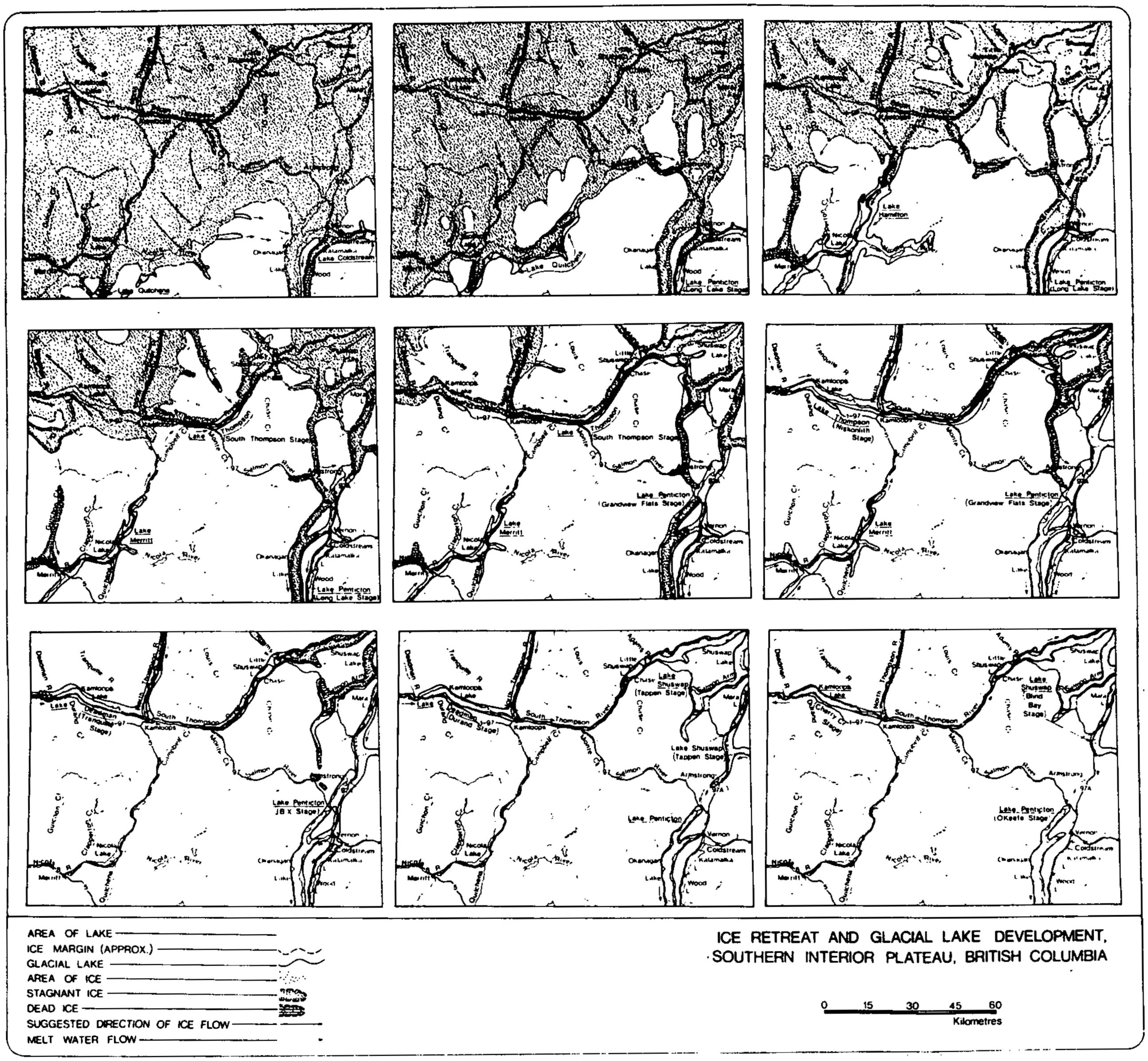


Figure 5. Ice retreat and the historical development of Glacial Lakes in the Southern Interior of British Columbia. Comments in the text. (From Fulton 1969).

Lake levels dropped intermittently as the ice tongues melted and drainage barriers were breached, overrun, or lowered. Eventually the lake which occupied the Thompson Valley (the Tranquille Stage of Glacial Lake Deadman; Fulton 1969) extended west to at least the mouth of the Nicola River and an unknown distance up the North Thompson River. The altitude of this lake's surface was approximately 427 m. A large deltaic deposit (containing buried ice) was deposited across Glacial Lake Deadman near the mouth of Deadman Creek. The material comprising this delta is believed (Holland 1964) to have resulted from massive drainage into Deadman Creek from the Fraser Valley north of Dog Creek, with meltwater escaping by way of Canoe Creek across the head of the Bonaparte River and into Deadman Creek. The Deadman Creek delta (180 m thick at the mouth of Deadman Creek to zero metres 32 km upstream; Mathews 1944) effectively divided Glacial Lake Deadman in two. A succession of lakes of various sizes occupied the Thompson Valley to west of Spences Bridge, each separated by extensive outwash deltas. When the Fraser Valley was finally deglaciated and the present drainage established, headward erosion processes captured and successively drained all the lakes in the Thompson Valley as far east as the Deadman Creek delta. Although Kamloops Lake remained, the changes in drainage caused a lowering of its water level to 353 m. Continued headward erosion upstream from Kamloops Lake, and through the soft South Thompson Silts, eventually captured the Shuswap drainage from the Okanagan-Columbia River drainage basin. The extra water flow, by increasing erosion, lowered the level of Kamloops Lake approximately 12 m to its present level. The North Thompson River is now supplying large quantities of sediment to the Thompson River delta and Kamloops Lake, the bottom topography of the lake is being smoothed, and the delta is advancing westward into the lake. Figure 5 shows the post-glacial history of the lake basin.

At present the Kamloops Lake surface is given as 336 m (Water Survey of Canada datum, 1102.95 ft), but it undergoes an annual change of up to 7.6 m due to the seasonal variations in water supply. Most of the water comes from snow-melt in the spring.

2.2 Methods

a) Field Procedures

An echo-sounding survey of the lake was conducted during July, 1973 using an Atlas DESO-10 dual frequency sounder. No allowance was made for changes in sound velocity resulting from water density differences associated with temperature stratification. Temperature data from July, 1974 suggest that the error in the 1973 soundings is *circa* 3%. Sounding lines (Fig.6) were run at constant speed between prominent topographic features on the shore. Aerial photographs and 1:50,000 scale topographic maps were used to identify landmarks.

Thirty-six Shipek grab samples of bottom sediment were obtained from the lake and the Thompson River east of the lake (Fig.7). Descriptions of texture, surface features, stratification, macrobiological content, and colour (against the Munsell Colour Chart) were made on all samples upon retrieval. Subsamples were taken of the upper 1-2 cm of sediment, and of the underlying material. If large-scale (1-3 cm) stratification occurred, subsamples were taken of each layer. All samples were sealed in plastic bags, transported in coolers, and stored at 4°C until freeze-dried.

Gravity cores were obtained from selected sites in the lake to provide historical information concerning changes in the lake's characteristics preserved in the sediments. Cores for geochemical analyses were collected with a triple-barrelled corer of the type described by Kemp *et al* (1971). Palynological samples and material for Ce-137 determinations (not reported here) and cores for sedimentological analysis were obtained using a Benthos corer with a two metre plastic barrel.

The sedimentology cores were split immediately to minimize disruption of laminations by escaping gases and described in the field. Half of the core was then permitted to air-dry; the remainder was stored moist at 4°C in thin plastic.

All other cores were subsampled shortly after collection so as to minimize bacterial alterations of the sediment chemistry and disruption by gas evolution; the piston extruder used for this purpose is described by Kemp *et al*

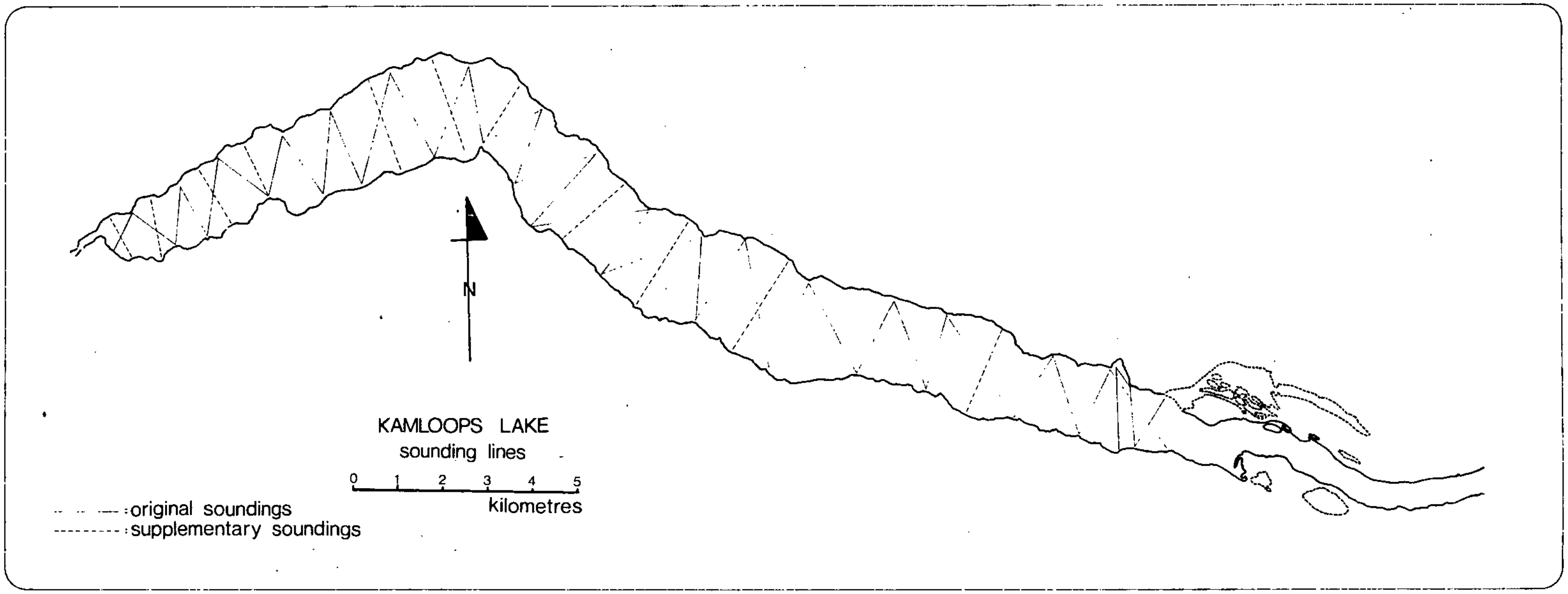


Figure 6. Echo-sounding survey lines in Kamloops Lake. Solid lines show transects run in July, 1973; dashed lines are additional transects run in 1974.

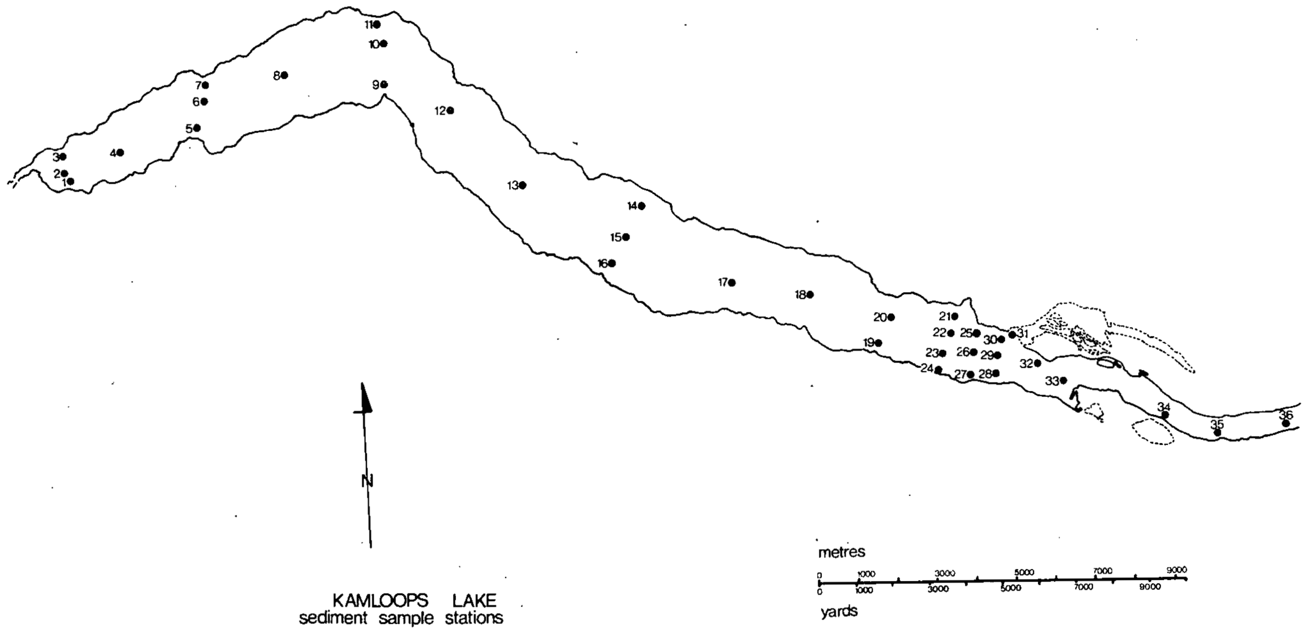


Figure 7. Distribution of sediment sampling stations in Kamloops Lake.

(1971). For the geochemical analyses, 1 cm sections were extruded at 1 cm intervals for the top 20 cm; 2 cm intervals between 20 and 30 cm; and every 5 cm for the rest of the core. One centimetre thick samples for palynology were taken every second centimetre to 20 cm depth, than a 1 cm thick slice was removed every 10 cm to the end of the core.

b) Analytical Procedures

All surface sediment samples and core subsamples were lyophilized, and all subsequent laboratory analyses were conducted on freeze-dried material. To establish whether lyophilization altered clay minerals or grain-size distributions, both wet and freeze-dried subsamples were compared. No detectable differences in grain size or clay mineralogy were identified beyond the range of normal intra-sample variation.

Most sediment samples consisted of silt and clay-sized material. Consequently, the grain-size distributions of most samples were obtained using a Sedigraph 5000 fine-particle analyzer. Approximately 2 g of sediment were blender homogenized for 6 min. in 0.05% Calgon solution. For samples containing more than 5% sand-sized material, a combined sieve and sedigraph technique and, for comparison, a sieve and pipette method was used. Statistical measures of grain-size distribution, mean, standard deviation, skewness, and kurtosis were computed for each sample.

Selective extractions to identify the forms of inorganic phosphorus and trace metal contents were determined on subsamples from cores. Total phosphorus was analyzed spectrophotometrically on acid extractions, while selective extractions for specific forms of phosphorus were made by Dr. J. D. H. Williams, CCIW-Burlington. Trace metal analyses were conducted on acid-extracts by atomic absorption spectrophotometry and by radio-frequency-induced argon plasma emission spectroscopy at Barringer Research Laboratories, Toronto.

Six surface samples and subsamples from one core were analyzed by x-ray diffraction for major mineral species present in the clay (finer than 2 μm), fine silt (2-5 μm), and medium silt (5-20 μm) size fractions. The sample preparation technique of Kittrick and Hope (1963) as modified by Harris and Lavkulich (1972) was employed. Semi-quantitative analysis of the clay mineral species in the finer than 2 μm fraction was accomplished using Biscaye's (1965) weighting factor.

Estimates of sedimentation rates were made from a series of cores collected along the axis of the lake basin. One-half of each of the split cores was allowed to dry completely, and the split surface scraped clean of oxidized material and smoothed with fine sandpaper. A 1:1 mixture of glycerine and water was sprayed on the smoothed surface to enhance laminations. Assuming most of the thin dark layers of each lamination couplet represented a single winter's accumulation, the number of dark layers was counted, and the annual vertical accumulation of dry sediment and the amount per unit area calculated. Since the couplets are composed of alternating light and dark layers that are interpreted as summer and winter accumulations respectively (ie. combined as annual deposits), the laminae can be interpreted as varves. While shrinkage of up to 15% due to water loss has occurred in some of the cores, the calculations have been made on a sediment dry-weight basis and are in error only to the extent that some dark laminae may represent intra-varve accumulations.

2.3 Bathymetry and Basin Morphology

Morphometric parameters for Kamloops Lake are given in Table 1. A hypsometric curve relating lake area and volume to depth, and a bathymetric chart are presented in Figures 8 and 9, respectively.

Kamloops Lake can be conveniently considered as two intergrading basins divided at about the point where the lake bends to the southwest. To the east, the basin sides are uniformly steep and the basin floor smooth, becoming gently undulating near the bend. At the extreme east end is the Thompson River delta,

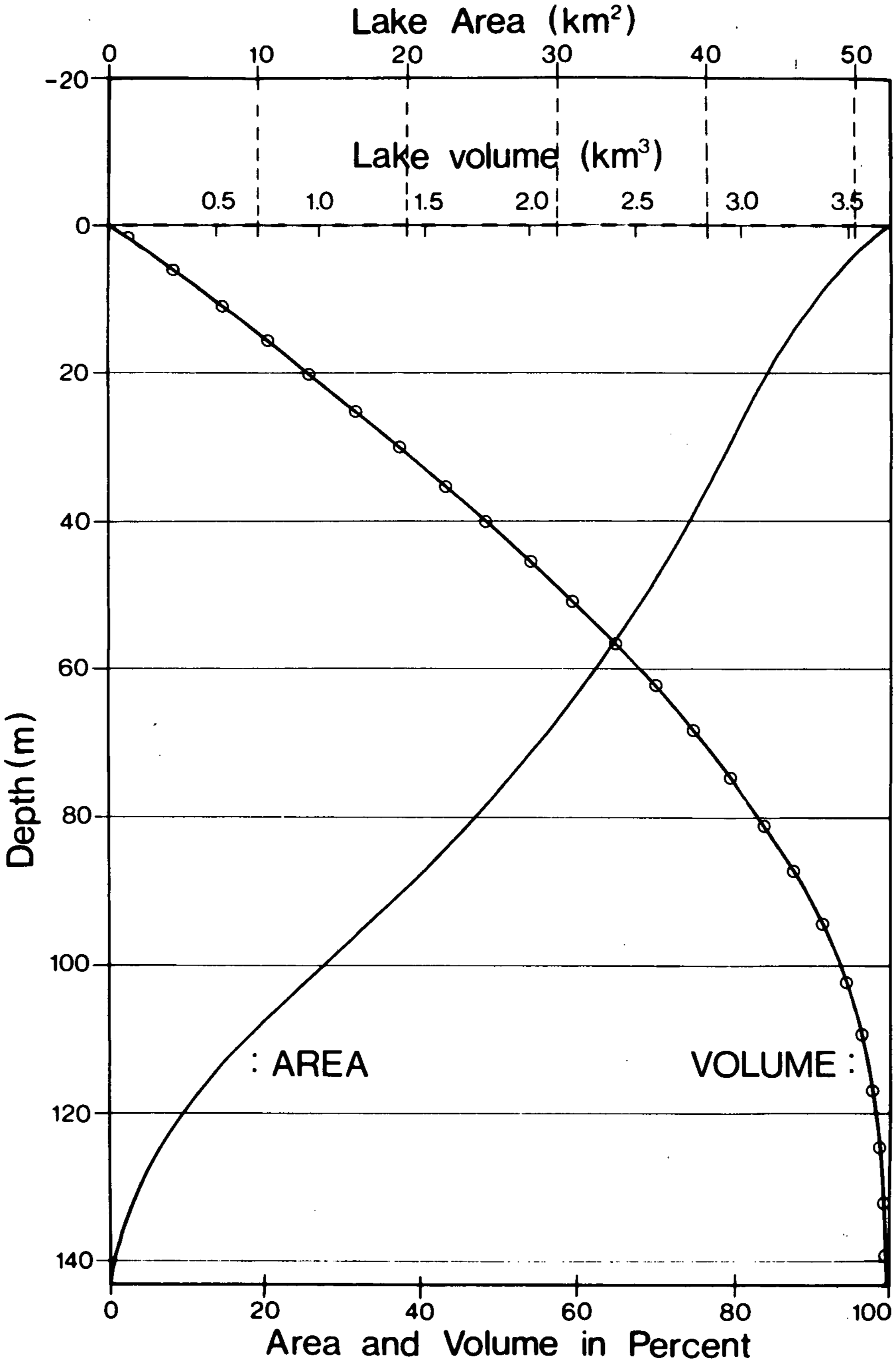


Figure 8. Hypsometric curve for Kamloops Lake showing relative areas and volumes of the lake above certain depths.

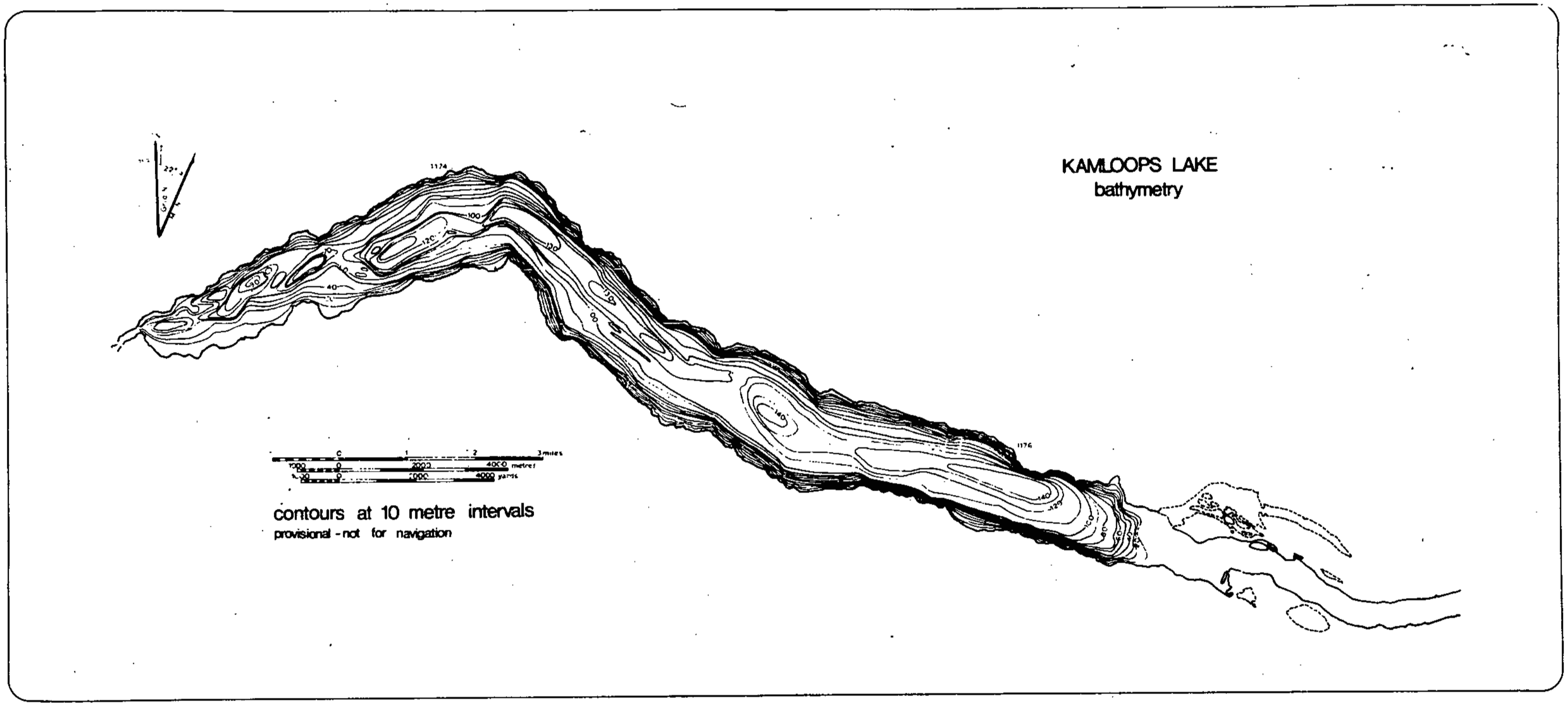


Figure 9. Bathymetric chart of Kamloops Lake. Data obtained from survey lines of Figure 6.

Table 1. Morphometry of Kamloops Lake

Area (A)	52.07 km^2
Volume (V)	3.70 km^3
Length (l)	25 km
Mean Depth ($\bar{z}$)	71 m
Maximum Depth (Z_m)	143 m
Mean Breadth ($\bar{b}$)	2.1 km
Maximum Breadth (b_m)	2.4 km
Shore Line (L)	60.5 km
Shore Line Development ($D_L = L/2\sqrt{\pi A}$)	2.37
Elevation of Datum (H)	336.18 m

a steep (gradient 1:16, locally as steep as 1:4; Fig.23), unstable slope where very rapid sedimentation is occurring. The basin floor immediately west of the delta front is smooth. The rate of sedimentation decreases away from the delta and, in consequence, basin floor relief becomes more pronounced with ridges and shelves covered, but not yet buried, by modern sediment.

West of the bend the average depth of the lake bottom decreases continuously and, except on the north side of the lake, the basin margins are less steep and locally show extensive shallow shelves. Bottom relief is pronounced. Bedrock, identified in seismic profiles, occurs at a shallower depth than in the eastern basin, and appears to have a more irregular surface. The general upward slope of the bottom and its rugged character indicate that the lake bottom in the eastern end of Kamloops Lake is situated on the edge of the old outwash from Deadman Creek.

2.4 Sediment Distribution

A description of shoreline sediments has not been included in this study. The bedrock or gravel and sandy gravel beaches forming the lake margins are regions of complex energy relationships resulting from wave action and water level fluctuations that occur naturally in Kamloops Lake. Most of the sediment supplied to the lake is deposited within the lake basin below the steeper marginal slopes.

The distribution of sediment types (Fig.10) is based on the nomenclature of Shepard (1954) as derived from the subdivision of a ternary diagram with sand, silt, and clay as end-members. Sediments are sandy at the east end of the lake and become increasingly enriched in clay toward the west. Silts extend further along the basin on the north side of the lake and grade into clayey silts to the south and west.

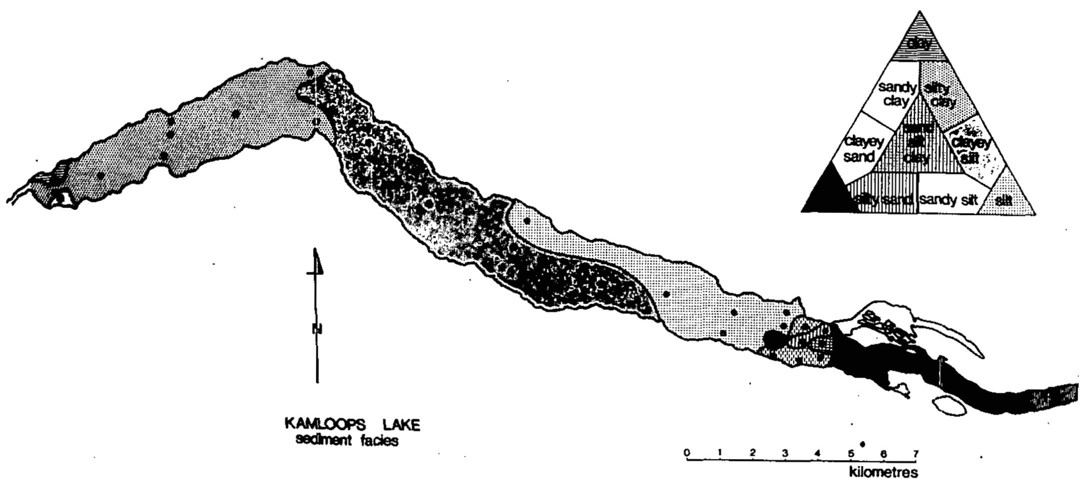


Figure 10. Distribution of sediment facies in Kamloops Lake according to the Shepard (1954) classification.

The mean grain-size of Kamloops Lake sediments decreases from east to west along the lake (Fig.11). Isopleths are concentrated at the eastern end of the lake, over the Thompson River delta, becoming more widely spaced toward the west. A tongue of coarser sediment extends along the lake on the north side.

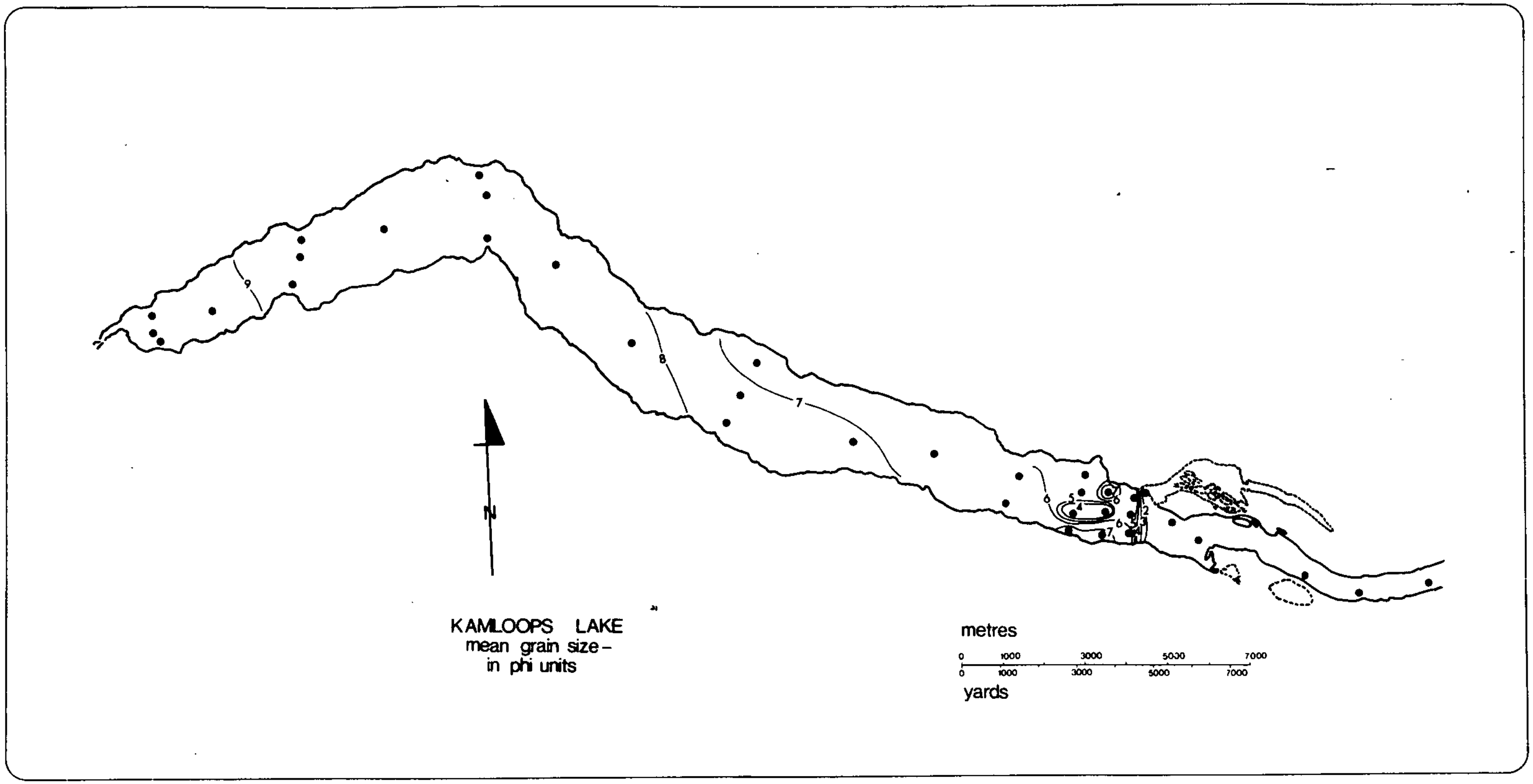


Figure 11. Distribution of mean grain size (in phi units: $\phi = -\log_2$(grain size in millimetres)) of Kamloops Lake sediments. Isopleths at whole phi intervals.

This assymmetric pattern, which is also apparent in the decreasing silt and increasing clay contents (Figs.12 and 13, respectively), reflects the extension

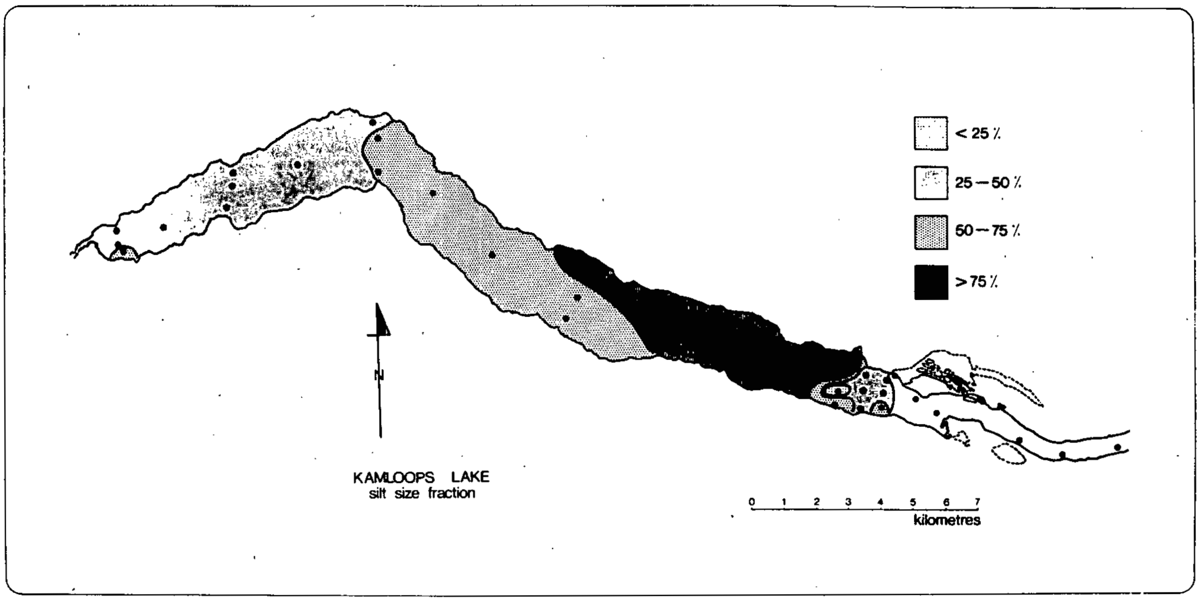


Figure 12. Distribution of the silt-size (63-4 μm) fraction of Kamloops Lake sediments.

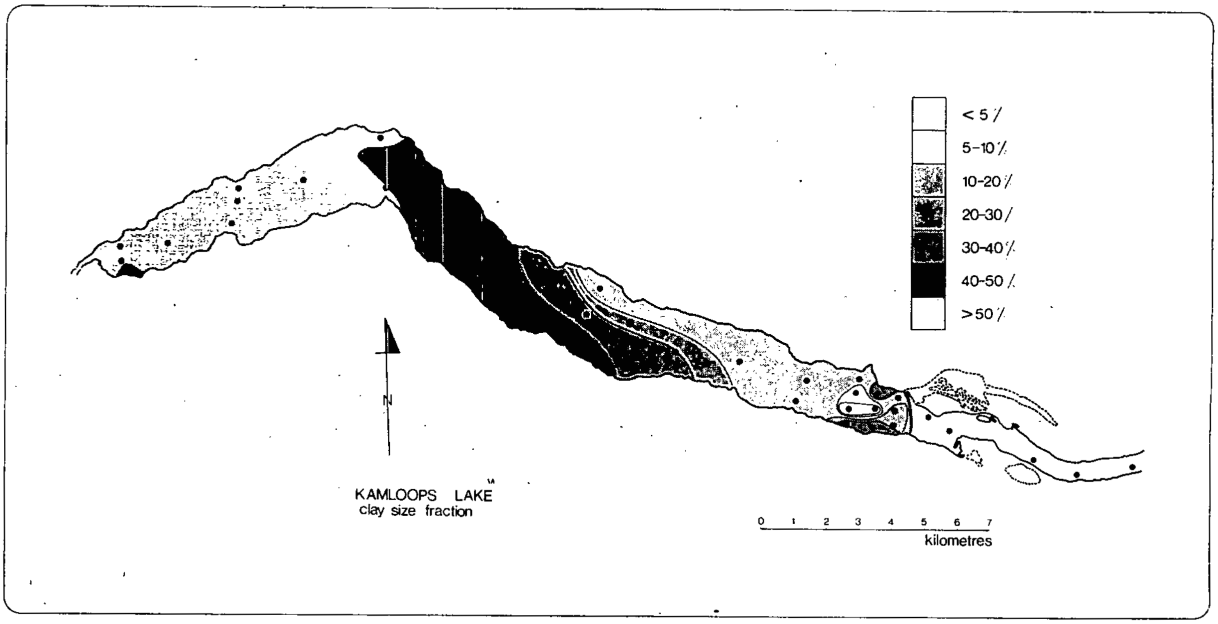


Figure 13. Distribution of the clay-size (finer than 4 μm) fraction of Kamloops Lake sediments.

and confinement of river-induced flow along the north side of the lake. A zone of anomalously coarse and sandy sediment occurs near the foot of the Thompson River delta (Figs.10,11). The delta profile suggests that mass movement of the sediments is occurring as small slumps, sandflows, or continuous creep. Underwater photographs suggest that massive slumps of sediment originate on the upper slope of the delta leaving vertical walls of bedded sand. The zone of coarse sandy sediment is believed to have originated from such a slump which may have developed into a sediment flow that extended a short distance beyond the delta front. The east end of the coarser sediments of the slump mass is slowly being covered by more recent sediments. Because of its location and the rapid rate of sedimentation in this area, the "slump" must have occurred in only the last few years.

The sedimentological patterns reflect only minor effects of the smaller streams that flow into the lake. For example, no modification to the distribution of sediment parameters is apparent near the mouths of Cherry or Carabine Creeks. Minor effects (slightly coarser mean grain-size and siltier sediment) occur near Savona (site 1, Fig.7). A sample near the mouth of the Tranquille River has a smaller mean grain-size than neighbouring samples, suggesting that the input from the Tranquille River has modified the pattern of sedimentation near its mouth. Benches or terraces constructed of gravels and gravelly sands, situated at the mouth of the Tranquille River between high and low lake levels, indicate that while this material is being supplied to the lake margin by the Tranquille River it is not being transported into the lake.

Sedimentary substrates at the inlet and outlet ends of Kamloops Lake reflect totally different sedimentologic and energy regimes. The delta at the eastern end is sandy, and is an area of rapid sedimentation. Substrate on the delta topset zone reflects the nature of the load of the Thompson River. At the outlet, in contrast, the substrate reflects the lack of sedimentation and the nature of the underlying sediments. The river bed is rocky, composed of cobbles, gravels and sand derived from the old glacial Deadman Creek outwash; it is relict rather than modern.

2.5 Mineralogy

Chlorite, illite (as a well-crystallized form probably representing finely ground mica), quartz, feldspar, and minor amounts of montmorillonite were identified from the clay-size (finer than 2 μm) fractions of the Kamloops Lake sediments; there is also some indication of the presence of mixed-layer minerals. Some of the illite may be finely ground vermiculite rather than mica. The fine silts (2-5 μm) have a similar mineral content, with an increase in the amount of feldspar and quartz and the appearance of amphibole. The 5-20 μm fractions contain quartz, feldspar, chlorite, mica (of more than one kind), amphibole and pyroxene. Quantitative assessment by x-ray diffraction of the amounts of various minerals present is not possible for other than clay mineral species. Small quantities of a particular mineral species (less than 5-10% by volume of the total) are not detected by this technique (eg. apatite, a resistant, phosphate-bearing mineral is present in quantities too small to detect and identify by x-ray diffraction analysis).

Increasing concentrations of pyroxenes and amphiboles occur adjacent to the Thompson River delta. Semi-quantitative analysis of clay mineral composition shows no regular change in proportion of the three main clay minerals present. The average composition for six samples is 2.7% montmorillonite, 71.5% illite, and 25.8% chlorite with ranges of 1-4%, 64-76% and 21-33%, respectively.

2.6 Sediment Geochemistry

a) General Element Distributions

The horizontal distribution patterns of most elements in the surface sediments of Kamloops Lake are strongly related to sediment particle size distribution. Both the clay minerals and the proportion of fine (clay-size) material comprising the sediment effect this control. Aggregations of small particles have greater surface areas than larger particles of comparable mass, and consequently more sorption sites for oxides and hydroxides of iron and associated trace elements. Some of the elements measured may also be an integral part of the clay minerals themselves. Evidence for the element/particle-size relationship is seen in the similarity of the distribution patterns of magnesium and potassium within the clay minerals (Figs.14,15), acid-extractable iron, which is commonly adsorbed onto the clay and fine particles (Fig.16), and the clay-size material (Fig.13). Similar distribution patterns were found for copper, zinc, vanadium, manganese, nickel, cobalt, chromium, scandium, lead, cadmium, mercury, strontium, aluminum, titanium, and calcium (none shown diagramatically).

The element-particle size relationship is also shown on plots of element concentration versus distance from source (the Thompson River delta). Such regression plots generally show quite high correlations, ranging from 0.976 for magnesium to 0.738 for cadmium (Figs.17,18). However, this high correlation does not occur with one group of elements. The concentrations and distribution patterns of fluorine, phosphorus, and a suite of lanthanides do not seem to be controlled by particle size in the bottom sediments (Fig.19).

b) Sediment Phosphorus Geochemistry

The various forms of phosphorus occurring in the sediments of Kamloops Lake were identified by selective chemical extractions (Chang and Jackson 1957; Williams *et al* 1976). Organically bound phosphorus was probably present in amounts ranging from 10-15%, while phosphorus included in the lattices of insoluble silicate minerals accounted for only a few percent of the total phosphorus (Dr. J. D. H. Williams personal communication). The remainder of the phosphorus in the Kamloops Lake sediments is inorganic. Selective extraction procedures

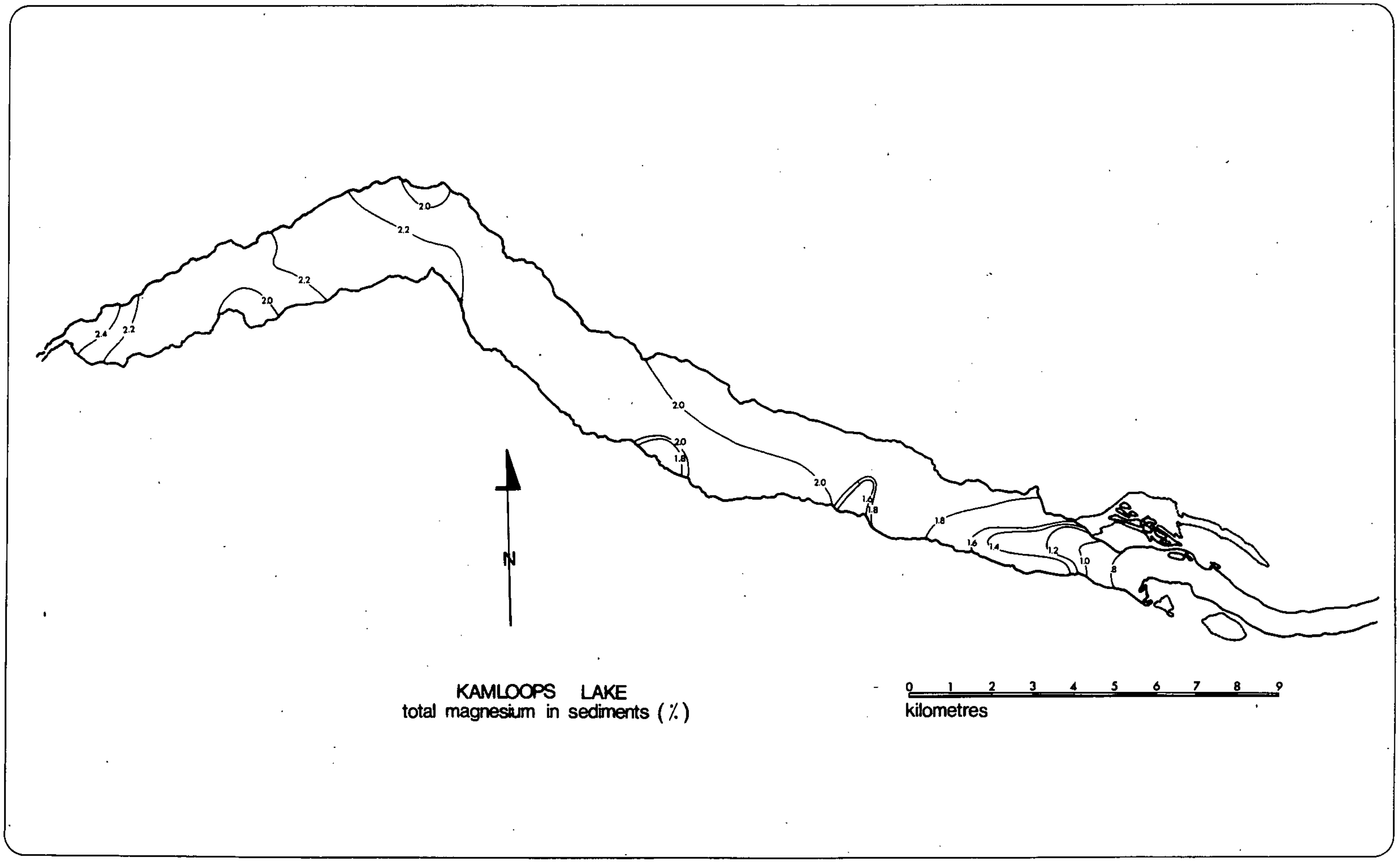


Figure 14. Distribution of total magnesium in Kamloops Lake sediments. Isopleths in percent.

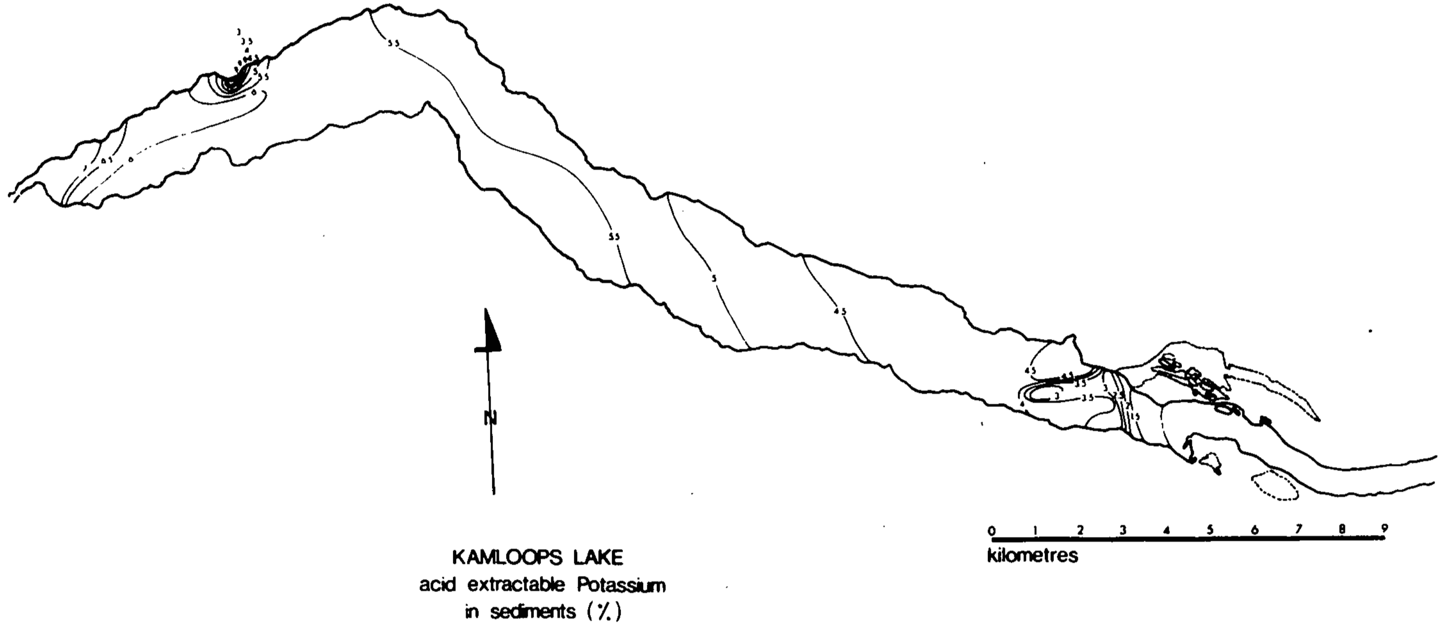


Figure 15. Distribution of acid-extractable potassium in Kamloops Lake sediments. Isopleths in percent.

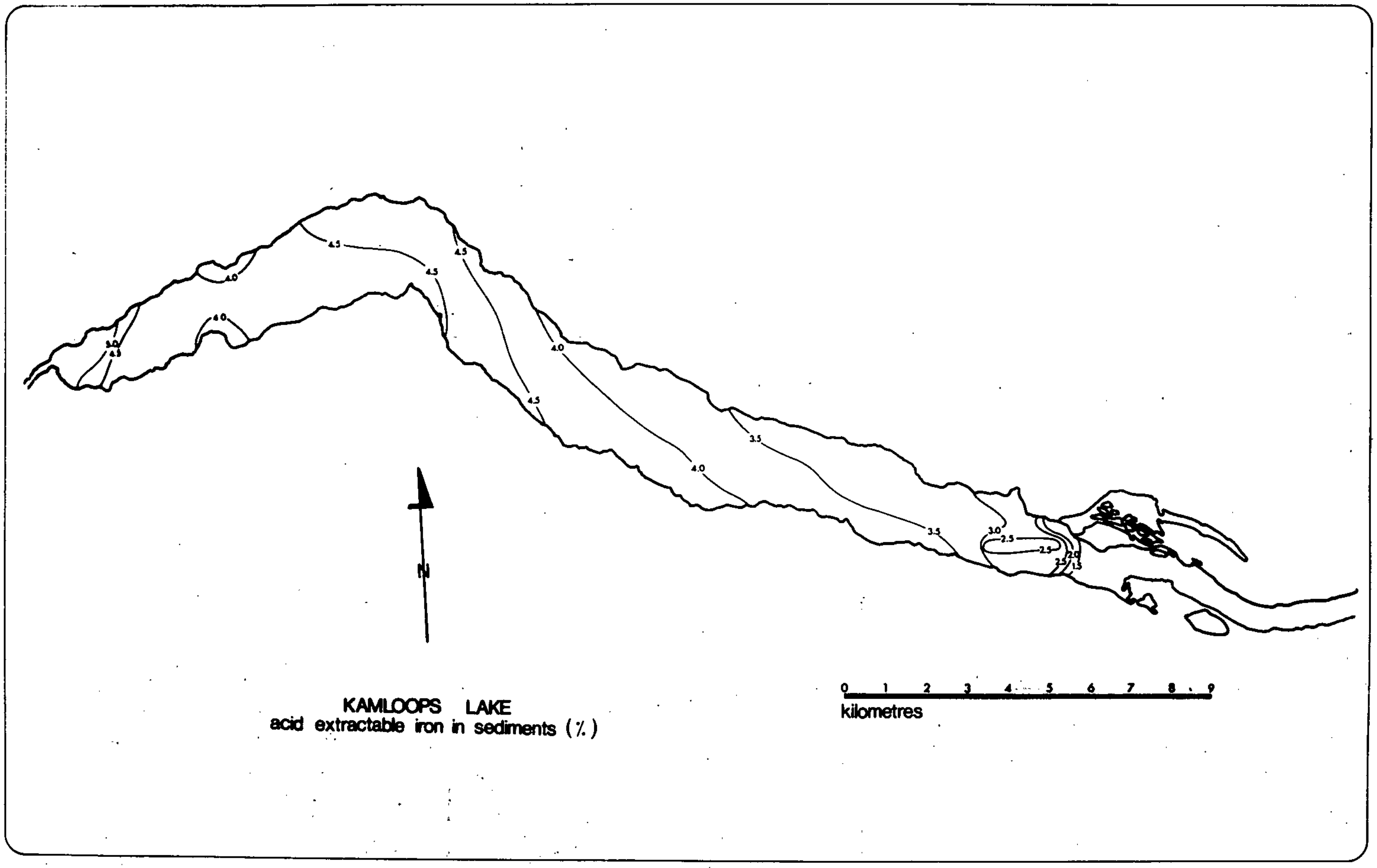


Figure 16. Distribution of acid-extractable iron in Kamloops Lake sediments. Isopleths in percent.

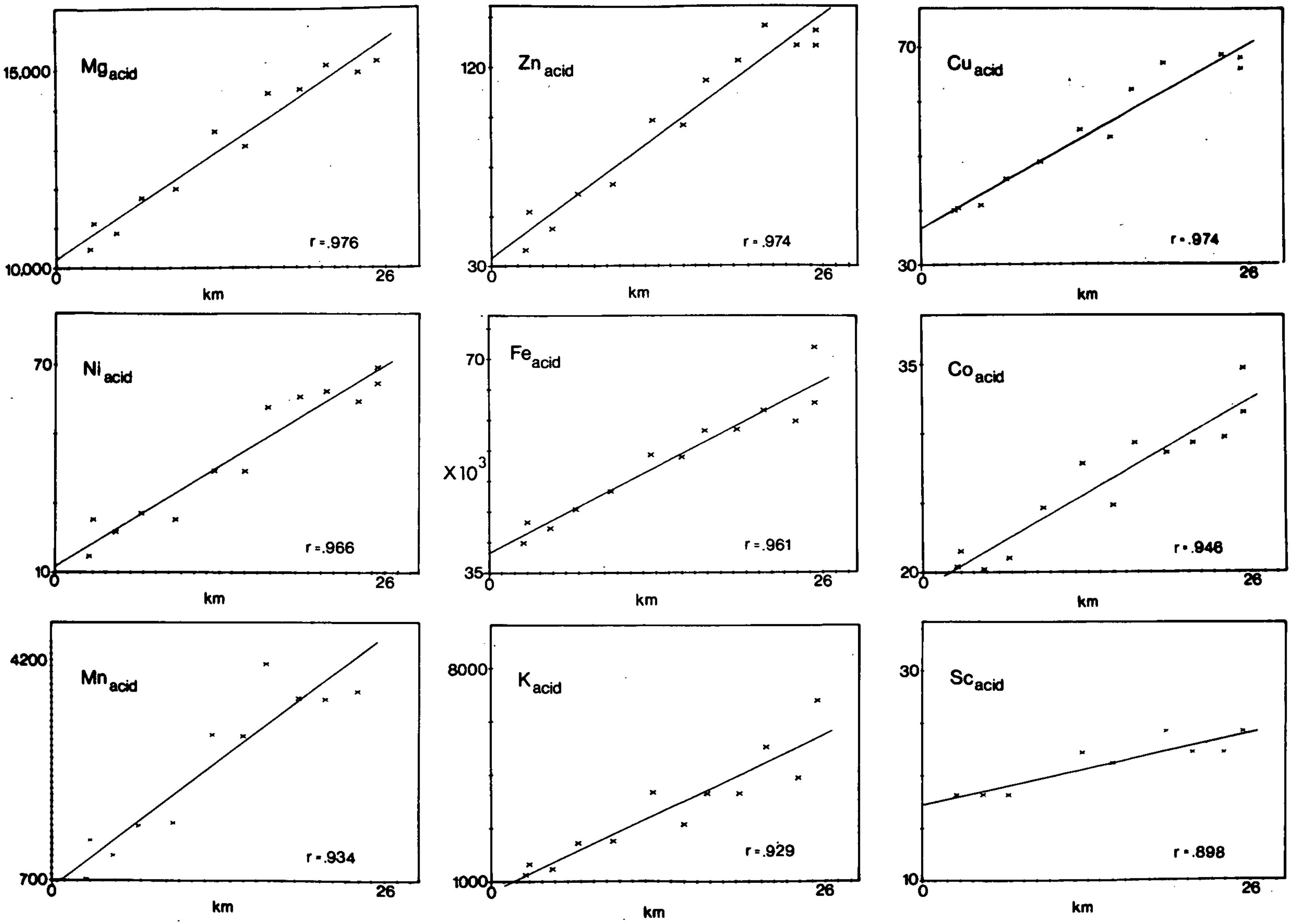


Figure 17. Regression plots of the concentrations (in micrograms per gram) of various trace elements in Kamloops Lake sediments against distance of sample sites from the Thompson River delta.

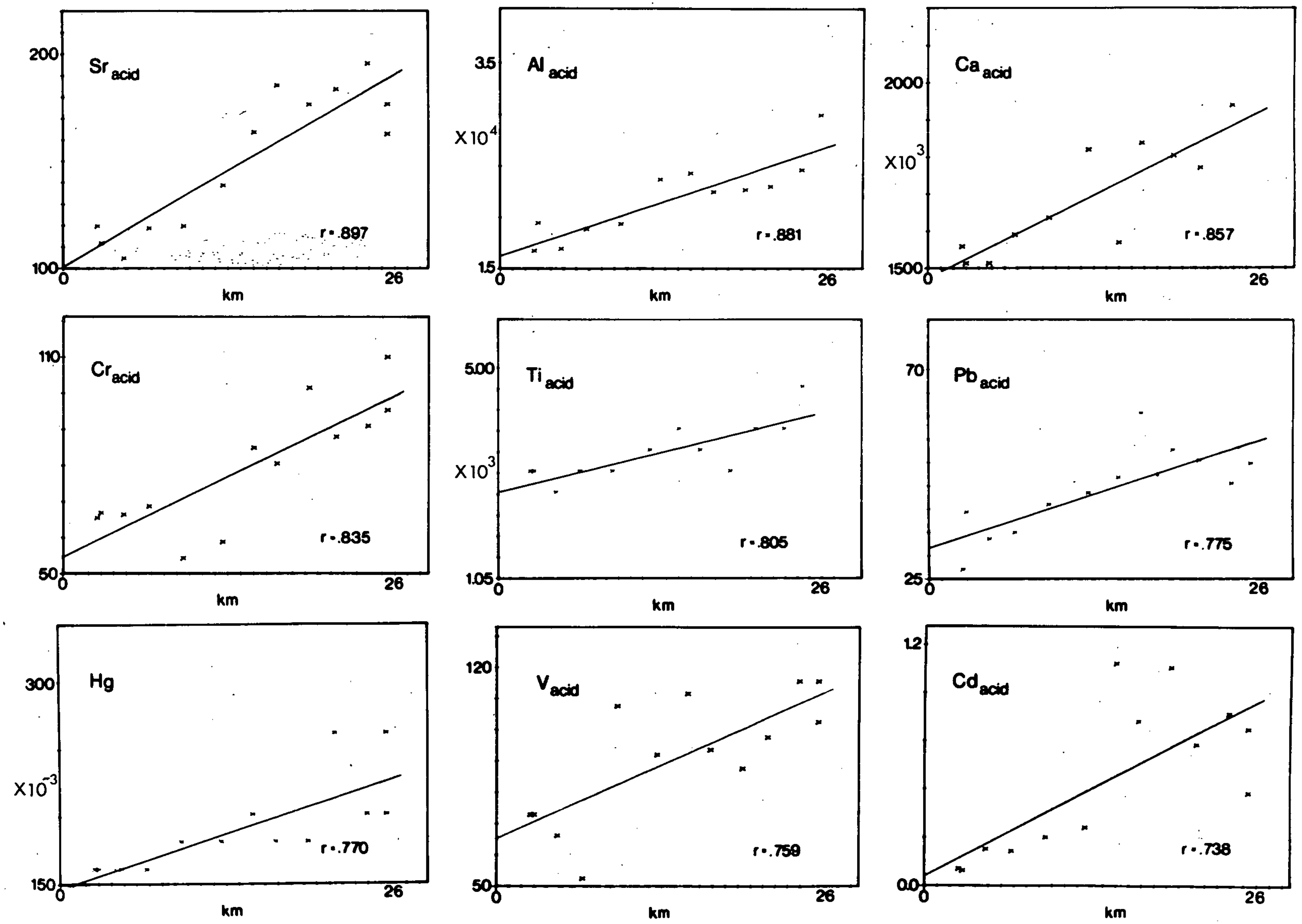


Figure 18. Regression plots of the concentrations (in micrograms per gram) of various trace elements in Kamloops Lake sediments against distance of sample sites from the Thompson River delta.

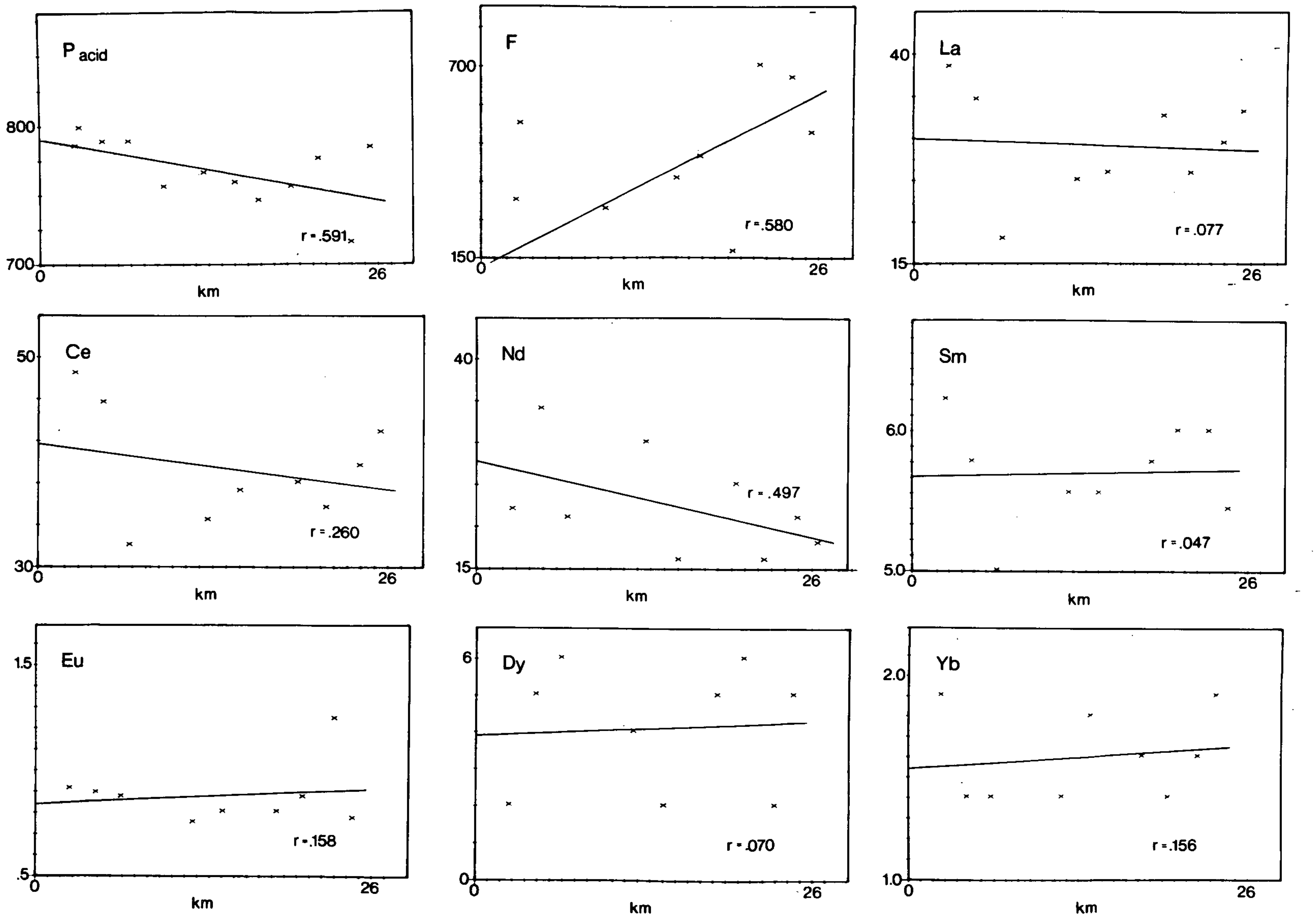


Figure 19. Regression plots of the concentrations (in micrograms per gram) of various trace elements in Kamloops Lake sediments against distance of sample sites from the Thompson River delta.

were used to characterize inorganic phosphorus as either 'apatite phosphorus' or 'non-apatite inorganic phosphorus (NAIP)'. The former is a mineral of general formula $Ca_{10}(PO_4)_6F_2$. It is extremely insoluble: the solubility product of fluorapatite (the most common form of primary apatite) is $10^{-118.8}$ (Wier *et al* 1972). Also, there is evidence that the dissolution rate of apatite under natural conditions is very low; for example, apatite persists in typical non-calcareous soils, with pH values of less than 7, for thousands of years (Williams *et al* 1969). Uniform concentration values of apatite phosphorus down the length of a core of Kamloops Lake sediment (Fig.20) indicates that, once incorporated into the sediment column, apatite is stable. In addition, the average time during which apatite is in contact with lake waters prior to burial by sediment is probably very short in view of the rapid sedimentation rate in Kamloops Lake (Section 2.7). It is therefore concluded that dissolution of apatite cannot support significant concentrations of biologically available phosphorus in the water column.

The nature and origin of NAIP is complex, but it appears to be produced or sedimented at the sediment-water interface as orthophosphate ions associated with amorphous hydrated iron oxides which are, in turn, associated with organic matter and clay minerals. This form of phosphorus may become available for biological utilization.

The relatively uniform concentration of acid-extractable phosphorus in the surface sediments of Kamloops Lake mentioned above (Fig.19) indicates that the phosphorus is associated with minerals of a wide range of grain-sizes. The grouping of phosphorus, fluorine, and the lanthanides, separate from the elements with gradational concentrations, and the estimation that approximately one-half of the total mass of the rare earth elements in the Earth's crust is bound in the minerals of phosphorus, titanium, niobium and zirconium, with the

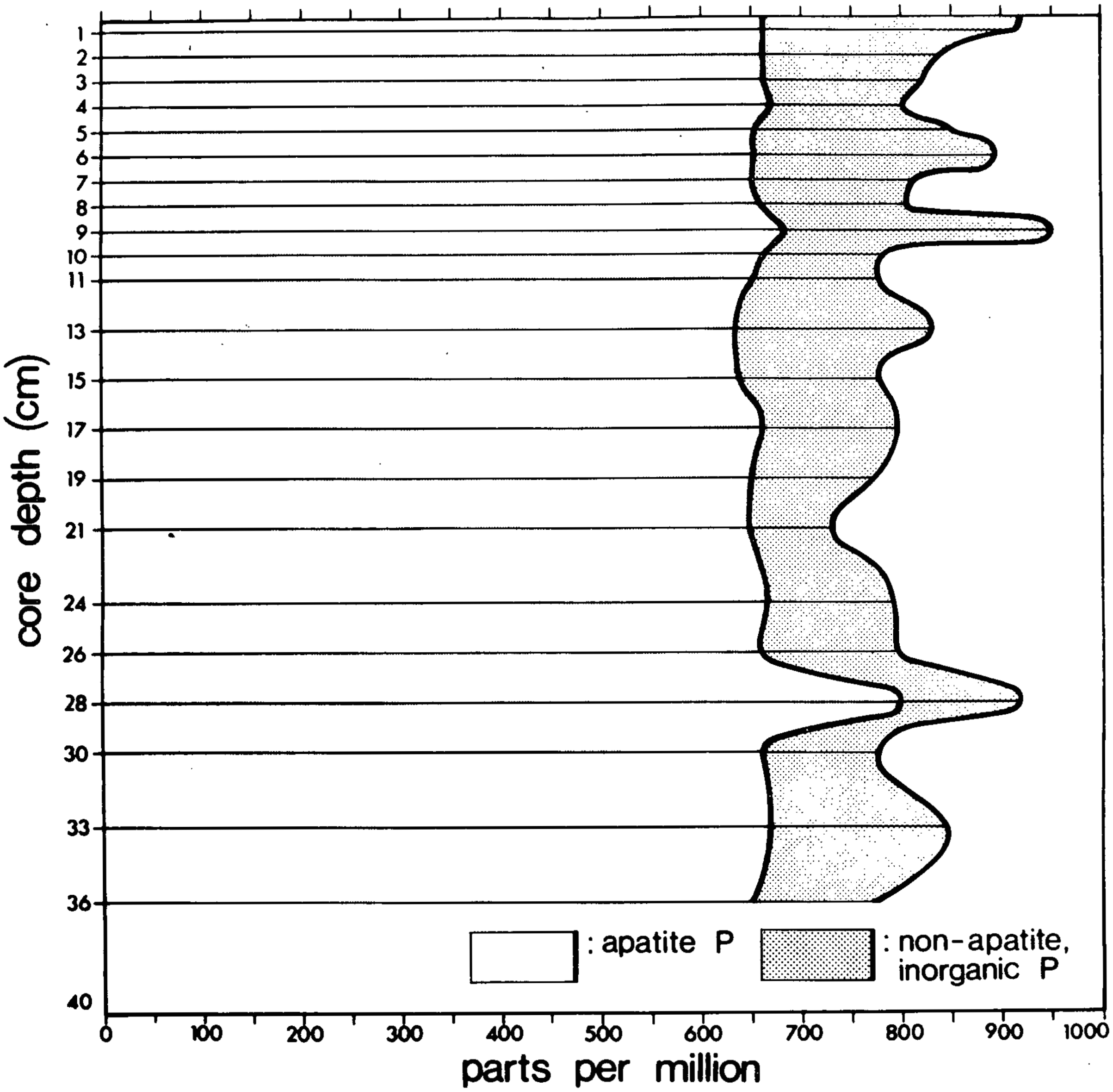


Figure 20. Concentrations of inorganic phosphorus forms in subsamples from a core taken from site 20, Kamloops Lake.

prime phosphorus mineral being apatite (Khomyakov 1971), suggests that these elements are present in the mineral apatite. Furthermore, these observations suggest that the apatite is widely distributed in particle size. If apatite occurred predominantly in a single particle size fraction, it would be largely removed in the basin unless that size was exceedingly small.

The mean content of apatite phosphorus relative to total inorganic

By comparing isobaths from these two charts, along a line perpendicular to the delta, estimates of delta growth and rates of advance of the delta front were obtained. Some error arises from the lack of coincidence of the lake's outline on the two maps. Nevertheless, the results indicate a rapid average annual advance of the delta front. Figure 22 shows profiles (31 x V.E.) of the Thompson River delta from the two charts, and includes figures of the total and average annual rate of growth of this section of the delta. It is unlikely that the entire delta front is advancing at the same rate, but further work comparing pre- and post-freshet accumulation in 1975 is expected to provide more information on the growth and development of the delta.

Locations of cores used for calculating sedimentation rates are shown in Figure 21. The map of the lake was arbitrarily divided into cells centred on each of the cores. Assuming a specific gravity for these sediments of 2.7

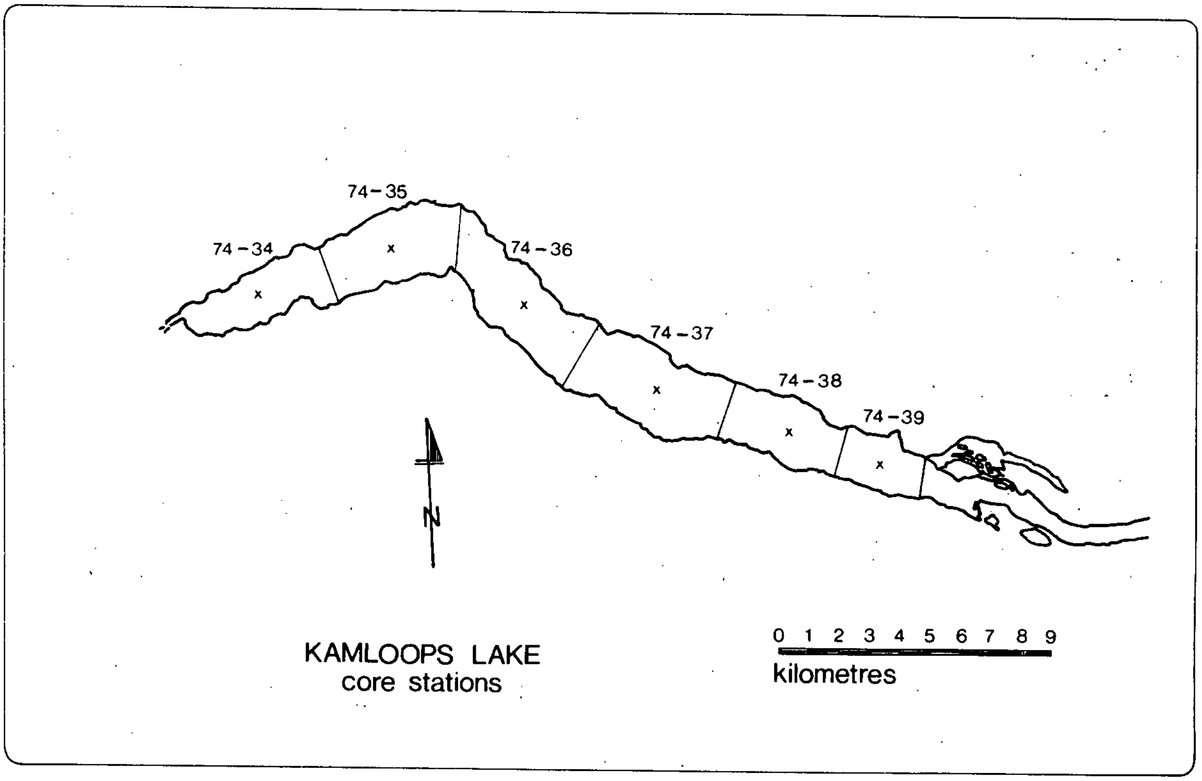


Figure 21. Location of core sites in Kamloops Lake from which accumulation rates were calculated, and cell boundaries used to calculate budgets.

phosphorus for a sediment core collected from Kamloops Lake (at the same station as sediment sample 20) is about 80% (Fig.20). The NAIP concentrations in the subsamples of the core are fairly uniform. The slightly higher value for the interface subsample (0-1 cm) is normal in lake sediments, and does not necessarily indicate increased loadings to the lake (Dr. J. D. H. Williams personal communication). This lack of apparent increased loading in the core does not indicate that such an increase did not occur in recent years, but rather that it was either small compared to the total NAIP load or was not of a form suitable for retention in the lake.

The occurrence of biologically unavailable apatite over a wide range of grain-sizes in the Kamloops Lake sediments is significant in that it suggests the presence of apatite in the water column in similar proportions to the sediments. This conclusion is of considerable chemical importance in relation to nutrient loadings to the lake. With apatite suspended in the water column, the total load of potentially available phosphorus is much lower than the total measured load (Sections 4.2b,6.1). The presence of apatite phosphorus causes further difficulties in determinations of lake trophic status by conventional models (Section 6.1).

2.7 Sedimentation Rates

Estimates of sedimentation rates have been made from investigations of cores, and by comparison of bathymetric charts made some years apart. The core studies give vertical accumulation, in dry weight of sediment per unit area per year.

In July, 1949 the International Pacific Salmon Fisheries Commission constructed a bathymetric chart of Kamloops Lake. During July, 1973, CCIW - Pacific & Yukon Region made a more intensive echo-sounding survey of the lake to trace sediment facies and to obtain more detail of the lake's bottom morphology.

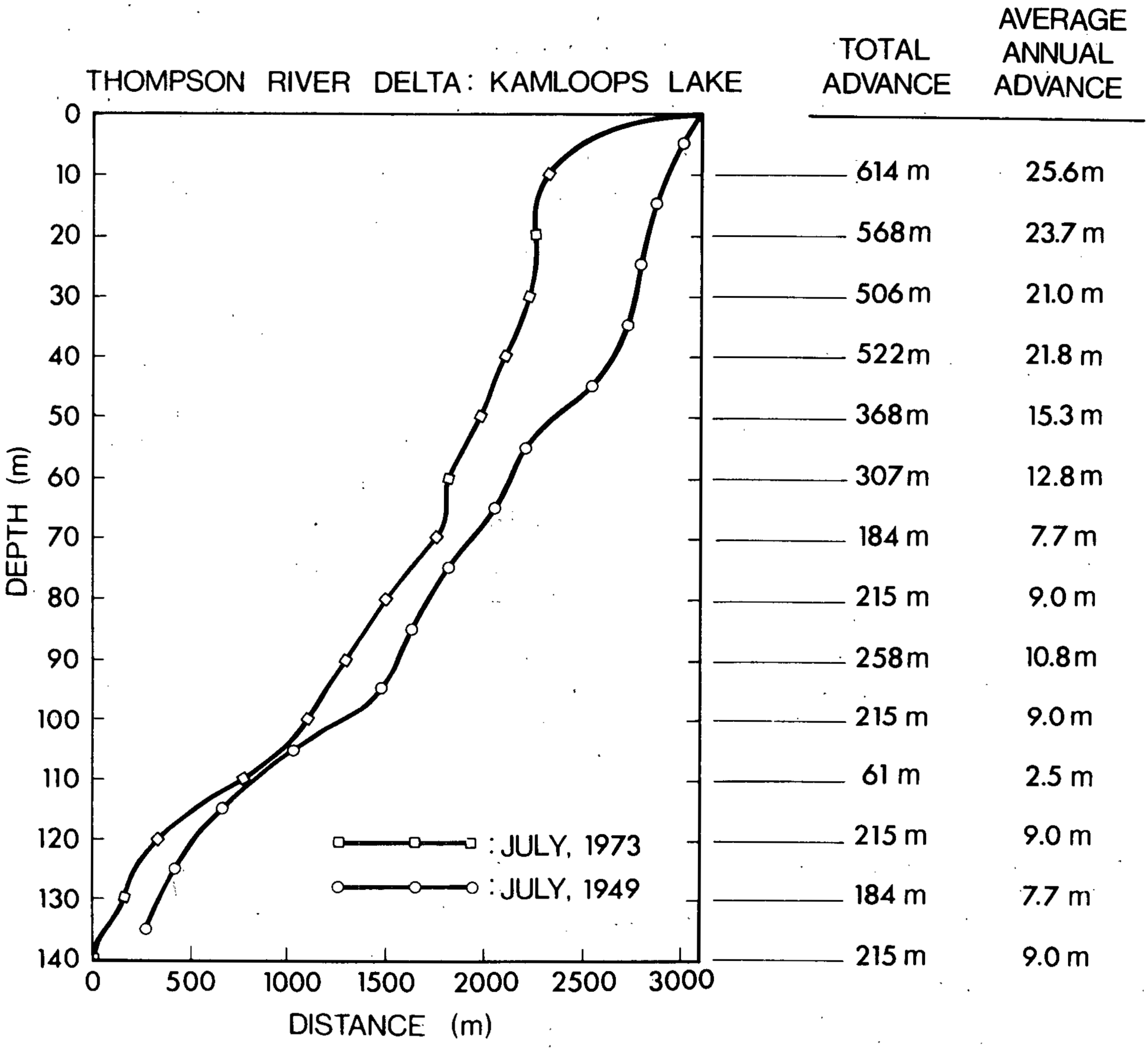


Figure 22. Profiles of the Thompson River delta at the east end of Kamloops Lake, determined from bathymetric charts compiled in 1949 and 1973. Vertical exaggeration of x31. Values of the total and mean annual advance of the delta front at 10 metre intervals are given.

g cm^{-3}, calculations were made of the amount of sediment accumulating in each cell per year assuming sediment accumulated at this rate over 80% of the cell area. Results of these calculations are given in Table 2.

The values given in Table 2 can be used to calculate budgets of chemical species in the sediments. By averaging the concentrations in each of the cells of each element measured, and calculating the mass of each element repre-

Table 2. Calculations of average annual sediment loading in cells centered on core sites.

Core#	Vert.accum. rate(cm yr^{-1})	Amount (g cm^{-2} yr^{-1})	80% of cell area(km^2)	Amt/cell (kg km^{-2} yr^{-1})	Amount (kg)
74-34	0.34	0.92	5.76	9.2×10^6	5.3×10^7
74-35	0.34	0.92	7.48	9.2×10^6	6.9×10^7
74-36	0.49	1.32	8.70	1.32×10^7	1.15×10^8
74-37	0.61	1.65	10.27	1.65×10^7	1.7×10^8
*74-38	1.5	4.05	5.40	4.05×10^7	2.2×10^8
*74-39	8.0	21.6	3.44	2.16×10^8	7.4×10^8

*Rates for these cores may be in error as a result of the rapid rate of accumulation and the short lengths of core over which rates could be calculated.

sented in the sediment budget of each cell, mean annual removal rates of the various chemical species into the lake can be obtained (see Table 3). Table 3 represents the sediment budget, on a mean annual basis, of various chemical species for Kamloops Lake. For the purposes of the present report only the figure associated with phosphorus is particularly important. The total mean annual removal rate of acid extractable phosphorus to the sediments is estimated at 1014 metric tonnes. This corresponds well with the estimate of total phosphorus retained in the lake during the study year through calculations based on water chemistry - 970 tonnes. As previously noted, however, about 80% of the acid extractable phosphorus is present as apatite, a mineral of negligible biological significance.

Table 3. Average annual loadings of trace and major elements to Kamloops Lake sediments.

Core around which sed'n "cell" is centred	Total sed'n in cell x 10^8 (kg)	Al_{total} (t)	Mg_{total} (t)	Fc_{total} (t)	C_{total} (t)	Hg_{total} (t)	S_{total} (t)	F_{total} (t)	Ti_{acid} (t)	Cd_{acid} (t)	Fe_{acid} (t)	Pb_{acid} (t)	Mn_{acid} (t)	Cu_{acid} (t)	Zn_{acid} (t)	Ni_{acid} (t)	Co_{acid} (t)	Cr_{acid} (t)	V_{acid} (t)	Sr_{acid} (t)	K_{acid} (t)	Ca_{acid} (t)	Mg_{acid} (t)	Sc_{acid} (t)	P_{acid} (t)	La_{acid} (t)	Ce_{acid} (t)	Nd_{acid} (t)	Sm_{acid} (t)	Eu_{acid} (t)	Dy_{acid} (t)	Yb_{acid} (t)
74-34	0.53	5031	1158	3749	901	0.01	20	36	71	0.05	3219	2.2	143	3.4	6.3	3.4	1.5	4.9	5.5	9.6	372	96	815	1.2	41.1	1.6	2.8	1.0	0.3	0.15	0.25	0.09
74-35	0.69	6429	1494	4663	1037	0.01	23	40	79	0.07	3931	3.5	248	2.4	8.2	4.3	2.0	5.9	6.3	12.2	376	118	983	1.7	52.6	2.1	3.3	1.4	0.4	0.06	0.21	0.11
74-36	1.15	10724	2381	7119	1529	0.01	28	52	132	0.11	6204	5.1	349	6.2	12.5	6.3	3.0	8.2	11.6	17.3	615	194	1518	2.5	87.6	2.9	5.1	2.6	0.6	0.09	0.40	0.18
74-37	1.7	15406	3273	9550	2316	0.03	56	87	179	0.15	8262	6.8	343	8.3	17.1	8.5	4.0	12.3	12.6	21.0	827	275	2091	3.7	131.8	4.1	7.7	3.7	0.9	0.13	0.78	0.27
74-38	2.2	17417	3799	10560	2933	0.04	67	116	213	0.16	9137	7.3	228	8.8	19.1	9.9	4.5	14.5	15.4	24.5	923	335	2369	4.0	173.9	8.0	16.0	6.2	2.6	0.20	0.77	0.36
74-39	7.4	53809	11343	30023	10064	0.11	233	316	814	0.48	24684	15.5	354	24.6	54.5	28.8	13.8	52.7	48.9	61.5	3023	989	6860	10.4	526.9	32.3	59.6	2.3	8.9	0.61	3.70	1.37
Total (tonne)		108816	23448	65664	18780	0.21	427	647	1488	1.02	55437	40.4	1665	53.7	117.7	61.3	28.8	98.5	100.3	146.1	6136	2007	14636	23.5	1013.9	51.0	94.5	17.2	13.7	1.24	6.11	2.38

3. PHYSICAL LIMNOLOGY

The physical limnology of Kamloops Lake exhibits several unique characteristics in comparison to other lakes of western Canada. Processes which affect the environmental condition of the lake are strongly influenced by the hydrology and climatology of the region. The purpose of this section is to summarize the salient physical processes and circulation features which directly bear on the chemical and biological condition of the lake and to interpret the important interaction of the Thompson River system with Kamloops Lake.

Physical monitor stations are presented in Figure 23. Electrobathythermograph (EBT) stations (for temperature and turbidity profiles) were occupied weekly for the study year. Supplementary EBT stations were added for the autumn and spring overturn periods. Three fixed temperature profilers (FTP) were also in place for twelve months. Each recorded the temperature at 21 depths to the bottom of the lake at 10 min. intervals in the summer and autumn and at 20 min. intervals in the winter and spring. Solar radiation measurements were recorded over the study year at Kamloops Airport (the easternmost "meteorological tower" symbol on Figure 23), while wind direction, wind speed, temperature, and humidity were recorded at the other "meteorological tower" site near Savona. Temperature recorders were emplaced above and below the lake to measure the temperature of the inflow and outflow at 10 min. intervals throughout the year.

3.1 Water Balance

The water balance of Kamloops Lake is dominated by the inflows of the North and South Thompson Rivers which merge near the city of Kamloops and enter the lake basin near Tranquille. The mean annual inflow, computed from historical streamflow data (Fig.24), is 720 $m^3 sec^{-1}$ or about 22.7 $km^3\ yr^{-1}$.

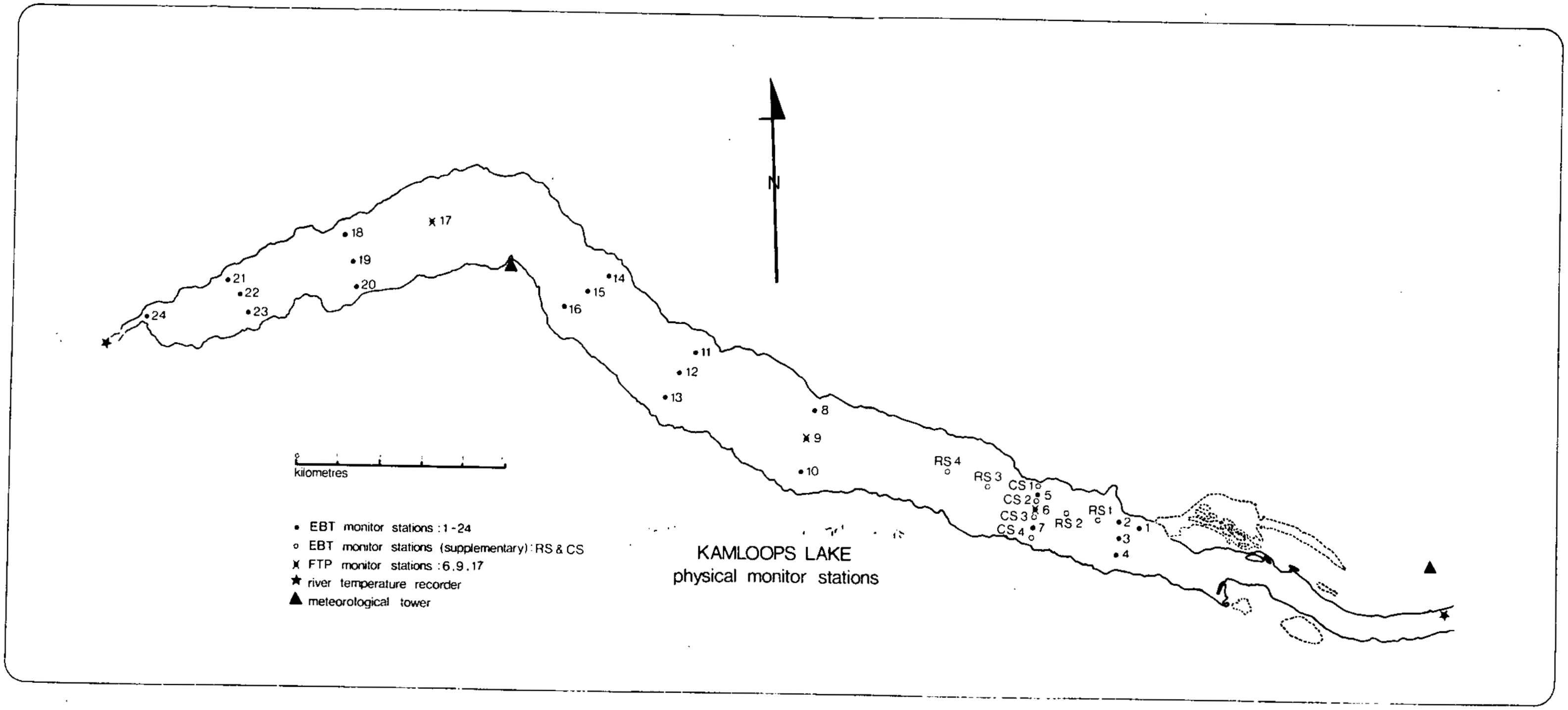


Figure 23. Physical limnology monitor stations on Kamloops Lake.

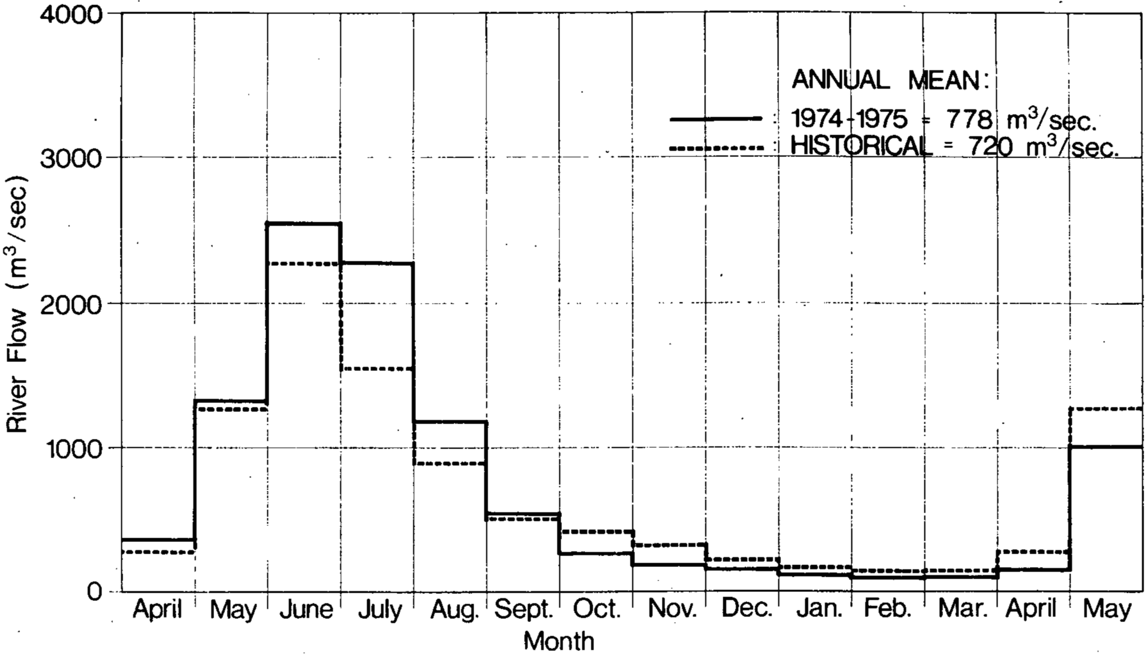


Figure 24. Mean monthly flow of the Thompson River inflow into Kamloops Lake. The solid line represents conditions during the Kamloops Lake study period; the dashed line represents the long-term mean.

For comparison, the mean inflow during the CCIW study period 1974-75 was 778 m^3 sec^{-1}, or about 8% higher than the historical average. Over 60% of the annual inflow comes in a three-month "freshet" period from May to July, with peak flows usually occurring in June. The mean inflow for the month of June is 2320 m^3 sec^{-1}. The river inflow declines sharply during winter reaching a minimum of about 170 m^3 sec^{-1} in February and March.

Several small tributary streams flow directly into Kamloops Lake, the most important of which are the Tranquille River, Cherry Creek, Copper Creek, and Durant Creek. Although these inflows were not gauged for streamflow, it is estimated that they contribute less than 1-2% of the total surface input.

The outflow of Kamloops Lake is hydraulically controlled. During periods of high streamflow, the lake inflow exceeds the outflow and, in consequence, the lake level rises. Figure 25 shows the mean monthly water level in Kamloops Lake. The highest water level recorded during the study year was

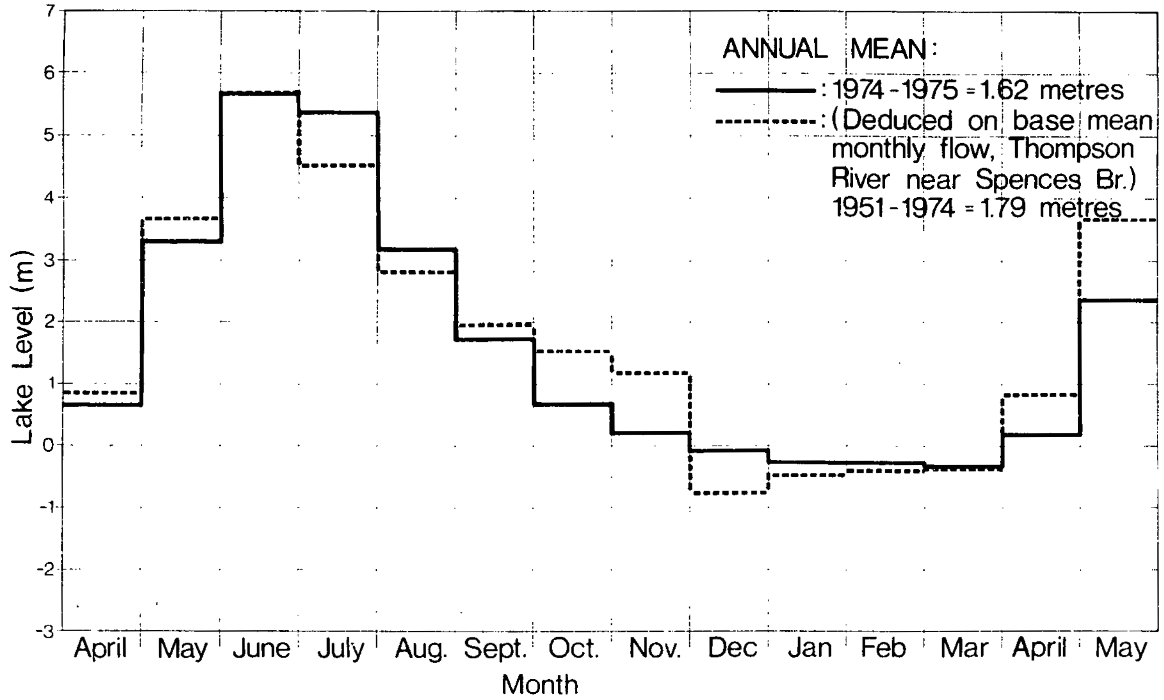


Figure 25. Mean monthly Kamloops Lake water level relative to lake datum level (336 metres). Solid line indicates conditions during the Kamloops Lake study period; the dashed line represents the long-term mean.

7.27 m above datum on 26 June, 1974; the lowest, -0.4 m on 24 February, 1975. This difference in lake level corresponds to a storage volume of *ca* 0.4 km , or 10% of the lake's total volume. Because of this feature, Kamloops Lake exhibits many characteristics of man-made reservoirs.

Perhaps the most significant aspect of the hydrologic regime in Kamloops Lake is the extremely short bulk residence time, T = V/R, where V is the volume of the lake and R is the river inflow. This parameter is also referred to as the 'basin filling time' for any given inflow rate. The bulk residence time (Fig.26) varied from about 18 days for June to about 340 days in February with an annual mean of 60 days. In comparison, the filling times for Okanagan and Kalamalka Lakes are 60 and 71 years, respectively. The extremely short filling time in Kamloops Lake effects a relatively rapid renewal rate for lake water and will be shown in subsequent sections to have an important effect on the distributions of physical and chemical properties.

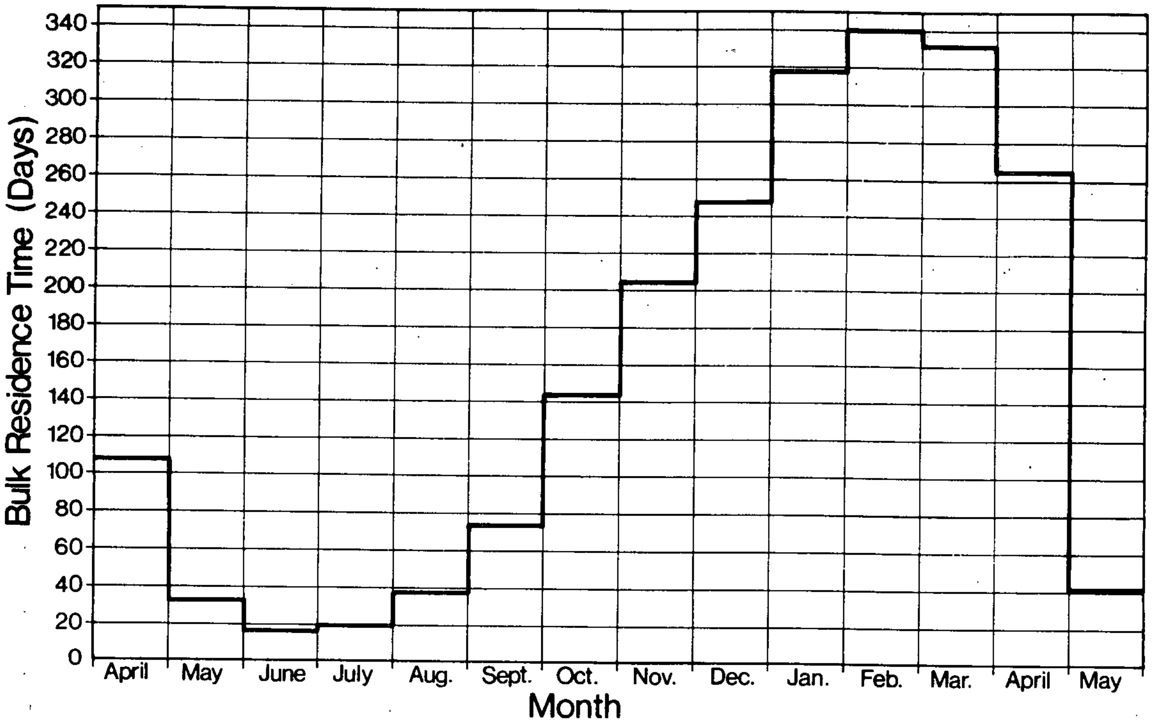


Figure 26. Mean monthly bulk residence time of Kamloops Lake, 1974-75.

3.2 Seasonal Trends in Temperature

Seasonal changes in the temperature structure of Kamloops Lake are conveniently illustrated on a plot of isotherm depths as a function of time (Fig.27). In this representation, stratification is indicated by a horizontal arrangement of isotherms; convection and mixing are indicated by vertical isotherms. Several general features of the thermal structure are of interest:

a) Kamloops Lake is dimictic, that is, it overturns twice yearly, in autumn and in spring. The two circulation periods are indicated by the nearly vertical 4°C isotherms in early January and early May.

b) The period of summer stratification extends from May to early November. The initial thermocline forms near the surface, rapidly sinks to a depth of 40-50 m, and remains at that depth until autumn overturn begins. During this period, the hypolimnion comprises *ca* 50% of the volume and covers about 70% of the surface area of the lake.

c) From September onwards, as air temperatures decrease, the isotherms develop progressive upward bends towards the surface. By mid-November stratification is so reduced that significant exchange between the epilimnion and hypolimnion is allowed. Subsequently, bottom temperatures are observed to increase rapidly as relatively warm surface waters are mixed downwards.

d) By mid-December the whole water column varies in temperature by only 1°C. Complete vertical circulation occurs in early January.

e) The winter period in Kamloops Lake is characterized by weak reverse stratification; that is, temperature increasing with depth. Bottom temperatures continually decline through February and most of March.

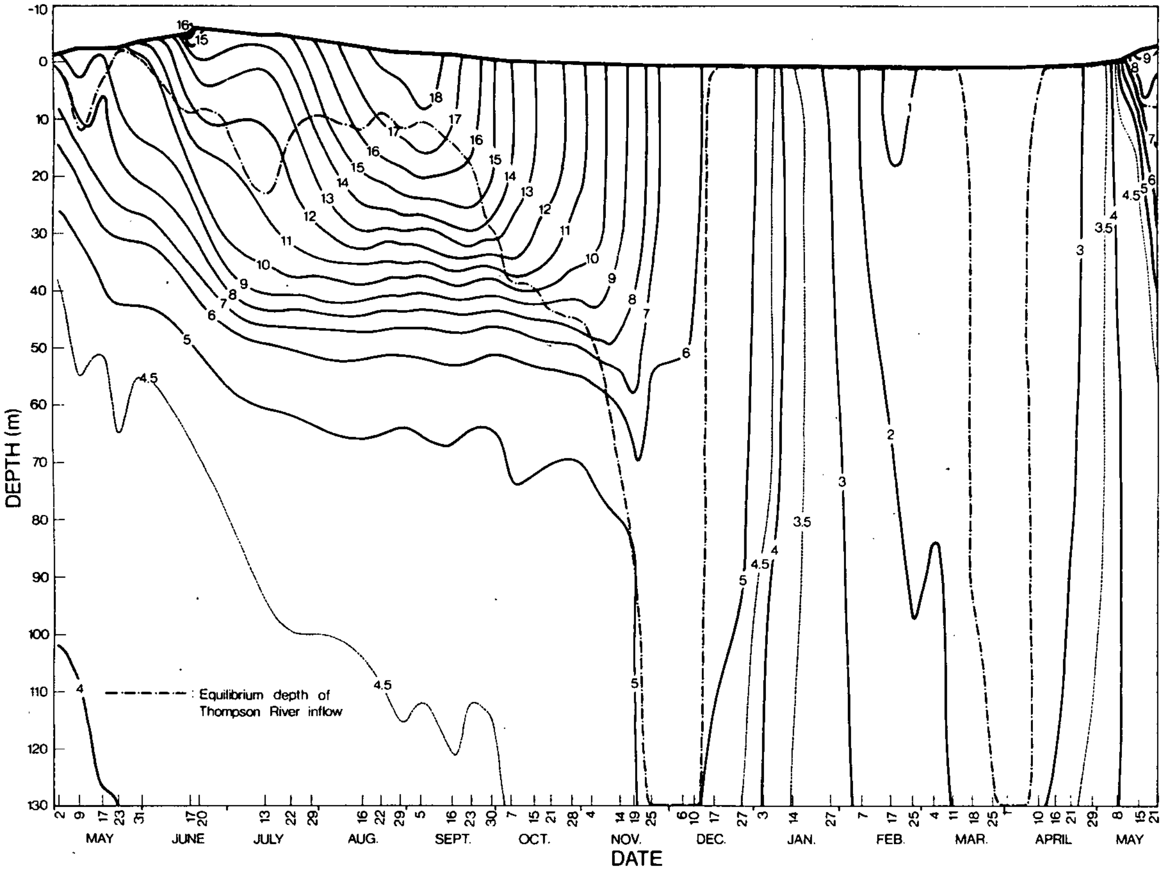


Figure 27. Plot of isotherm depth versus time in Kamloops Lake, 1974-75. The equilibrium depth of the inflow water is indicated by the dashed line.

Also shown in Figure 27 is the equilibrium depth of the inflow water from the Upper Thompson River. This is the depth of the water column at which the density of the lake water equals the density of the incoming water. If no mixing were to occur, river water would spread across the lake at this depth.

The equilibrium depth has a complicated seasonal pattern (Fig.27). During summer stratification, the temperature of the incoming water is such that it would tend to interflow at depths of 10-20 m. As fall cooling begins, the temperature of the inflow water decreases rapidly and the equilibrium depth increases. By late November the inflow water is sufficiently dense (T = 4°C) to sink to the bottom as an underflow. However, further cooling to 0°C decreases the density of the incoming water so that it becomes less dense than the lake water, and subsequently tends to spread across the surface of the lake. This condition persists throughout the winter. A similar sequence of events char-

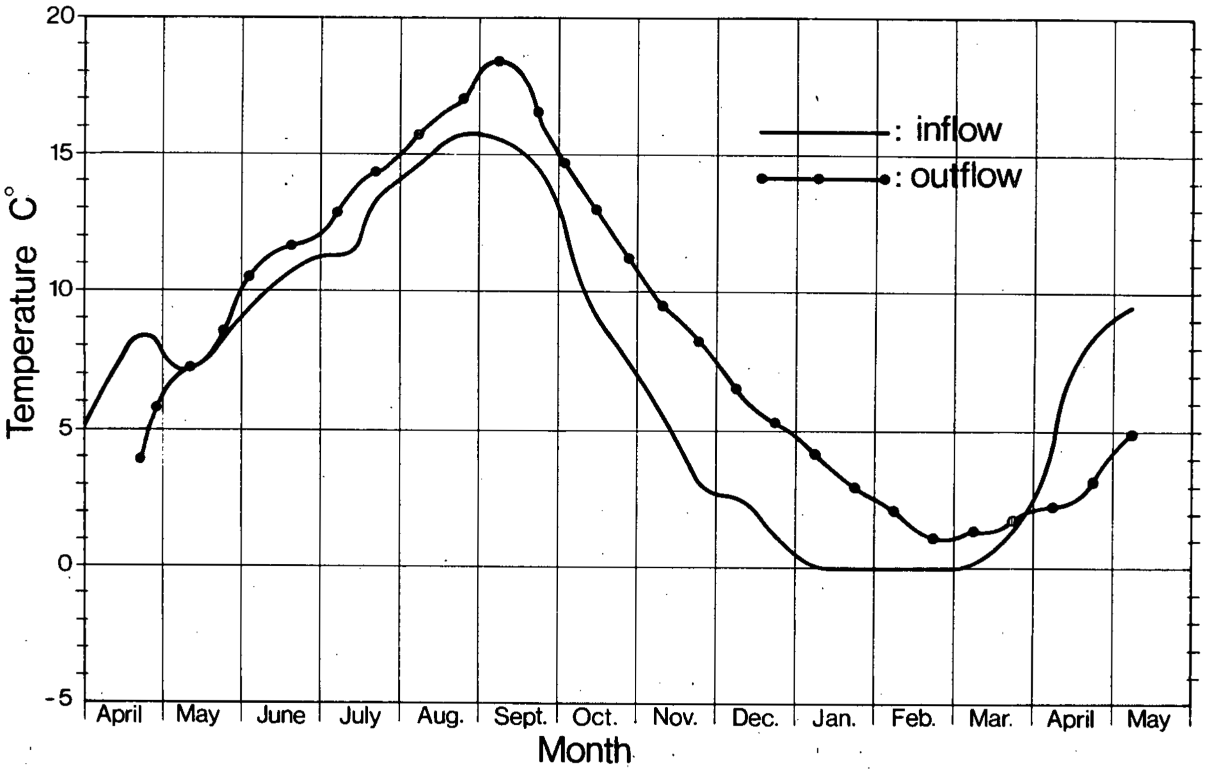


Figure 28. Mean bimonthly water temperatures of the Thompson River entering Kamloops Lake above Tranquille (inflow) and leaving Kamloops Lake below Savona (outflow) in 1974-75.

acterizes the spring period. The inflow water warms to 4°C more rapidly than the lake water and thus tends to sink as an underflow. Further warming of the inflow water reduces its density to less than that of the lake water. (The foregoing arguments are extremely simplified in that no mixing between lake and inflow water is assumed to occur. Further aspects of mixing effects on the lake circulation pattern are discussed below.)

Due to complicated circulation patterns in the lake, the temperatures of the inflow and outflow water are typically different (Fig.28). Except for the period of spring overturn, outflow temperatures are generally higher than inflow temperatures. Thus, the Thompson River effectively removes heat from Kamloops Lake, except in spring when it warms the lake.

3.3 Seasonal Trends in Water Turbidity

Turbidity is a convenient measure of the effect of suspended particulate material on the transparency of the water column, with high values of turbidity (in Jackson Turbidity Units or JTU) indicating low transparency. Since the turbidity of Kamloops Lake is caused mainly by the suspended sediment load of the Thompson River, turbidity was found to be an excellent tracer property of the inflow water. Secondary causes of turbidity include organic material and materials resuspended by bottom stirring or slumping. (The relationship between turbidity and transparency is discussed further in Appendix I.)

Changes in turbidity with depth and time in Kamloops Lake are summarized in Figure 29. The following important features are emphasized:

a) High values of turbidity are correlated with the beginning of the spring freshet and the onset of stratification. This resultant reduction in water transparency tends to limit biological production in early spring (Section 6.2a).

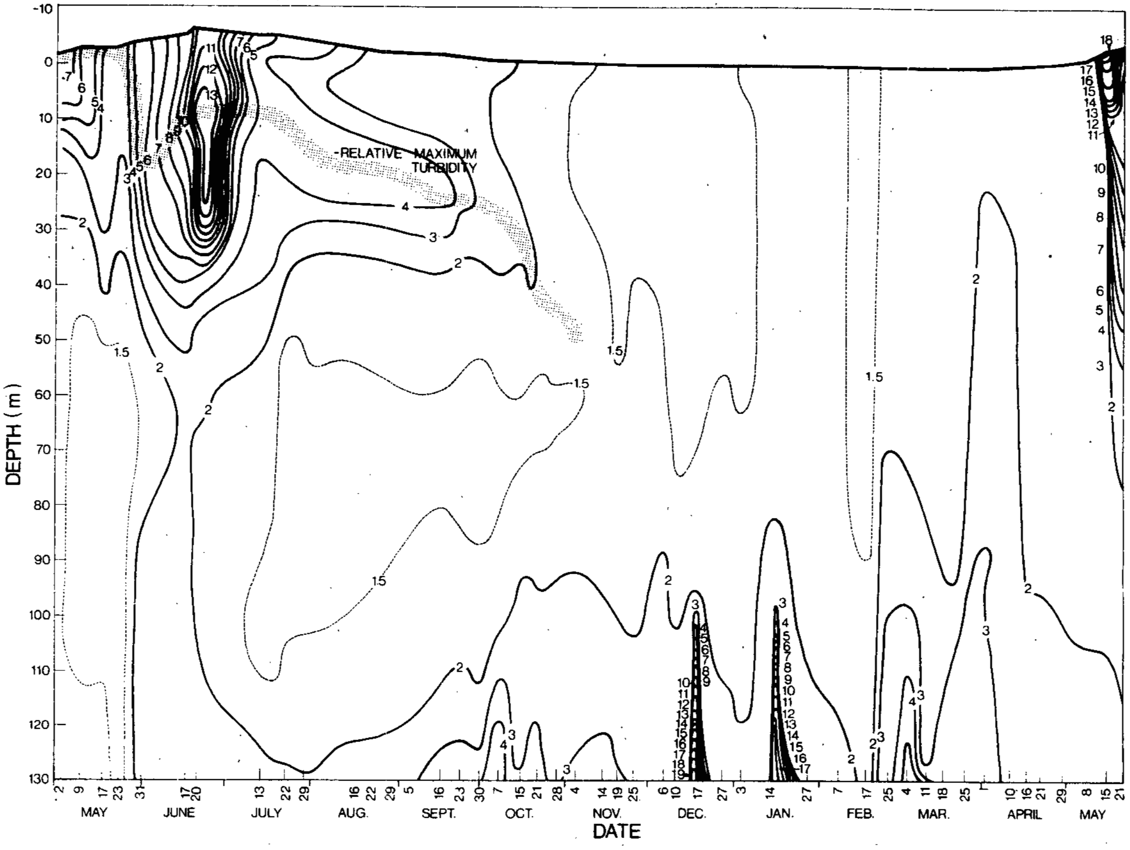


Figure 29. Plot of turbidity isopleth depth versus time in Kamloops Lake, 1974-75.

b) A turbid intermediate layer is established at depths of 10-20 m during early June and persists through October. This layer coincides with the equilibrium depth of the inflow water (cf. Fig.27) and is a clear indication of the interflow of water from the Upper Thompson River.

c) Near bottom values of turbidity are generally quite low during early and middle summer, but increase in September and October due, perhaps, to bottom stirring and slumping. The highest values of turbidity near bottom were observed on 17 December, 1974 and 14 January, 1975 (Fig.29). These abrupt increases were an apparent result of turbidity flows of material dislodged along the face of the river delta near Tranquille. Mass movement of sediment is also evidenced in the geological record (Section 2.4).

The flow velocities of the Thompson River, and hence its carrying capacity for suspended materials, is decreased as the river enters Kamloops Lake. Thus, the lake acts as a sink for suspended and bed load material with the result that the turbidity of the outflow is much reduced (Fig.30). Typically, there is a three- to four-fold decrease in turbidity at the outflow relative to the inflow.

3.4 Seasonal Trends in Lake Stability

The static stability of a water column is a measure of resistance to convective overturn or mechanical mixing due to the presence of a vertical density gradient, hence,

$$E = -\frac{g}{\rho}\frac{\delta\rho}{\delta Z}$$

where ρ is density, g is gravity, and Z is the depth co-ordinate (cf. Bennett 1975). The stability, E, has the dimensions $\sec^{-2}$. In Kamloops Lake, density is primarily determined by water temperature.

Figure 31 shows the isopleths of stability for Kamloops Lake. In this representation, high values of E denote thermocline conditions while low values of E are suggestive of isothermal conditions and strong vertical mixing. Certain features are apparent:

a) Initial stratification is established in the upper layers of the water column (2-4 m) coincident with the freshet. This condition persists to the end of September.

b) A deeper thermocline forms early in June and persists until autumn overturn. This thermocline is especially well developed in August and September in the region of the 10-14°C isotherms. In early summer, when river discharges are maximum, the deeper thermocline sinks rapidly to about 40-45 m. This is likely due to mechanical stirring in the water column above. As river flows diminish, the depth of the lower stability

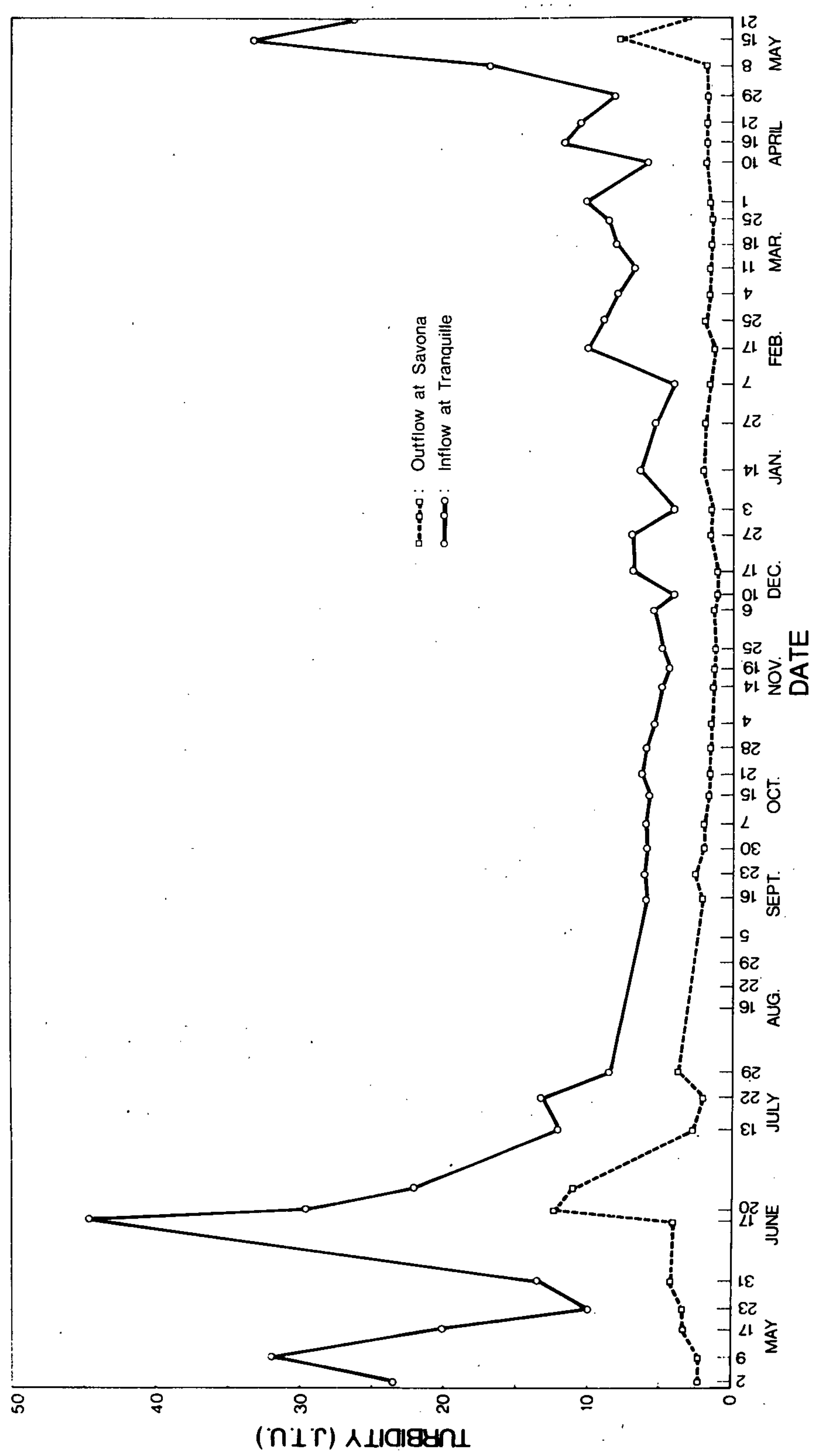


Figure 30. Water turbidity near the inflow and outflow of Kamloops Lake, 1974-75.

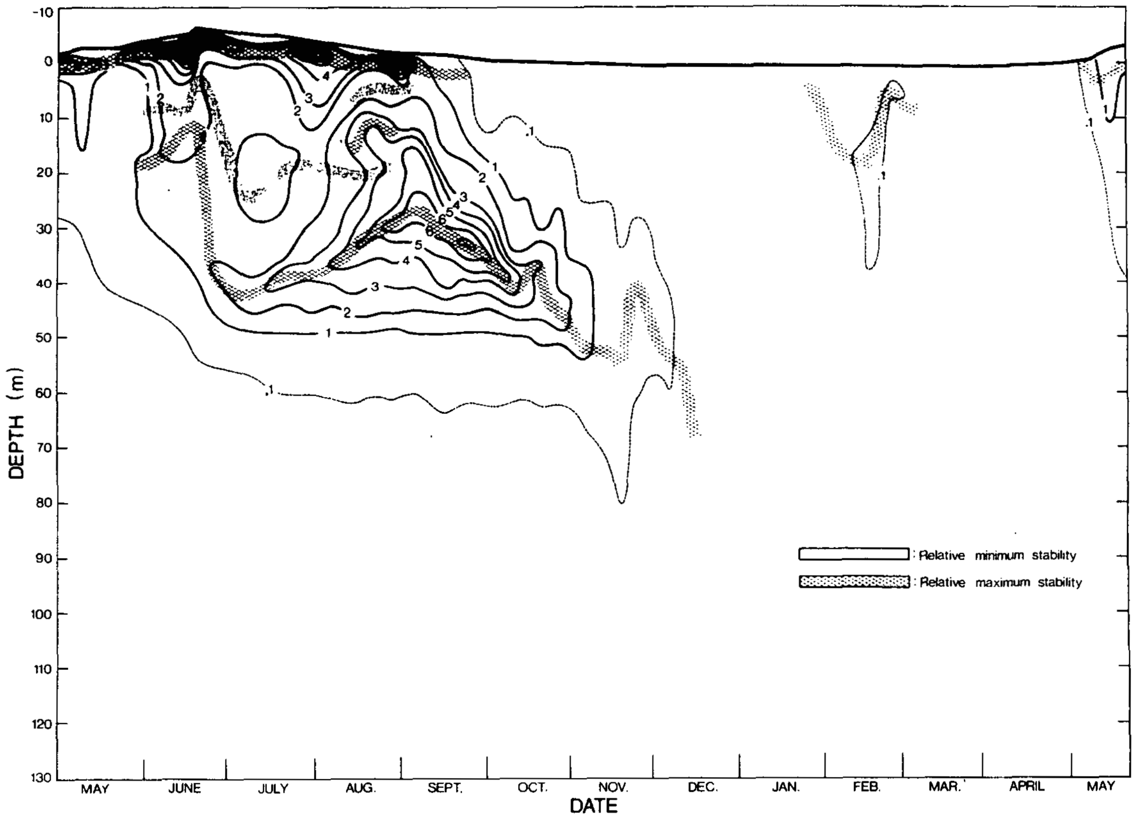


Figure 31. Plot of stability isopleth depth versus time in Kamloops Lake, 1974-75.

maximum decreases, reaching 25-30 m in late August, but then sinks again as fall cooling begins.

c) In summer, a relative stability minimum is maintained between the upper and lower thermoclines. It is in this layer that the Thompson River water interflows, apparently mixing water along its flow path.

d) A very weak region of stability is observed during winter in the upper layers of the lake.

3.5 Seasonal Changes in Heat Content

A maximum heat content of 40.4×10^{15} g cal (relative to 0°C) was observed in mid-August in Kamloops Lake (Fig.32). The peak in heat content thus occurs 1-2 weeks after maximum surface temperatures (Fig.27) and 1-2 weeks

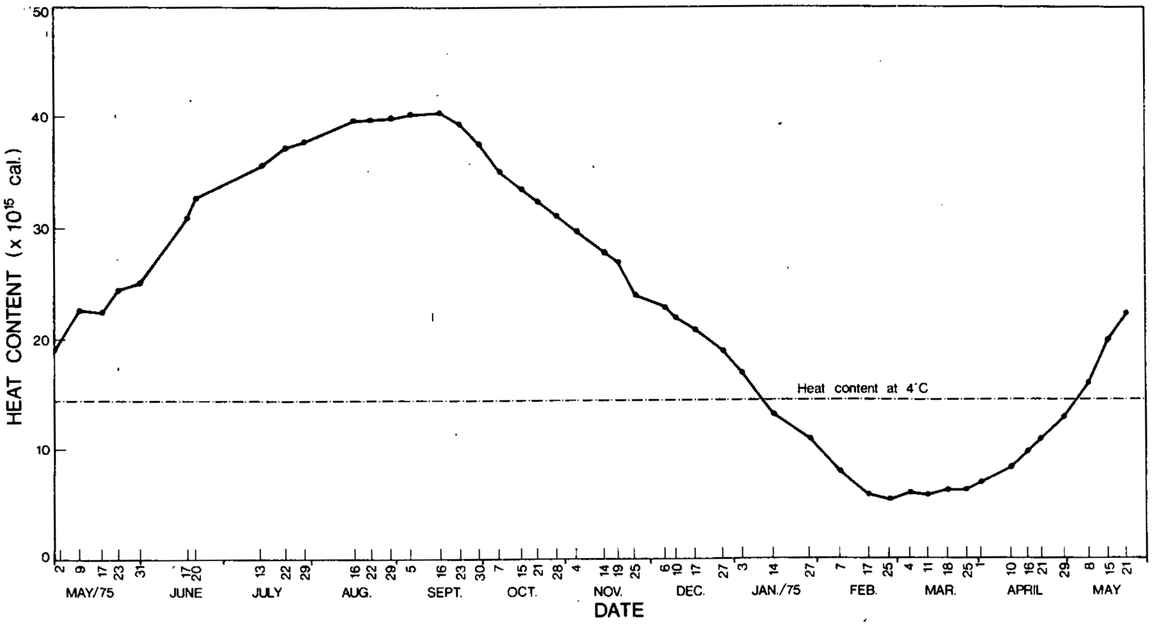


Figure 32. Heat content of Kamloops Lake (relative to 0°C) calculated from lake monitor data at approximately one-week intervals in 1974-75.

before the maximum thermocline stability (Fig.31).

Summer and winter heat incomes can also be calculated from Figure 32. The summer heat income, defined as the amount of heat needed to raise the lake from a spring isothermal condition at 4°C, up to the highest summer heat content is 25.6×10^{15} g cal or about 47,000 g cal cm^{-2}. This value is relatively high for deep intermontane lakes (cf. Hutchinson 1975) and reflects the importance of the inflowing river in mixing heat downwards. The winter heat income, similarly defined as the amount of heat needed to raise the water from temperatures characterizing the minimum heat content up to 4°C, is 9.5×10^{15} g cal or about 18,000 g cal cm^{-2}.

Because of differences in the temperature of the inflow and outflow waters, the Thompson River system has a pronounced effect on the heat budget of Kamloops Lake. The effects of the freshet on the spring heat budget were first indicated by Ward (1964). Further confirmation is given in Figure 33 which compares the rate of change of heat content in the lake to the net heat

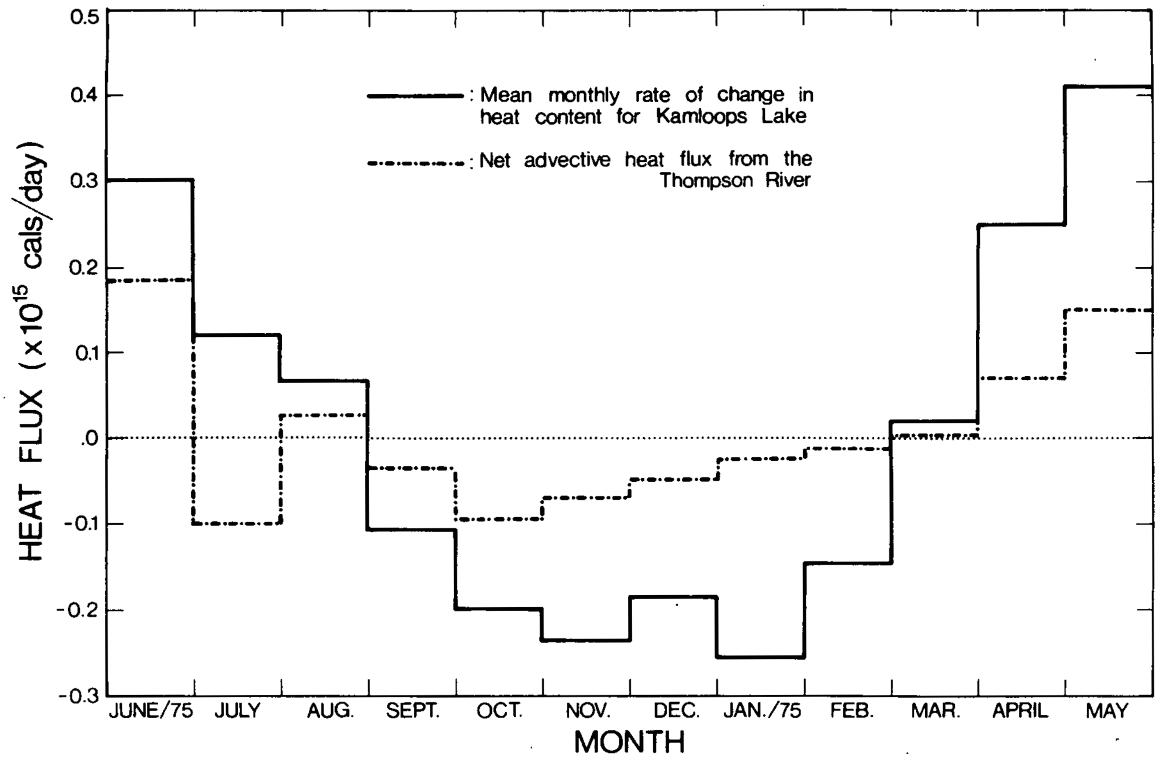


Figure 33. Mean monthly rate of change in heat content of Kamloops Lake (solid line) compared to net advection of heat by the Thompson River (dashed line) in 1974-75.

advected by the Thompson River. The largest effects are clearly apparent in spring where up to 40-50% of the heat input can be attributed to advection by the river. A net loss of heat from the lake by advection is observed to be of importance during autumnal cooling.

A complete annual heat budget for Kamloops Lake is presently being prepared for a supplementary report.

3.6 Circulation and Distribution of Physical Properties During Spring

"Limnological" spring (April-May) begins in Kamloops Lake with the onset of convective overturn and ends after direct thermal stratification is established. During this period the mean temperature of the lake fluctuates through 4°C, the temperature of maximum water density. The consequent variations in water density in relation to temperature (Appendix I) affect the springtime circulation structure in Kamloops Lake in several important ways.

Towards the end of winter, the thermal structure of the lake consists of a weak reverse stratification. Bottom temperatures are about 1.6-2.0°C, surface temperatures somewhat less, and turbidity values generally low throughout the lake. Water from the Upper Thompson River enters the lake at temperatures near 0°C, and thus tends to remain near the surface unless diffused downwards by wind or turbulent mixing.

When air temperatures begin to rise in spring, the shallow river waters are warmed more rapidly than the deep waters of the lake. This occurs because the incoming heat is distributed through a shallower depth (smaller volume) in the river and because additional radiant energy is absorbed by the river bed. As the inflow water warms toward the temperature of maximum density, it becomes denser than the lake water and thus tends to sink to the bottom upon entry into the lake.

The initial spring circulation pattern is best seen in longitudinal sections of water temperature and turbidity (Fig.34a,b). The temperature of the river water is about 3.2°C, while the mean lake temperature is only 1.8°C. The mixtures containing river water are thus clearly represented by the thin layer of relatively warm (1.9°C) and turbid (2.5 JTU) water flowing down the slope of the river delta. By this process new (warm) water is advected into the lake's hypolimnion thus initiating the springtime convective overturn. Since the sinking water that initially reaches the bottom is only 0.1 to 0.2°C warmer than the ambient lake water, it contains only a small percentage of "pure" river water, and thus only a small inflow of warm water is required to start the spring circulation. Although advective warming from the river is the principal cause of overturn, additional heat absorbed at the lake surface also aids in warming the lake. This is particularly evident near the west end of the lake where warm (dense) water is observed to accumulate in shallow regions.

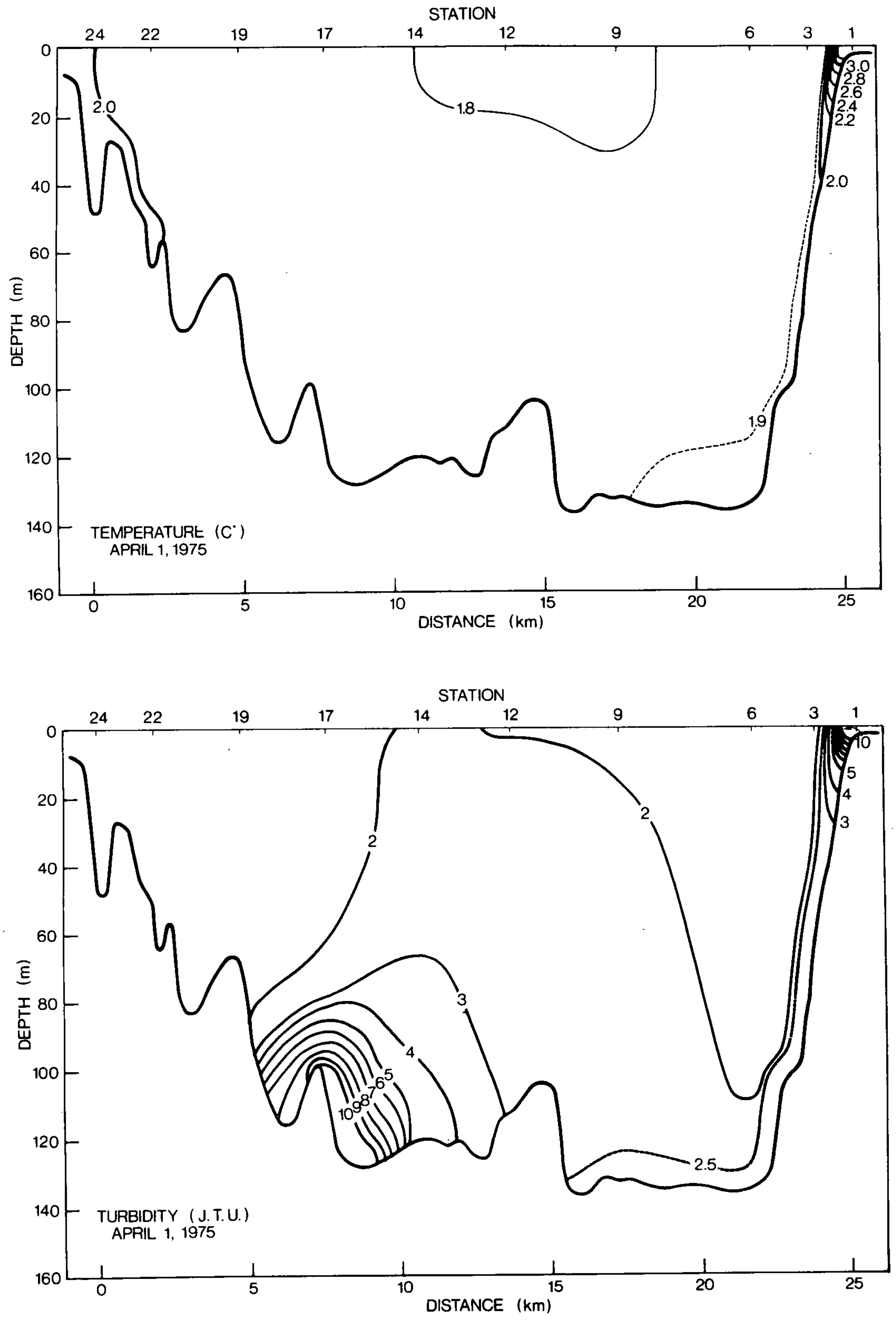


Figure 34. Longitudinal sections of (a) temperature, and (b) turbidity in Kamloops Lake on 1 April, 1975.

It is important to note that from the time the inflow water initially sinks to the bottom until the spring overturn is complete, all inflow waters are retained within the lake. Thus only "wintertime" lake water exits from the lake during this period.

As the temperature of the inflow water increases with further warming, its density drops below that of the lake water. At this point, the river water <u>tends</u> to enter the lake as a surface overflow. Figure 35a,b shows longitudinal sections of temperature and turbidity at the east end of the lake at a time when the inflow temperature is about 10°C and the mean temperature of the lake is 3.4°C. Although the inflow water is less dense than the lake, some mixtures of the two will have temperatures very close to 4°C and will thus be denser than either parent water mass. This mixing process is often referred to as cabbeling (cf. Foster 1972). The dense mixtures then sink to the lake bottom and spread westward, filling the lake basin with 4°C water from the bottom up. The net result of the cabbeling process is to hold the inflow water (as an arrested plume) at the eastern end of the lake until it mixes with the lake water and sinks. Thus no new inflow water leaves the lake during spring overturn. Transverse sections of temperature and turbidity during this period (Fig.36a,b) show that the wedge of water moves down the lake as far as Battle Bluff. Note that the east-west flow of warm,turbid river water is confined to the north shore (right-hand side) of the lake. Plots of surface and bottom temperatures midway through overturn (Fig.37a,b) clearly show that inflowing water is confined at the surface near Tranquille. In addition, water near 4°C formed by cabbeling, sinks and flows along the axis of the lake basin. Further convective overturn is indicated in the shallow water near Savona.

Although the cabbeling process appears to dominate the spring circulation pattern, additional heat is absorbed in the surface layers of the lake and this in turn promotes vertical circulation.

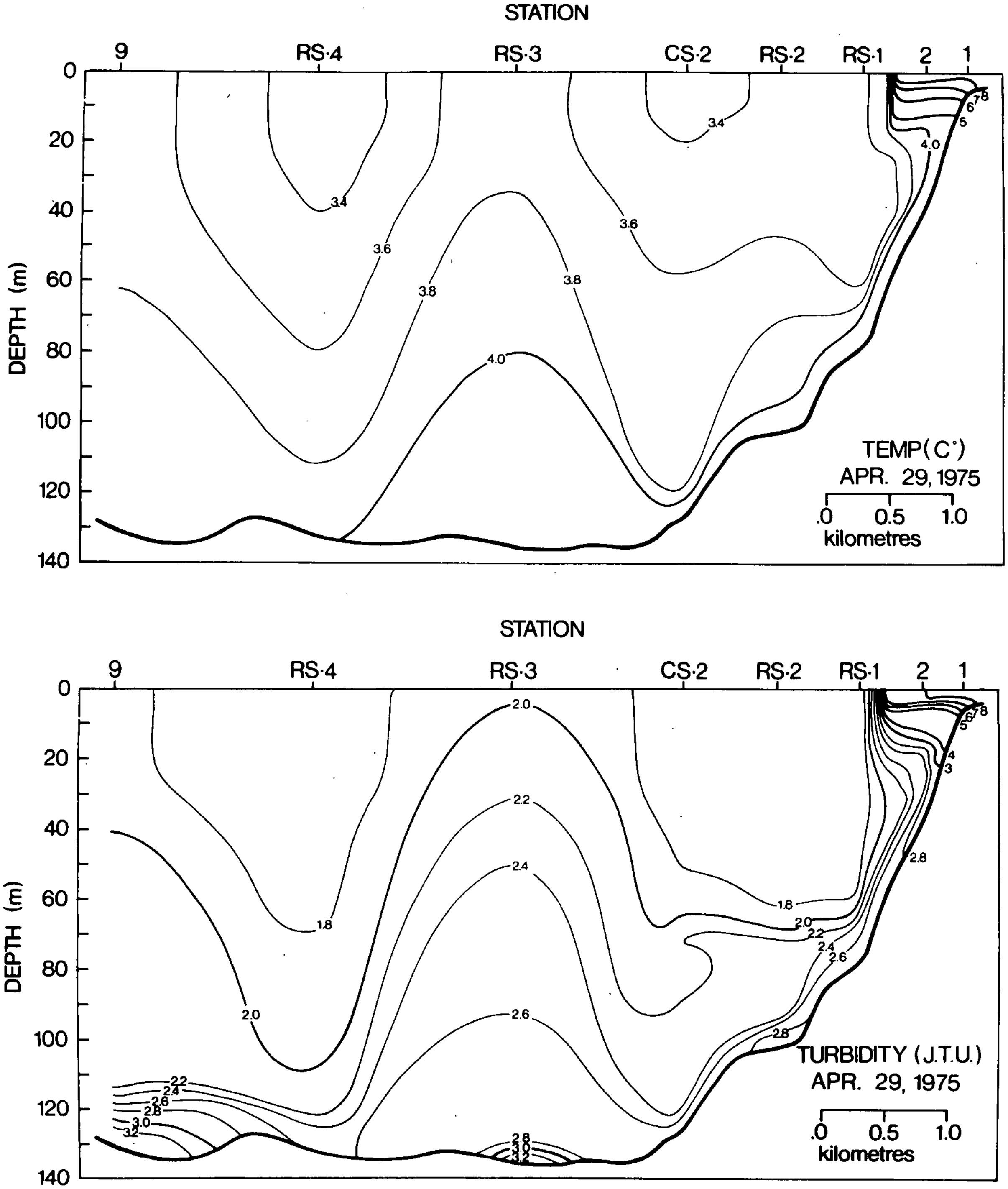


Figure 35. Longitudinal sections of (a) temperature, and (b) turbidity in Kamloops Lake on 29 April, 1975.

Since the thermal mixing processes described above act to retain all new inflow water within the lake during overturn, the lake's outflow into the Lower Thompson River during spring is derived from lake surface water reflecting winter properties.

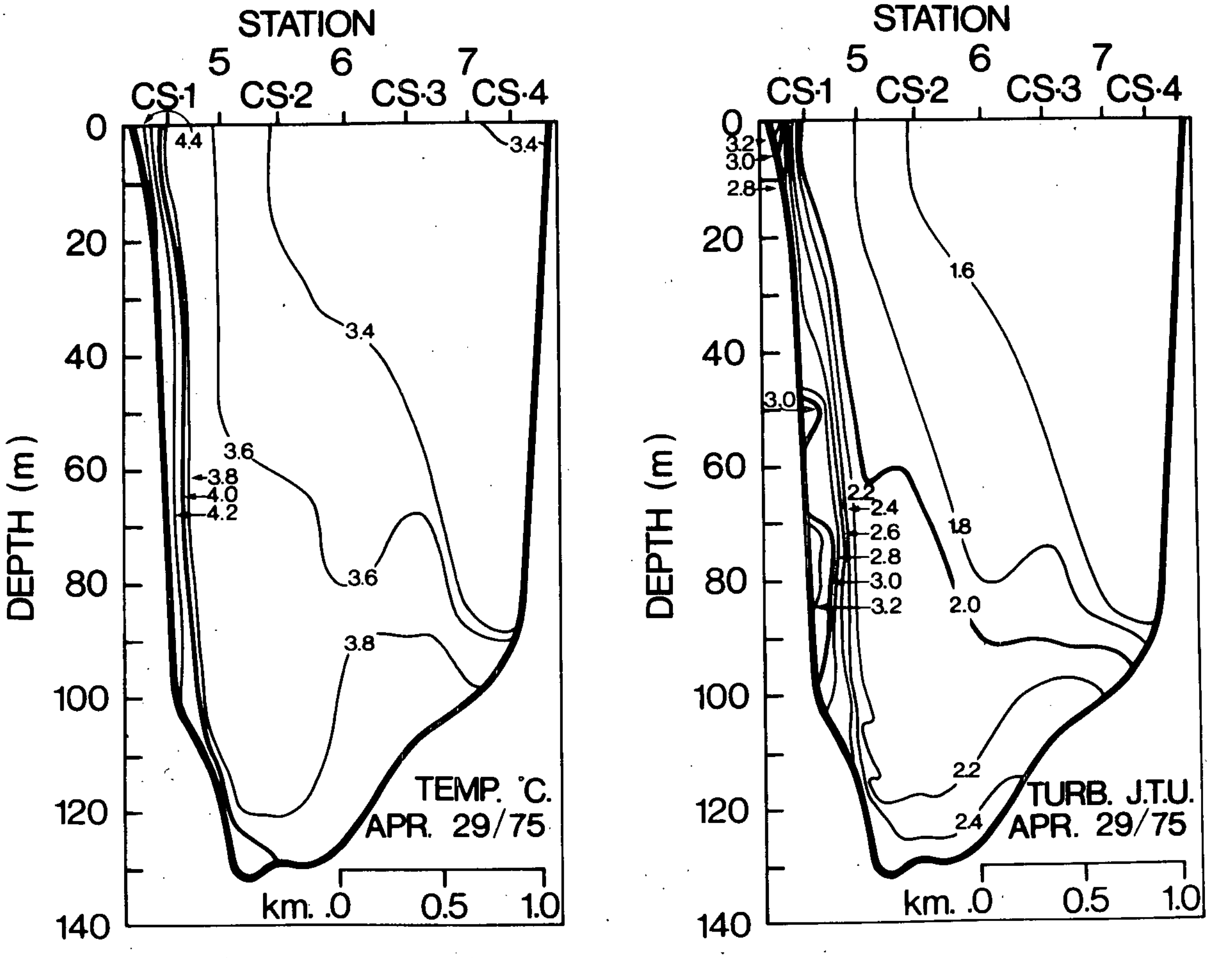


Figure 36. Transverse sections of (a) temperature, and (b) turbidity in Kamloops Lake on 29 April, 1975.

When the whole lake is finally warmed to 4°C or above, the cabbeling process stops and the wedge of warm water near Tranquille is released to flow down the lake. Transport of inflow water down the length of the lake actually <u>forms</u> the initial thermocline. Evidence from FTP records indicates that the warm plume traverses the length of the lake in about one week. The temperature and turbidity structures midway through this spreading stage are shown in Figure 38a,b. Thin wedges of warm and turbid water can be seen spreading from the east end of the lake.

The thermal histories of the inflow and outflow water and the lake itself are summarized in Figure 39.

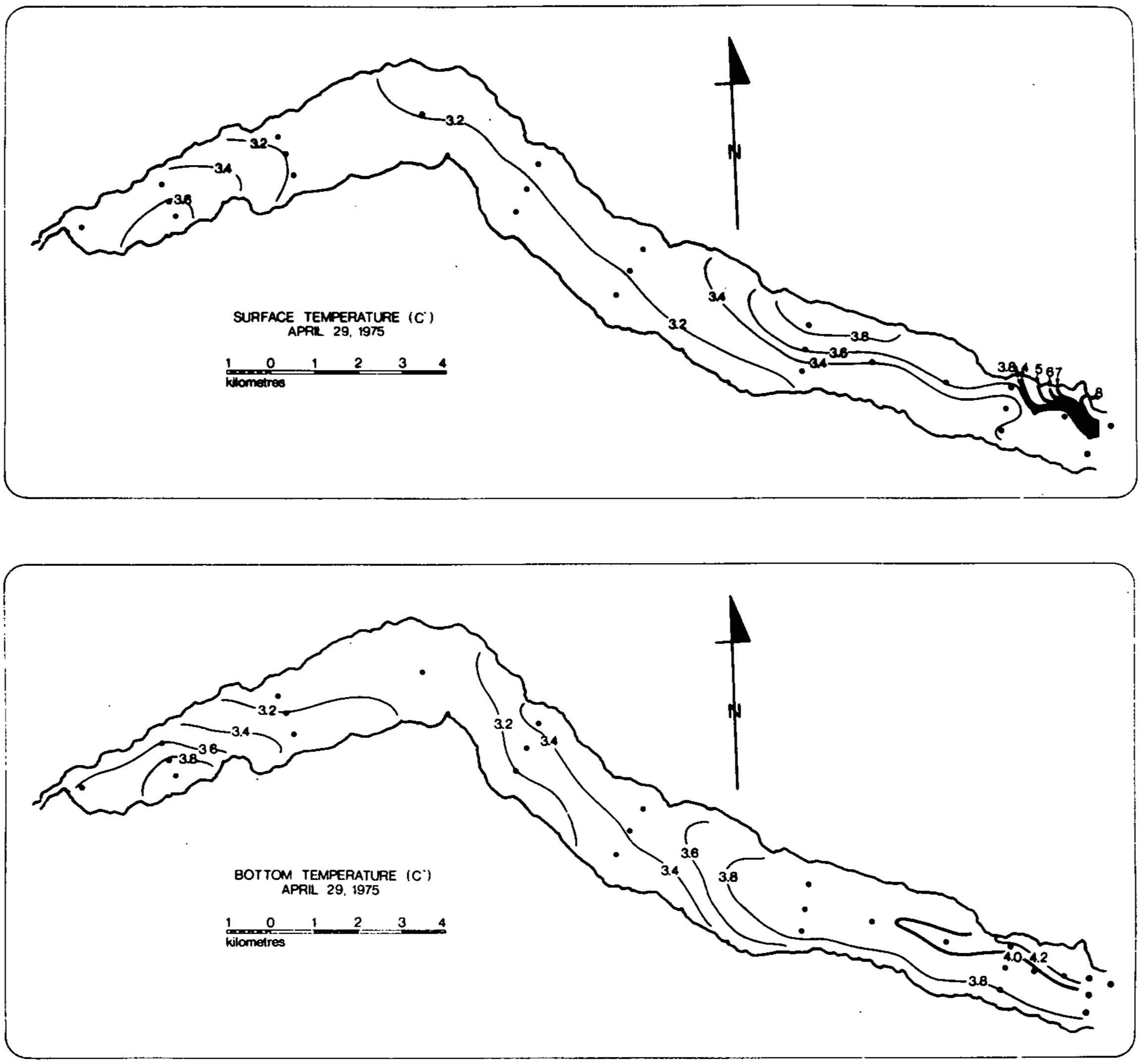
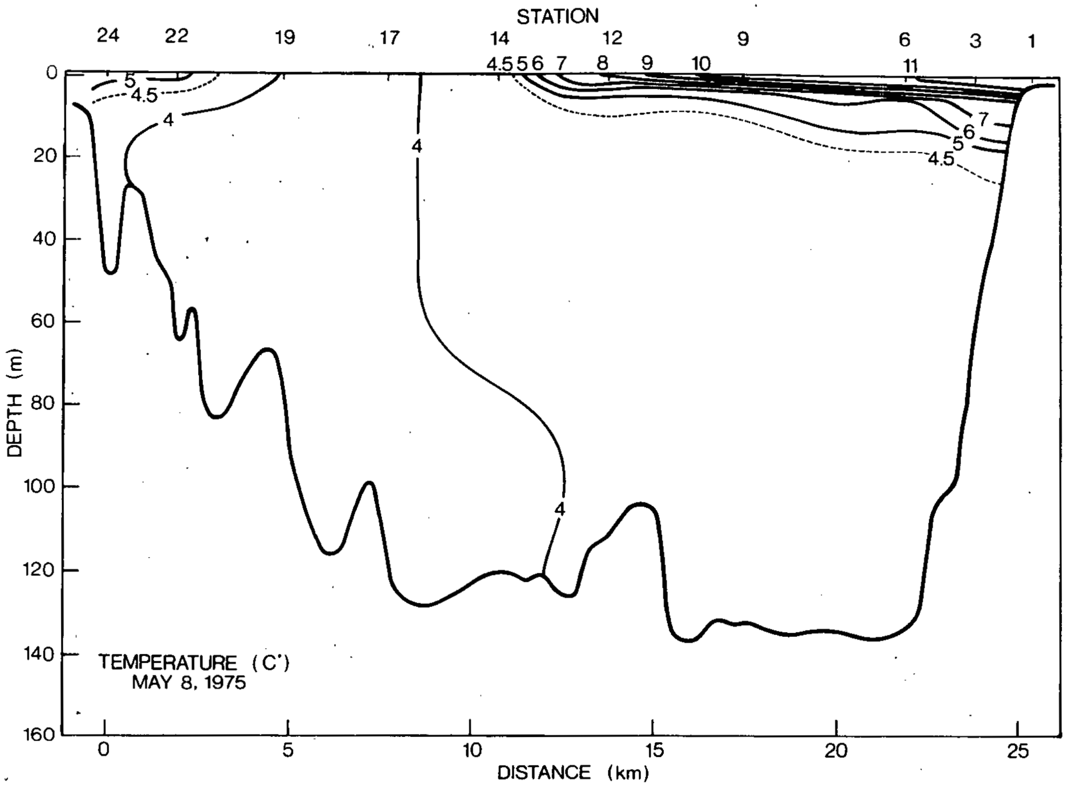


Figure 37. Horizontal distributions of (a) surface temperature, and (b) bottom temperature in Kamloops Lake on 29 April, 1975.

3.7 Circulation and Distribution of Physical Properties During Summer

The "limnological" summer (June-October) in Kamloops Lake is characterized by direct thermal stratification. With the onset of stratification, the surface layers of the lake begin to warm more rapidly than the waters of the Upper Thompson River. Subsequently, the inflow sinks to a depth determined



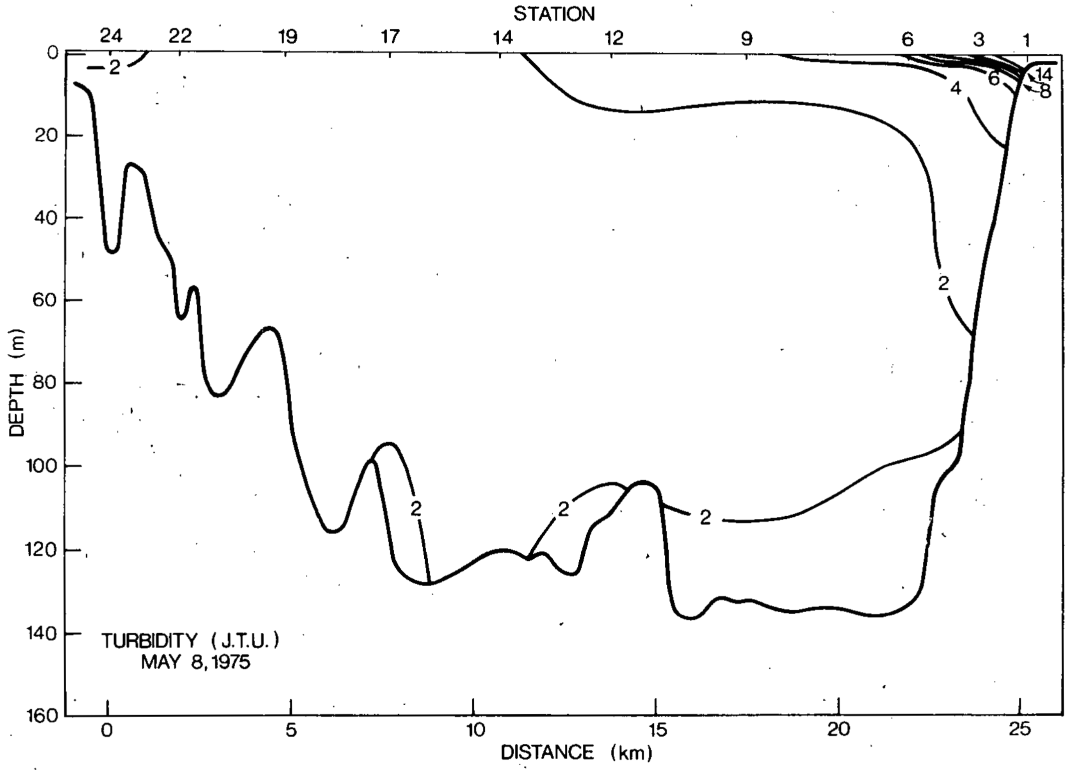


Figure 38. Longitudinal sections of (a) temperature, and (b) turbidity in Kamloops Lake on 8 May, 1975.

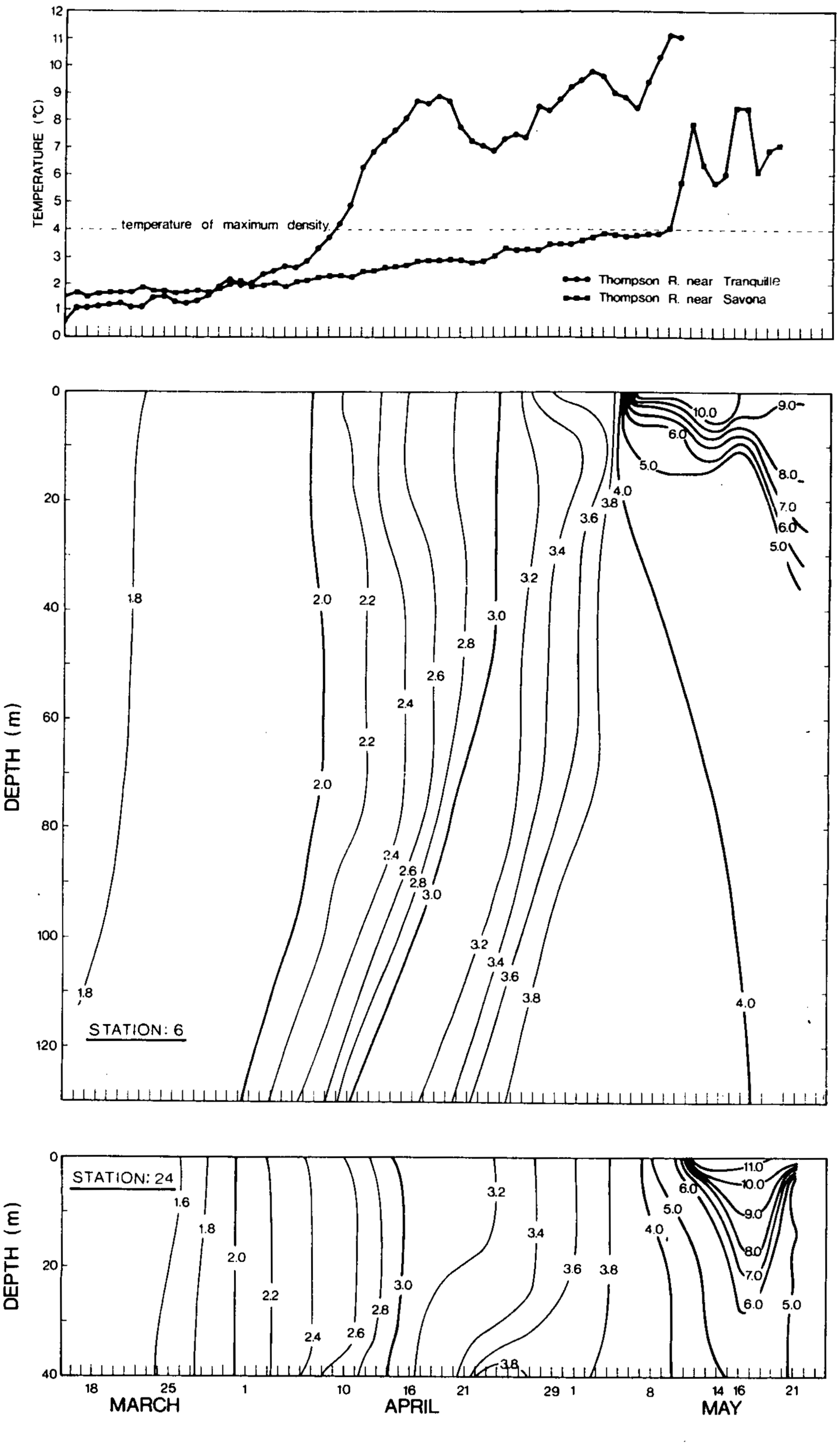


Figure 39. Temperature fluctuations during the 1974 spring overturn in Kamloops Lake. Top: temperature history of Thompson River inflow near Tranquille compared to temperature history of Thompson River outflow near Savona. Middle: isotherm depth versus time at Station 6 near inflow. Bottom: isotherm depth versus time at Station 24 near outflow.

by its density relative to that of lake water, and passes through the lake as a turbid interflow. Throughout the summer period direct exchange with the hypolimnion is inhibited by stratification. The relatively high inflow discharges, together with the confinement of the river water to the upper layers of the lake, result in a relatively short residence time of river water during the summer.

The volume discharge of the Upper Thompson River reaches a maximum in early summer, some of the effects of which are shown in Figure 40a,b. The Thompson River effluent is clearly indicated by the high values of turbidity in the upper 25-30 m of the lake. The tongue of highly turbid water below Station B2 illustrates the sinking and subsequent interflow of turbid Thompson River water. High values of turbidity (up to 18 JTU, in comparison to 28 JTU above the delta) extending almost the entire length of the lake suggest that the effects of dilution and particle settling are minimal. The thermocline at 10-6°C effectively separates the high turbidity water in the upper layers of the lake from the highly transparent hypolimnion waters.

The mid-summer conditions of the lake following the major freshet are illustrated by sections of temperature and turbidity (Fig.41a,b) on 29 July, 1974. The interflow of Thompson River water is again clearly seen as a tongue of turbid water (>4 JTU) spreading the length of the lake between 10 and 25 m. It should be noted that within this core of river water, the isotherms diverge forming a layer of reduced thermal stratification or thermostad. Stratification is greater above and below the interflow. It would thus appear that turbulence induced by the interflow is effective in mixing the intermediate region of the epilimnion.

Some effects of transverse flow on the temperature and turbidity structures of Kamloops Lake are indicated in Figure 42a,b. There is a pronounced tendency for incoming river water to deflect to the right and flow westward

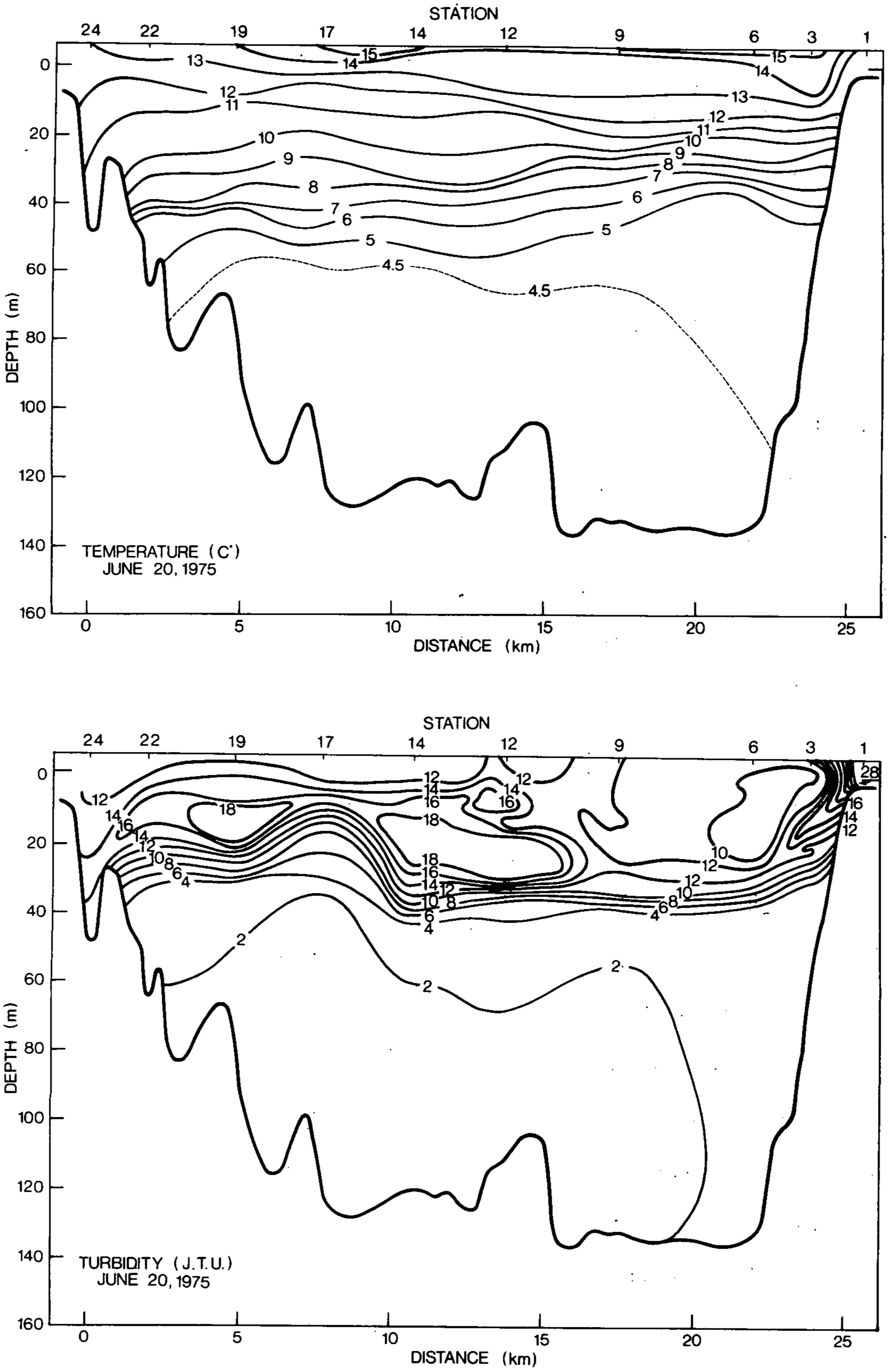


Figure 40. Longitudinal sections of (a) temperature, and (b) turbidity in Kamloops Lake on 20 June 1975.

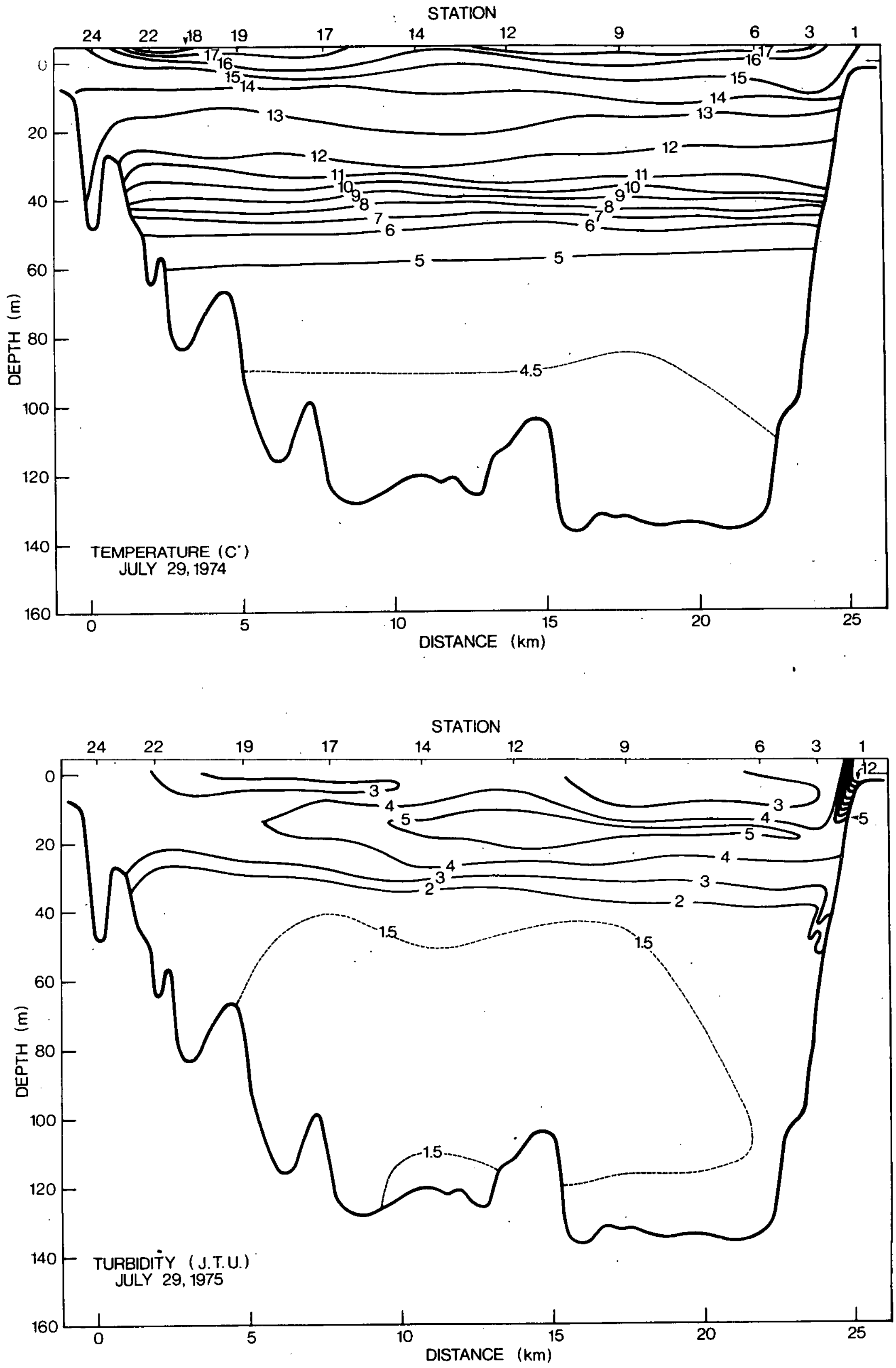


Figure 41. Longitudinal sections of (a) temperature, and (b) turbidity in Kamloops Lake on 29 July 1975.

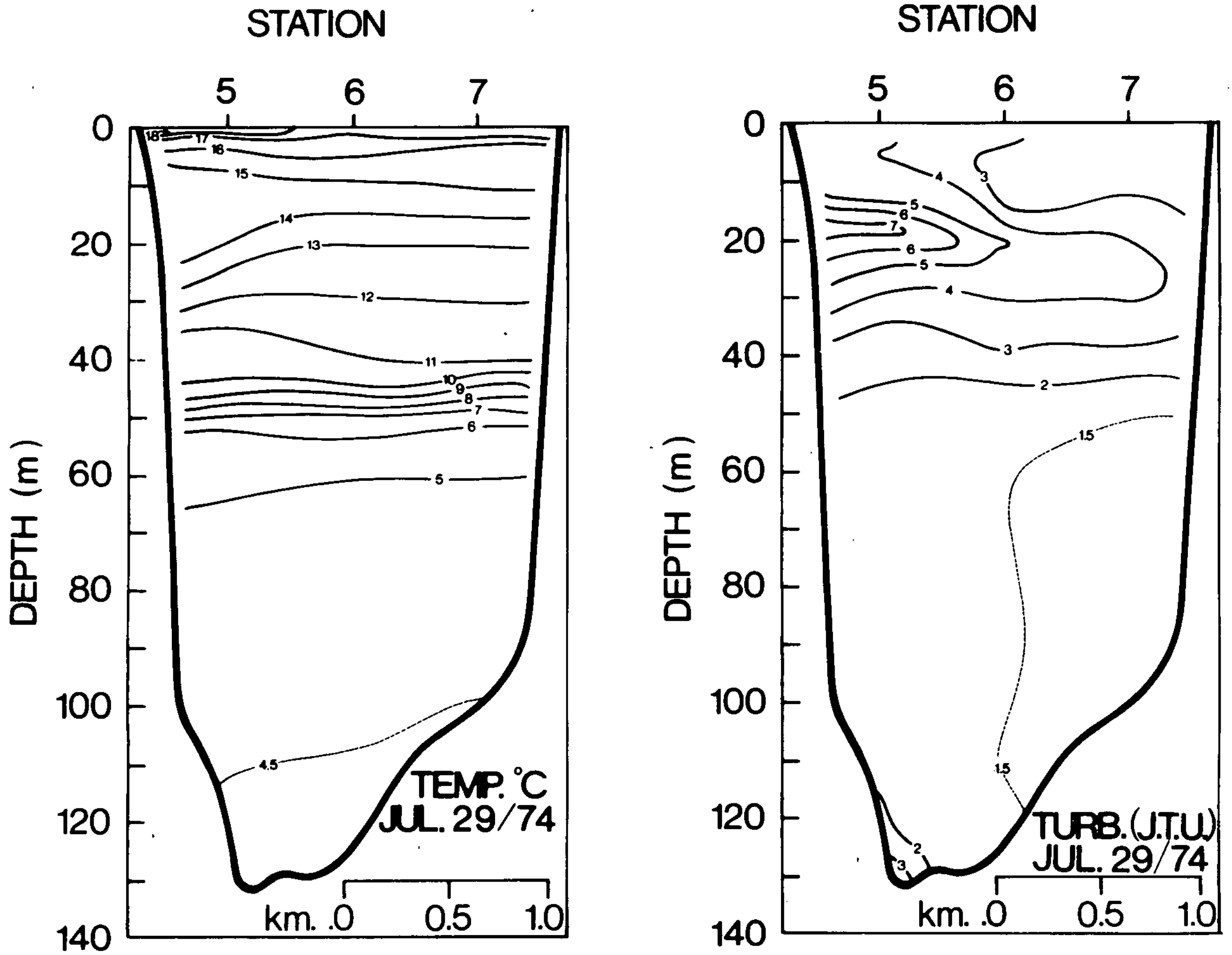


Figure 42. Transverse sections of (a) temperature, and (b) turbidity in Kamloops Lake on 29 July 1974.

along the north bank of the lake as indicated both by the increased turbidity and by the divergence of the 15-12°C isotherms along the north shore of the lake. This movement along the north shore is also apparent in Figure 43, which is a map of the maximum observed turbidity at each station. The tendency for interior flows to deflect to the right is observed throughout the year in Kamloops Lake, and is likely due to the Coriolis effect (cf. Hamblin 1974).

As air temperatures begin to fall in late September, and as winds increase, the surface layers of the lake mix deeper and deeper. In addition, the foregoing river effects diminish as flows decline. Thus it is only in late summer that a "classic" temperature structure (cf. Hutchinson 1957) develops

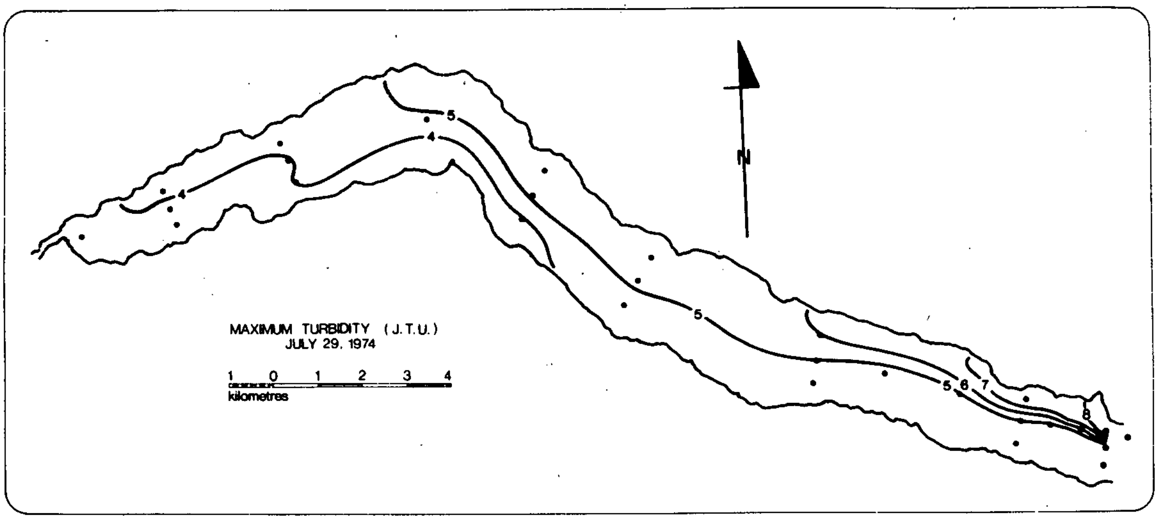


Figure 43. Horizontal isopleths of turbidity at the turbidity maximum in Kamloops Lake in 1974-75.

in Kamloops Lake. The epilimnion (Fig.44a,b) is isothermal to within 1 or 2°C down to about 30 m. Below the epilimnion a well-developed thermocline between 11 and 6°C extends across the lake. Bottom temperatures are still relatively cold (≃4.5°C) indicating that little downward mixing has occurred during the period of summer stratification. The temperature of the incoming water begins to decrease in October so that the interflow now occurs at greater and greater depths.

Some quantitative aspects of the interflow of Thompson River water through Kamloops Lake are given in the summary of drogue current measurements in Appendix III.

Throughout the above discussion, attention has been focused on the interaction of the lake and river systems. Because many aspects of the physical limnology studies have been simplified, discussions on other topics, for example, the very important effects of the wind and atmospheric energy fluxes, are being prepared in supplementary reports.

It should also be noted that internal wave motions are a characteristic feature of the lake's thermal structure throughout the stratified period

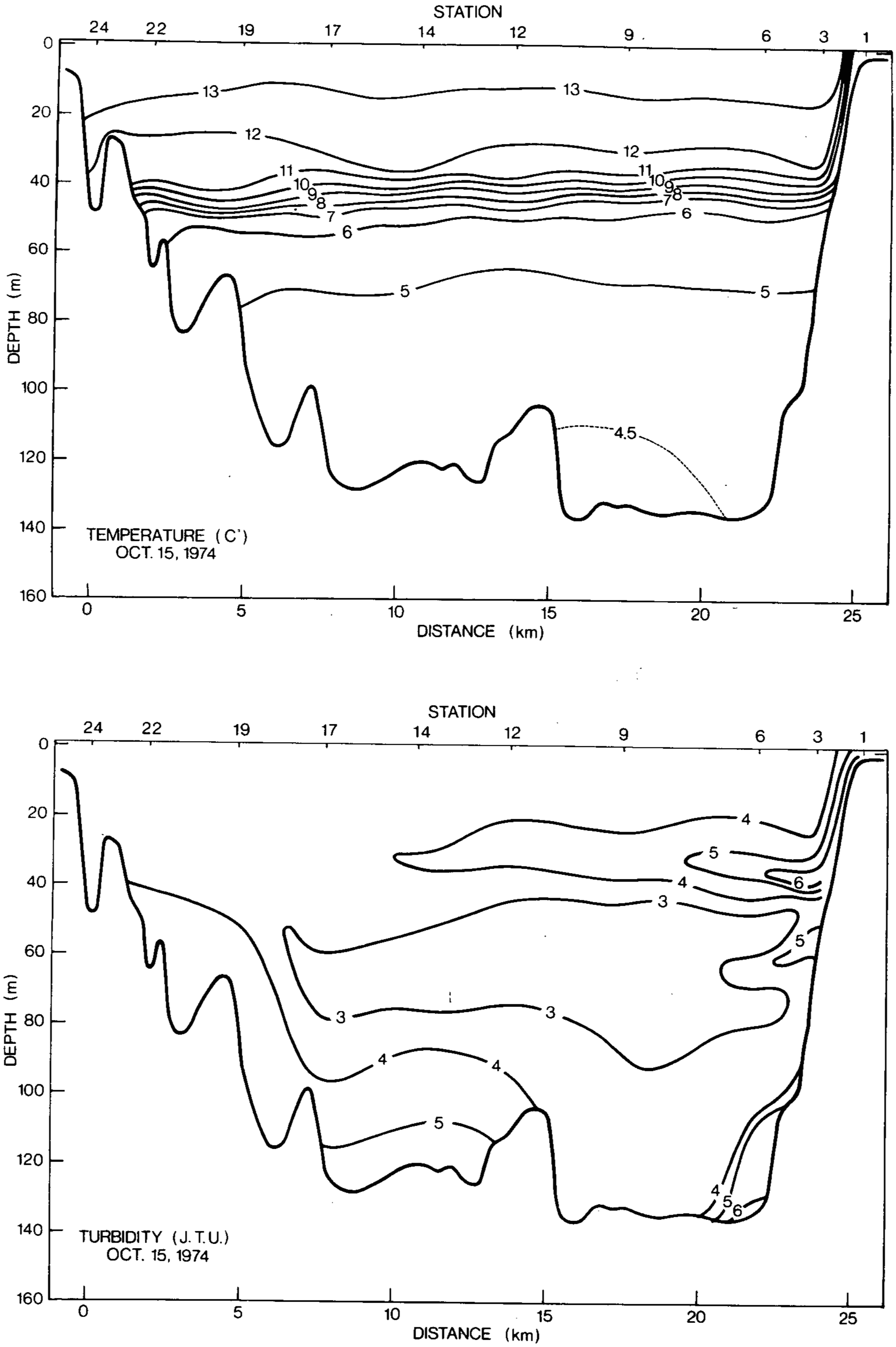


Figure 44. Longitudinal sections of (a) temperature, and (b) turbidity in Kamloops Lake on 15 October 1974.

and internal displacements of up to 20 m in the vertical have been observed. A summary of internal wave characteristics is given in Appendix IV.

3.8 Circulation and Distribution of Physical Properties During Autumn

"Limnological" autumn (November-December) in Kamloops Lake commences with the rapid breakdown of summer stratification and ends following convective overturn. During autumn the mean temperature of the lake again passes through 4°C, the temperature of maximum density. As in spring, the non-linear relationship between water temperature and density (cf. Appendix II) has an important effect on the gross circulation of the lake during overturn.

Autumnal cooling reduces the surface temperature of the lake and sets up convection currents that steadily cool and deepen the epilimnion. Stratification is reduced (cf. Fig.31) so that wind-mixing erodes the surface layers even deeper. At the same time, the temperature of the inflowing water drops rapidly, thus increasing the equilibrium depth of the interflow. Sections of temperature and turbidity during the initial stages of autumnal circulation (Fig.45a,b) show the interflow as a faint tongue of slightly turbid water spreading westward from the river delta at a depth of about 50 m. The striking feature of the thermal structure is the pronounced divergence of isotherms at the eastern end of the lake. Isotherms above the interflow bend upwards, one after another, while isotherms below the interflow bend downwards. Inflow water thus appears to both cool the epilimnion and erode the thermocline. Throughout the autumn overturn the eastern end of the lake remains cooler than other regions of the lake. There is, however, another process occurring; not only is the epilimnion cooler, but the hypolimnion is warmed, evidently due to decreased stratification and increased turbulent movement at the bottom of the epilimnion.

Heat loss at the surface cools the shallow waters of the Upper Thompson

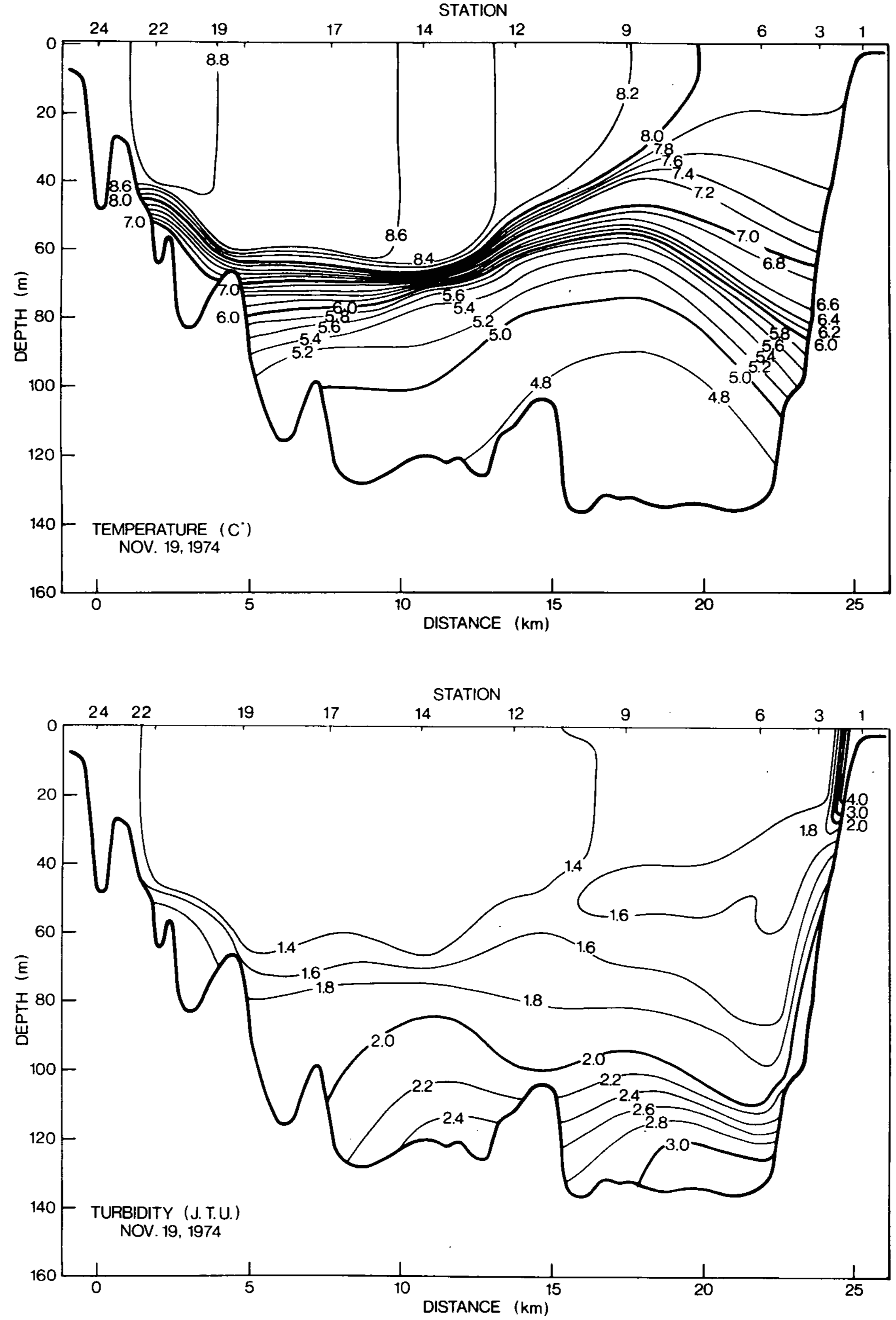


Figure 45. Longitudinal sections of (a) temperature, and (b) turbidity in Kamloops Lake on 19 November 1974.

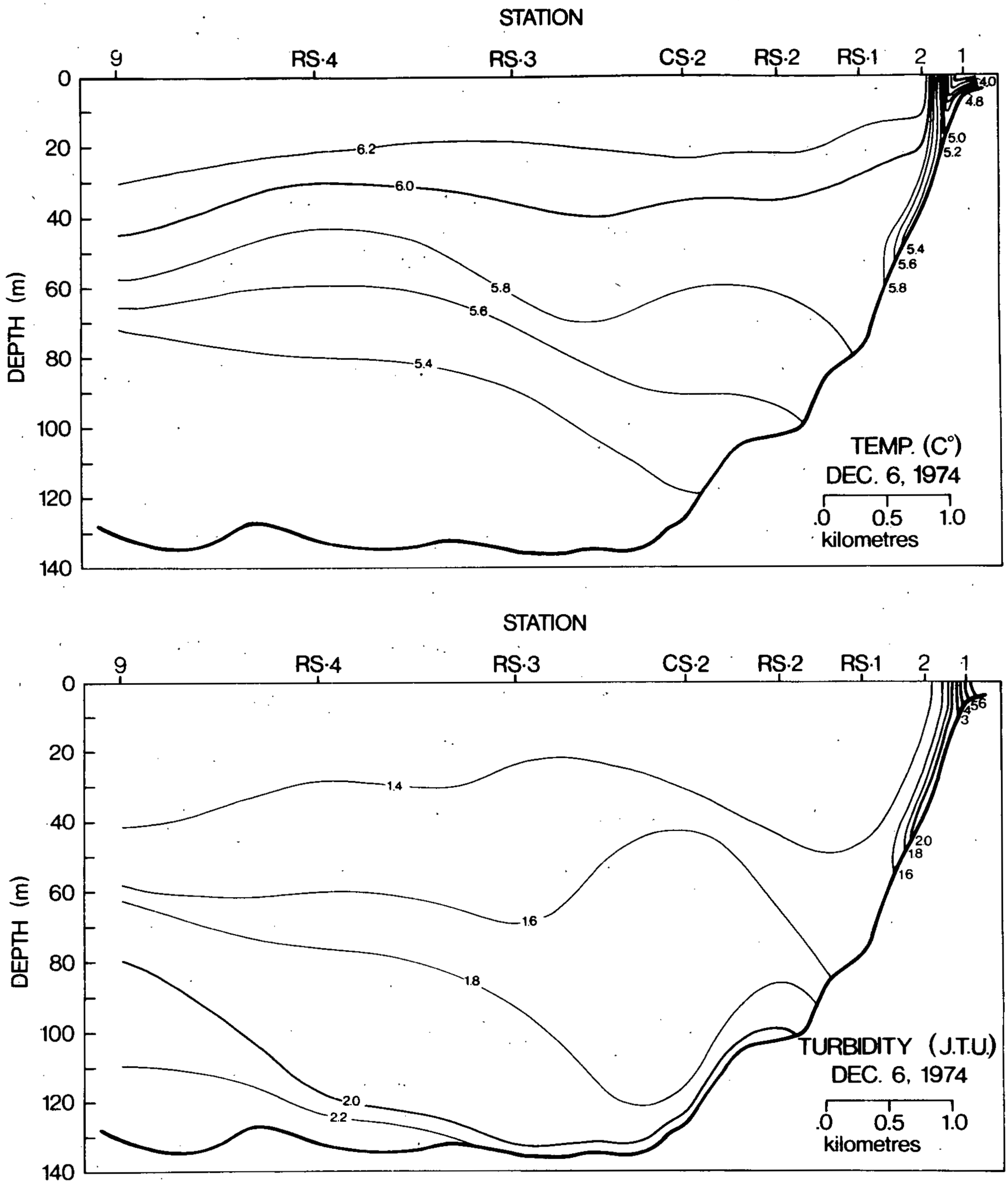


Figure 46. Longitudinal section of (a) temperature, and (b) turbidity at the east end of Kamloops Lake on 6 December 1974.

River more rapidly than the deeper waters of the lake. Upon reaching 4°C, the inflow waters become sufficiently dense to sink to the bottom and promote full autumnal circulation. The initial sinking of inflow water and its mixtures is indicated in Figure 46a,b by the tongue of cold, relatively turbid water flowing down the slope of the river delta. The temperature of the inflow, before entering the lake, is near 4°C while bottom temperatures in the lake are 5.2 to 5.4°C. Rapid mixing, however, increases the temperature of the sinking waters, so that the water that initially underflows is only 0.1 to 0.2°C colder than the ambient bottom water. Throughout the remainder of the autumn overturn, all new inflow waters are contained within the lake basin and ultimately go to replenish the bottom waters. The outflow, consequently, is derived almost entirely from the epilimnion waters remaining from late summer and early autumn.

Further cooling of the inflow water below 4°C decreases its density below that of lake water, so that eventually the river water enters the lake as a surface overflow. However, when water colder than 4°C contacts water warmer than 4°C, mixtures will be formed that are denser than either original water mass, starting the so-called cabbeling instability. An example of the ensuing convective circulation, when the inflow temperature is near 0°C and the mean temperature of the lake is 4.6°C, is illustrated in Figure 47a,b. (From Appendix II we note that all mixtures 3.4<T°C<4.6 effect the cabbeling instability.) River water extends as a buoyant plume about 0.5 km out into the lake. Lateral boundaries of the plume are well-defined by abrupt temperature and turbidity gradients. Sinking of dense water is indicated by the vertical arrangement of the near 4°C isotherms at the frontal edge of the plume. After sinking, this water then spreads westward along the axis of the lake effectively filling the lake basin with 4°C water from the bottom up. As in spring, the cabbeling instability prevents any new inflow water from passing directly down the lake. The inflowing water is also influenced by the Coriolis effect, so that the river plume is held against the north shore (right-hand side) of the lake. The arrested wedge condition of inflow water, and the corresponding

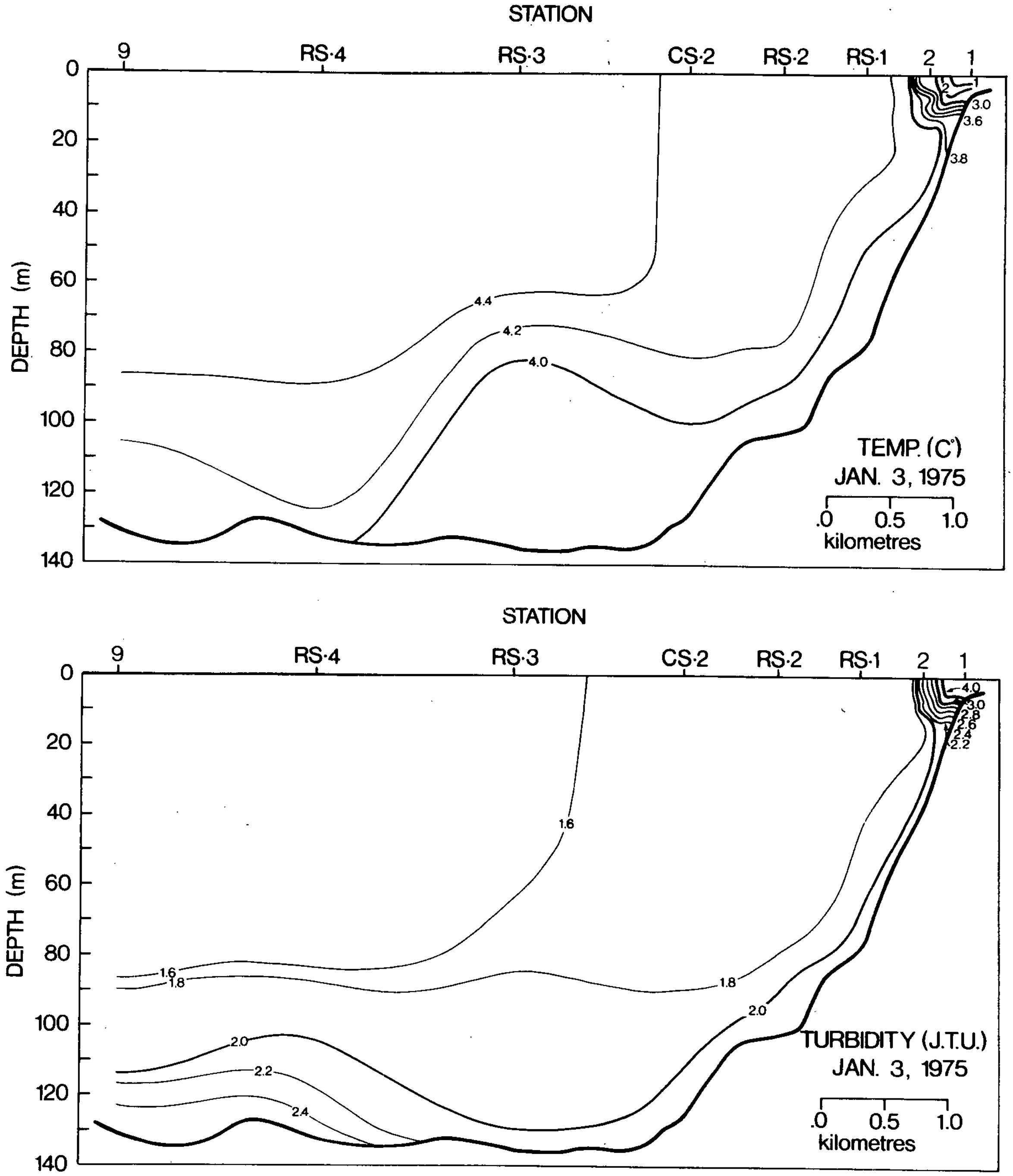


Figure 47. Longitudinal section of (a) temperature and (b) turbidity at the east end of Kamloops Lake on 3 January 1975.

westward spreading of new bottom water, is shown in Figure 48a,b.

It should be noted that the circulation described above is similar to that of the thermal bar described in the Great Lakes by Rodgers (1965) in

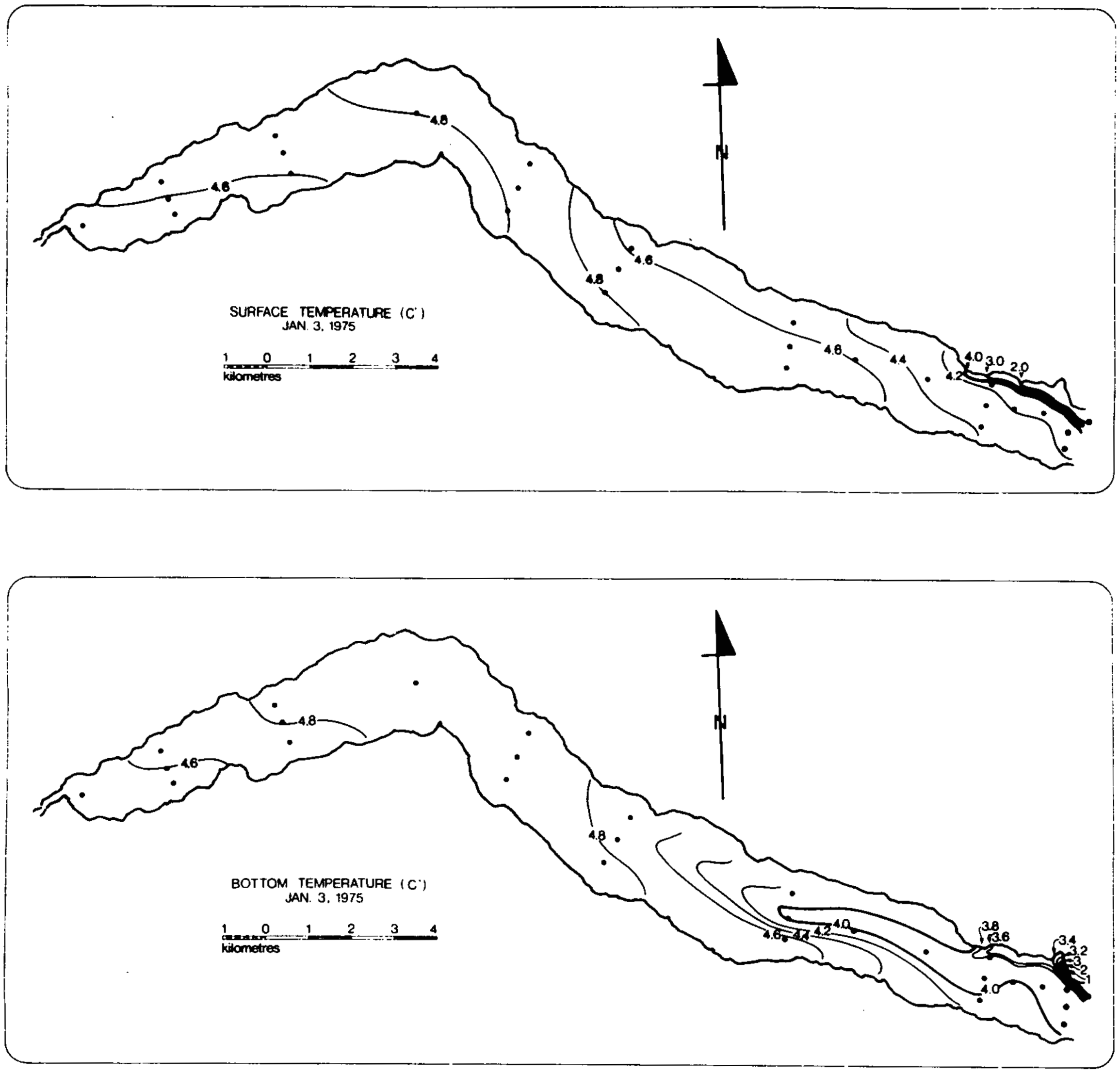


Figure 48. Horizontal distributions of (a) surface temperature, and (b) bottom temperature in Kamloops Lake on 3 January 1975.

that both are driven by the cabbeling instability. The main difference is that in Kamloops Lake the reservoir of cold water is derived from river inflow, whereas in true thermal bar circulations the cold water comes from shallow inshore areas. There is some evidence that a true thermal bar circulation may form in the shallow regions near Savona, but its role in the autumn circulation appears to be secondary to the effects of the Thompson River inflow.

Immediately after autumn overturn (Fig.49a,b) all lake waters are

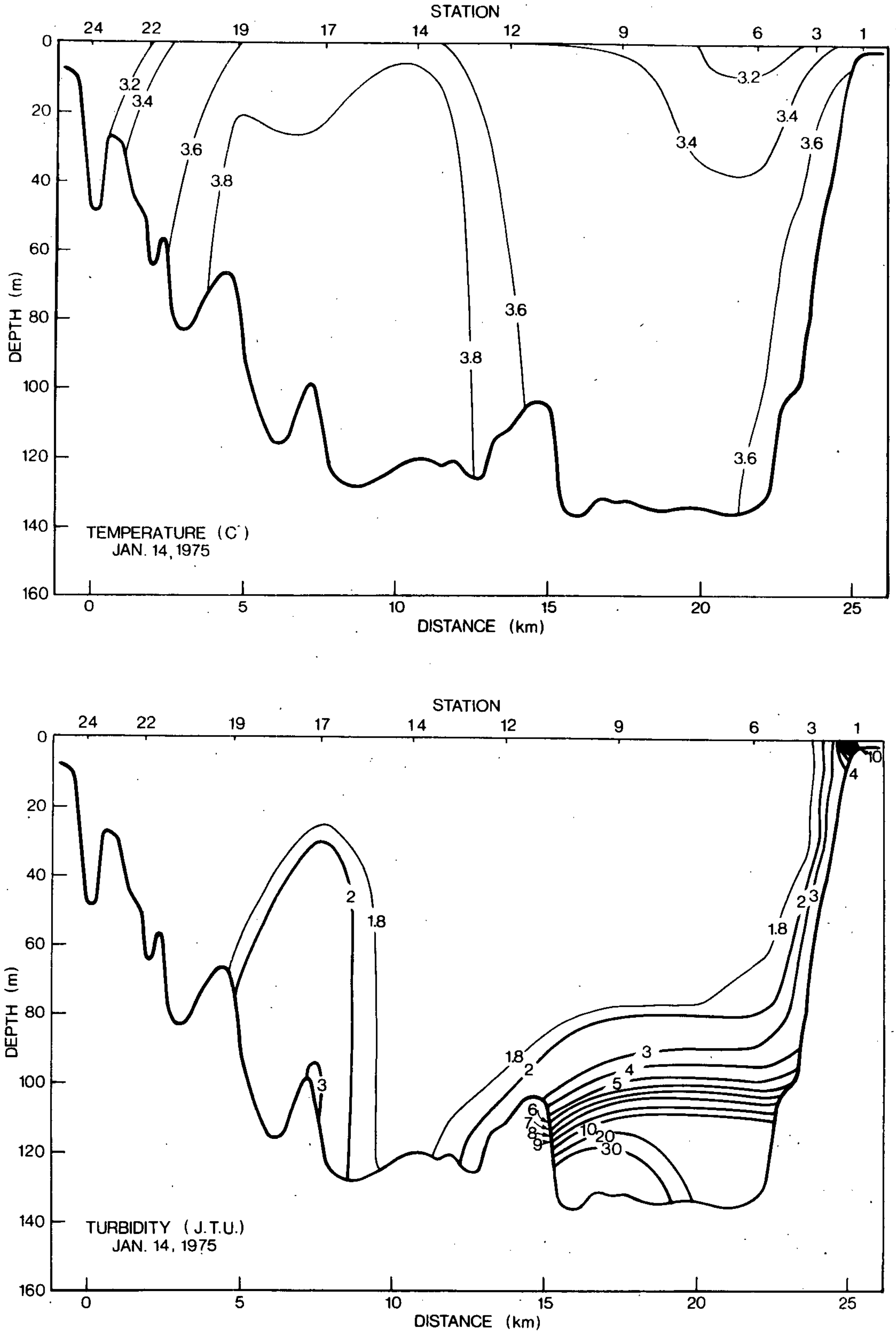


Figure 49. Longitudinal sections of (a) temperature, and (b) turbidity in Kamloops Lake on 14 January 1975.

colder than 4°C. It is curious that the warmest (3.8°C) and hence densest water is observed to stand as a vertical curtain of water in the central basin of the lake, perhaps as a final remnant of the two cabbeling circulations. The beginning of winter is marked by the collapse of this structure.

3.9 Circulation and Distribution of Physical Properties During Winter

Limnological winter (January-March) in Kamloops Lake covers the time between the autumnal and spring circulations. Inflow rates are minimal (150-200 m^3 sec^{-1}) and inflow water temperatures remain near 0°C. All lake waters are colder than 4°C.

The temperature structure of Kamloops Lake thus exhibits reverse stratification, with temperatures generally increasing monotonically with depth (Fig.50a). Turbidity values in the lake (Fig.50b) are generally quite low during winter, except for occasional increases at depth due to bottom stirring.

Throughout winter, the temperature of the incoming river water remains near 0°C. (The excess turbidity (≃5 JTU) of the inflow water maintains a density difference equivalent only to about 0.05°C at 0°C so that temperature remains the main determinant of density.) Since the inflow water is less dense than the lake water, it will exhibit a tendency to transit the lake as a surface overflow. It should be noted, however, that the stability imparted by a given change in temperature near 4°C is much smaller than at higher temperatures so the water column, during winter, offers little resistance to mechanical mixing induced by the wind or by the momentum of the inflow itself. Since bottom temperatures continue to decrease throughout the winter, reaching a minimum of 1.8-2.0°C in late March, it is likely that some vertical exchange extends to the bottom of the lake. The resulting vertical distribution of river water within the lake thus reflects a balance between the effects of stability and mixing. That is, the inflow water tends to remain in the sur-

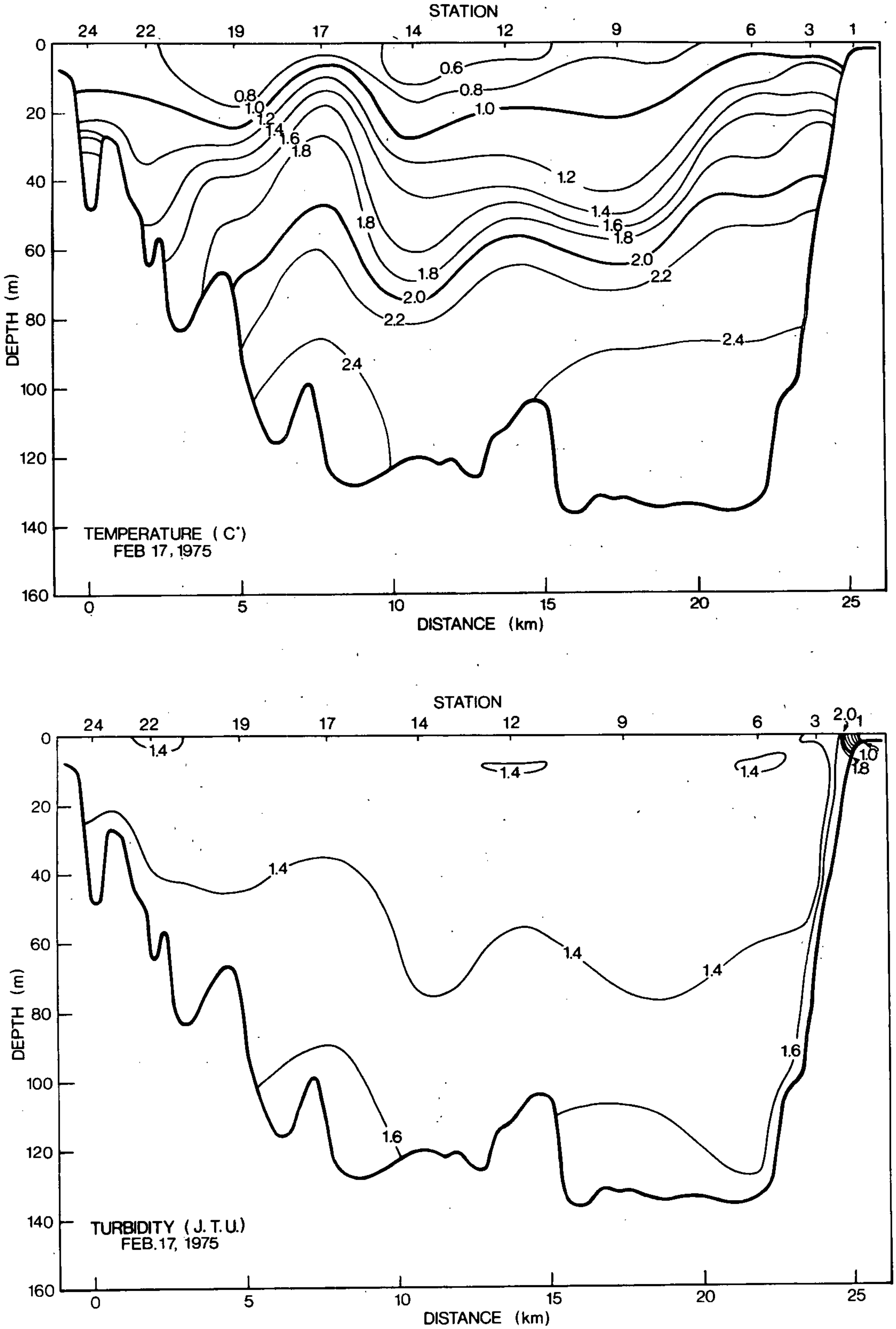


Figure 50. Longitudinal sections of (a) temperature, and (b) turbidity in Kamloops Lake on 17 February 1975.

face layers but is continually mixed deeper within the water column as it crosses the lake. Thus it is reasonable to assume that the concentration of river water remains higher at the surface of the lake than at the bottom.

Two other aspects of the lake-river interaction are of particular interest. First, since river inflow rates are low, the effective dilution of cultural effluents introduced above Kamloops Lake at a constant yearly rate is reduced by a factor of as much as 40:1 over freshet conditions. Second, the low river discharge effects a significantly longer bulk residence time for any soluble material entering the lake during winter.

The above factors combine to allow a significant build-up during winter, especially in the upper layers of the lake, of soluble material introduced into the lake-river system (Section 4). Since, as noted in Section 3.6, the outflow into the Lower Thompson River during spring is derived from lake surface water reflecting winter conditions, the quality of water accumulating in Kamloops Lake during winter can have an important effect on the environmental condition of the Lower Thompson River during the subsequent spring period. The ramifications of this circulation feature will be apparent in the following sections.

4. CHEMICAL LIMNOLOGY

Introduction

A fourteen month survey of the chemical limnology of Kamloops Lake was undertaken from March 12, 1974 to April 22, 1975 in co-operation with the Environmental Protection Service (EPS), Department of Environment. At monthly intervals, ten stations on the lake were occupied in one day and sampled at five depths. The depths were chosen so that two samples representative of the epilimnion, two samples representative of the hypolimnion, and one sample representative of the thermocline (or high turbidity area during some surveys) were taken. The depth intervals of the epilimnion and hypolimnion were obtained from temperature-turbidity profiles measured with a submersible temperature-turbidity sensor. A sample of both the inlet of the Thompson River and the outlet of the lake was taken at 0.1 m depth. The samples were analyzed by the Water Quality Branch of the IWD for major cations and anions; most forms of carbon, nitrogen and phosphorus; reactive silica; dissolved oxygen; specific conductance; turbidity; colour; tannins; and some extractable metals. The samples were subdivided in the field into groups requiring similar preservation procedures. Analyses were begun and completed the next day on those components which are sensitive to storage. Figure 51 shows the location and identification numbers of the stations and a complete list of the chemical components that were measured.

Contour maps of the distributions of all the components were made. The horizontal concentration gradients were generally much smaller than the vertical gradients. It was convenient then to reduce all the ten station profiles into a single, lake-wide mean profile using a computer program that accounted for the effects of bottom topography on the volume-weighted means. The plotting of these average profiles over time provides an overview of the seasonal processes and trends. The annual distributions of chemical components

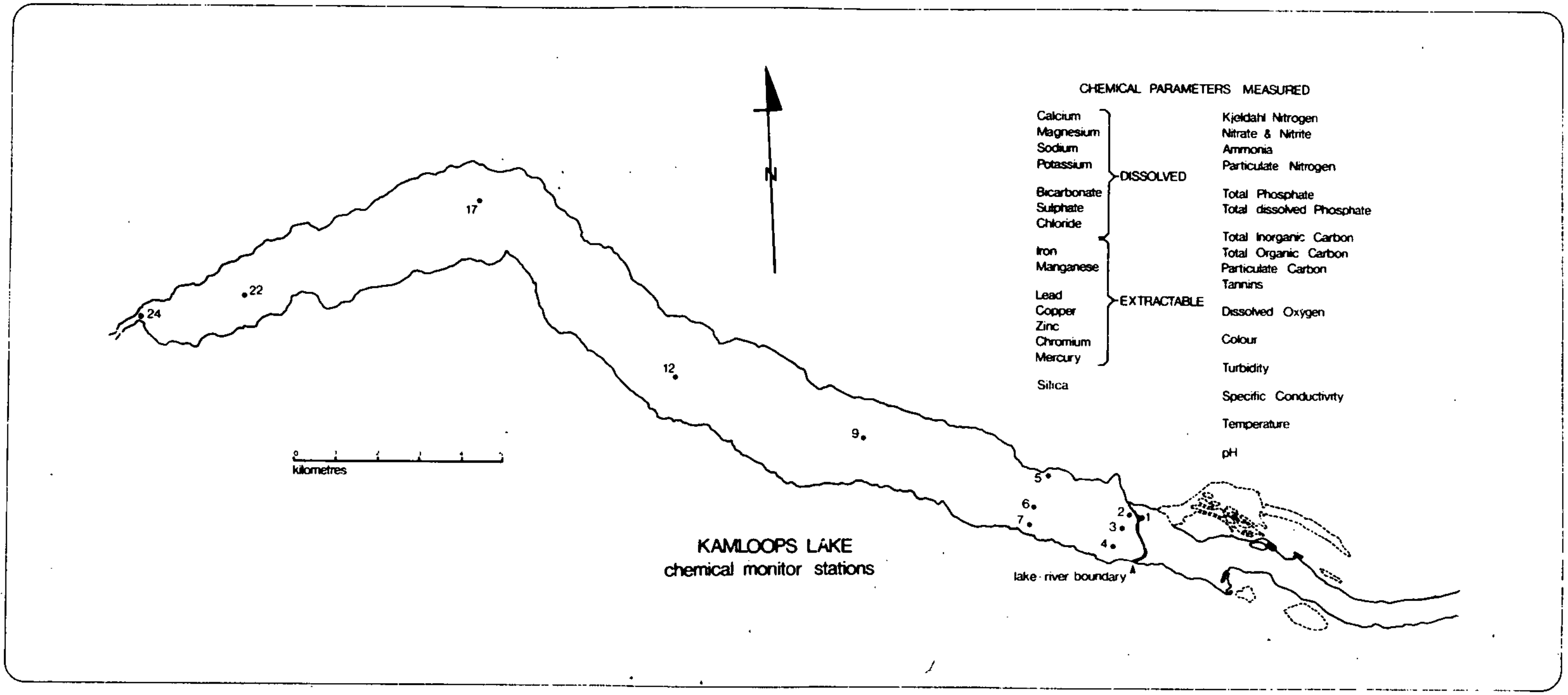


Figure 51. Chemical limnology monitor stations in Kamloops Lake and chemical component list.

will be discussed under separate headings.

4.1 Nitrogen

The water samples were analyzed for nitrate + nitrite, ammonia and Kjeldahl nitrogen. Separate subsamples from each sample were filtered through Whatman GF/C glass fibre filters (roasted at 550°C for more than an hour before use) and the filters were then analyzed for particulate nitrogen. The results are reported as concentrations of atomic nitrogen. Nitrate + nitrite are the two dissolved inorganic nitrogen species. Particulate nitrogen is mostly proteinaceous detritus. By subtracting particulate nitrogen and ammonia from Kjeldahl nitrogen, dissolved organic nitrogen is obtained.

The total nitrogen concentrations in the lake vary between 100 and 380 $\mu g\ l^{-1}$ annually and tend to be highest in spring and early summer. At spring overturn, the concentrations are about 250 $\mu g\ l^{-1}$, which are similar to those seen at spring overturn in the Okanagan lakes (Stockner and Northcote 1974).

a) Nitrate + Nitrite

In fresh waters, nitrite concentrations are usually very low relative to nitrate so that this nitrogen fraction will be considered as nitrate only. Large vertical concentration gradients of nitrate develop in the lake from spring to the end of summer, but become insignificant by the beginning of winter (Fig. 52). The concentrations in the upper 20 m of the epilimnion drop from initial levels of *ca* 100 $\mu g\ l^{-1}$ in April to 20-50 $\mu g\ l^{-1}$ in August and September. This decrease can be accounted for both by algal uptake and by the admixture of river water low in nitrate (20-70 $\mu g\ l^{-1}$; Fig.56) into the epilimnion. The latter process is probably the major cause of the decrease in June and July, while the growth of algae could be the major cause in August and September when the turbidity is low and algal biomass is highest.

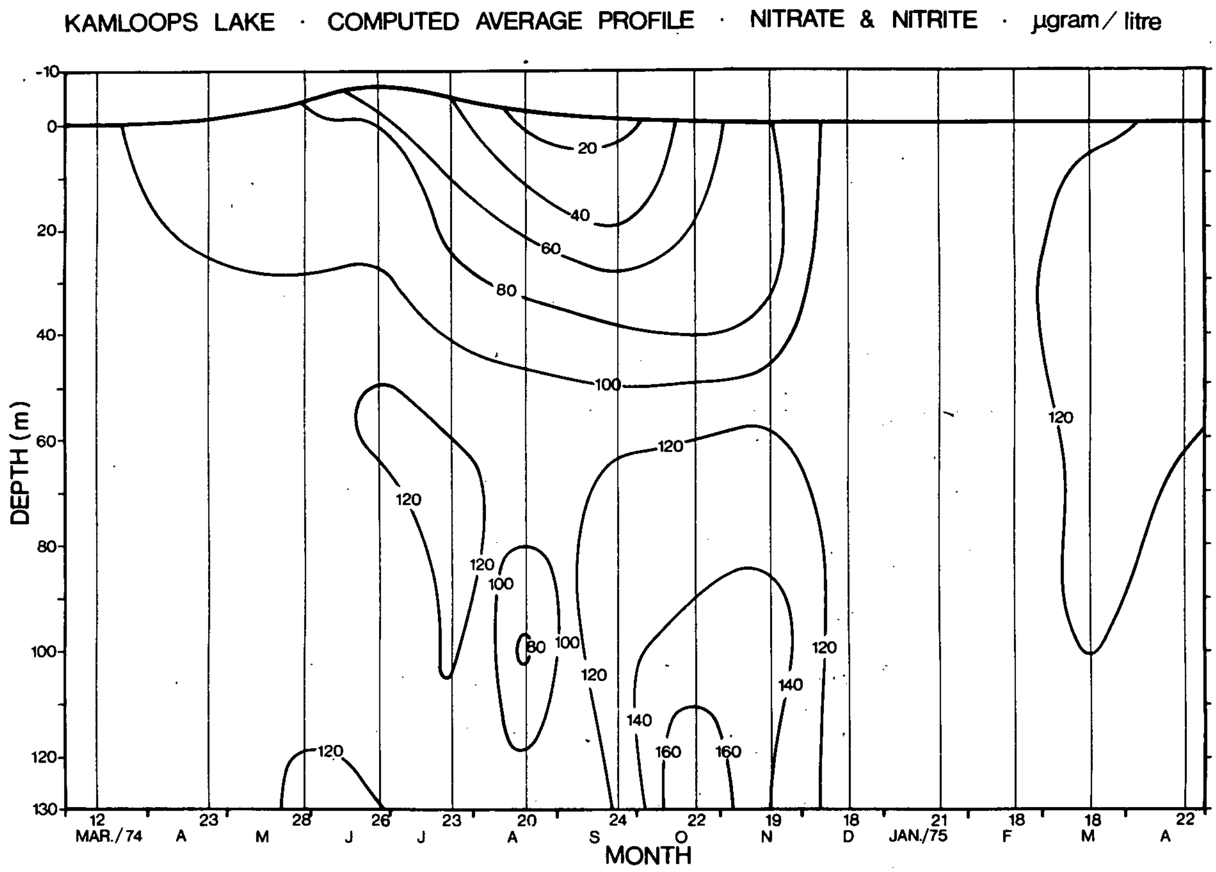


Figure 52. Annual isopleths of nitrate + nitrite nitrogen from the monthly computed average profiles in Kamloops Lake, 1974-75.

In contrast to declining concentrations in the epilimnion, the nitrate concentration in the hypolimnion (below 115 m) increases from 100 µg l^{-1} in August to 170 µg l^{-1} in October. (Within 7 m of the bottom at Station 6 the concentration reaches 200 µg l^{-1}.) The source of this extra nitrate is unclear, but some speculation is possible. Over the same time period, the ammonia, particulate and dissolved organic nitrogen concentrations are relatively constant. Therefore, in the water column, these fractions can be ruled out as sources unless they are being replenished at the same rate that they are converted to nitrate (see Figs.53,54,55). Hence, release from sediments is the most probable cause of the extra hypolimnetic nitrate. The sediment nitrate is likely derived primarily from the particulate nitrogen settling to the sediment during the early summer.

The magnitude of the nitrate production from the sediment is considerable when compared to the loading of nitrate to the lake from the two point sources at Kamloops. For example, during the 60-day period from late August to late October, the internal production or "loading" is approximately 25 metric tonnes, or about five times the point source loading of nitrate for the same interval. Subsequently, the mixing of this internally produced nitrate upwards into the water column during the autumnal overturn (December) increases the lake-mean nitrate concentration to about 105 µg l^{-1}.

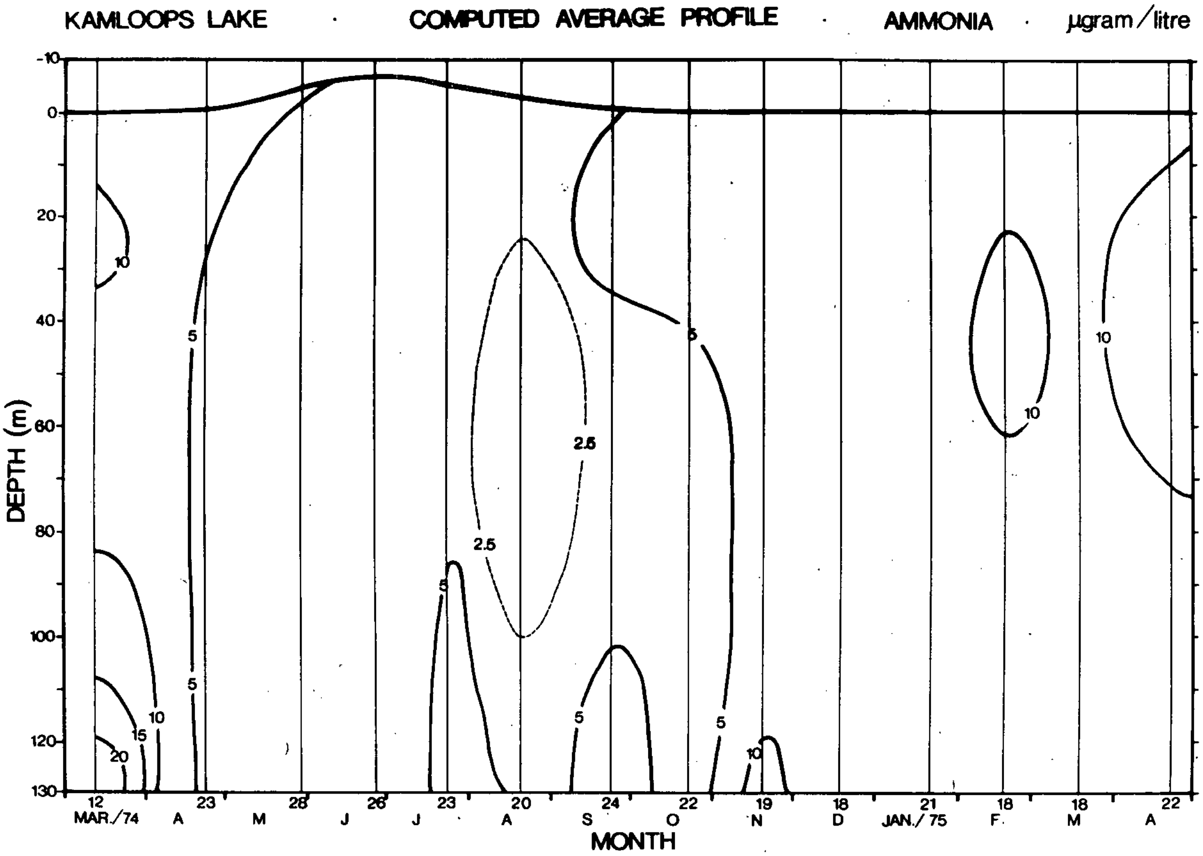


Figure 53. Annual isopleths of ammonia nitrogen from the monthly computed average profiles in Kamloops Lake, 1974-75.

Nitrate concentrations in the inflowing river increased from a minimum of 22 µg l^{-1} in August to an average of 100 µg l^{-1} between December and

April, 1975 (Fig.56), but only 8% of this increase was due to point source loadings (IWD Report, 1976). Furthermore, the entrance of river water containing nitrate at slightly lower concentrations than in the lake did not dilute the lake concentrations as expected. In fact, over the winter, the nitrate concentrations continued to rise in both the lake and outflow to approximately 120 µg l^{-1} (a 17% increase). This increase would require a calculated production of 55.5 metric tonnes of nitrate from other nitrogen forms in the water column and sediments. Although these internal generation processes significantly increase the nitrate concentrations in the lake during the winter, the concentrations in the inflowing river above the point sources are still sufficiently high that algal production is likely not limited in such a system (Section 5). We calculate that if the nitrogen source for the internal generation processes was the point source loading near Kamloops and was eliminated, the concentrations of nitrate would only be reduced to approximately 90-100 µg l^{-1}, the same concentration range as the river above the location of the point source inputs.

b) Ammonia

The ammonia nitrogen tends to be homogeneous with depth with a slight tendency to increase in the bottom 40 m of the lake (Fig.53). The seasonal maximum occurs in late winter and early spring, while the minimum occurs at mid depths in the summer. Neither the net uptake of ammonia as a nutrient by micro-organisms nor the net conversion of ammonia to nitrate by bacteria seem to be occurring to any significant extent.

The concentration of ammonia in the output river remains relatively constant between 5 and 10 µg l^{-1} throughout the hydrologic cycle (Fig.56). The input river, however, fluctuates between 5 and 30 µg l^{-1} with the highest values occurring in March.

c) Dissolved Organic Nitrogen

Dissolved organic nitrogen only shows strong, vertical concentration

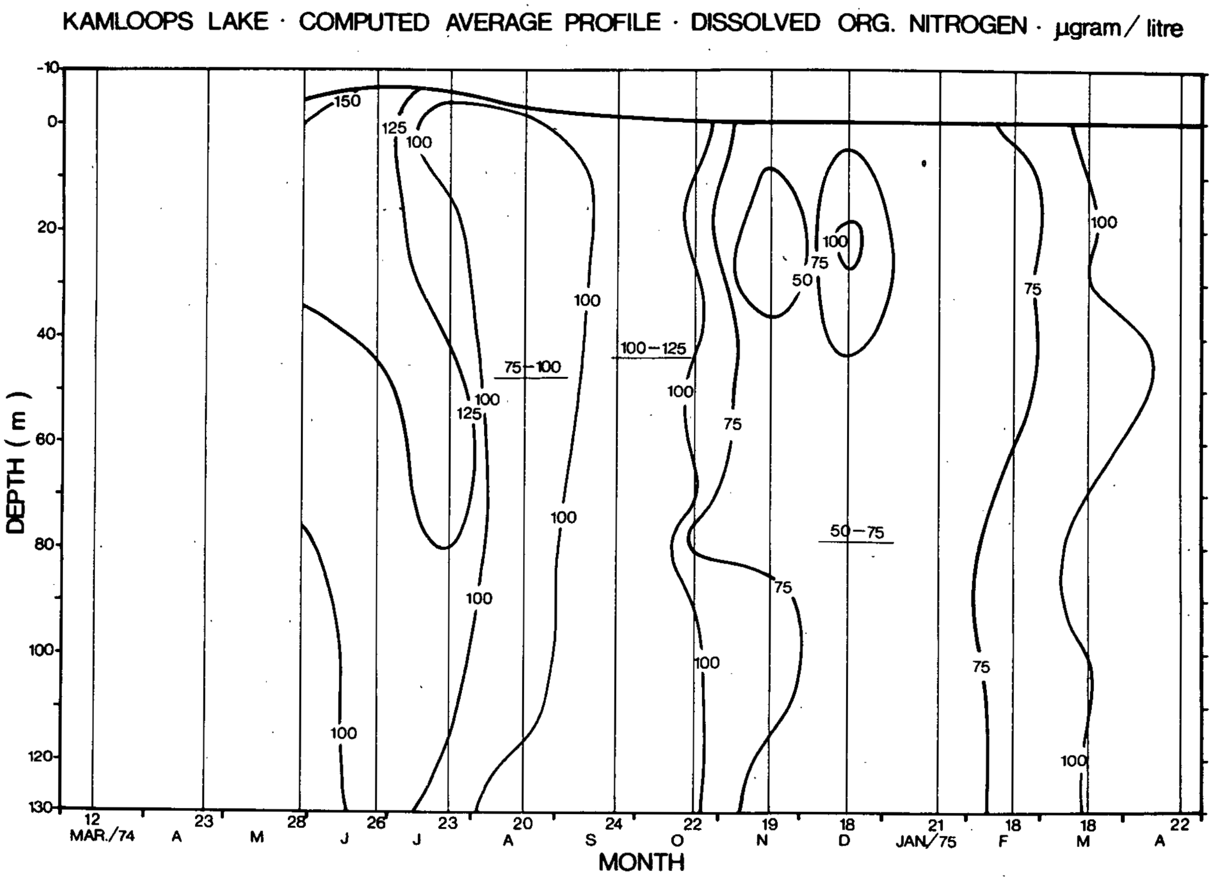


Figure 54. Annual isopleths of dissolved organic nitrogen from the monthly computed average profiles in Kamloops Lake, 1974-75.

gradients during the freshet when high concentrations of 150 µg l^{-1} are found at the surface and 100 µg l^{-1} near the bottom (Fig.54). These high concentrations of dissolved organic nitrogen in the epilimnion seem to reflect the river concentrations entering the lake (Fig.56). The concentrations then decrease erratically from the seasonal maximum to the seasonal minimum in early winter. As the concentrations of dissolved organic nitrogen increase in the input river during February, March and April, there is a corresponding concentration increase in the lake throughout the water column.

There is no indication in the data that dissolved organic nitrogen is converted to nitrate in the hypolimnion during August, September or October. During the winter, however, the concentrations of dissolved organic nitrogen leaving the lake are always 25-100 µg l^{-1} less than the input concentrations, while nitrate nitrogen concentrations are always 14-30 µg l^{-1} higher in the output than the input during the same period. Some of the nitrate increase could be due to conversion of dissolved organic nitrogen by biological processes.

d) Particulate Nitrogen

The nitrogen of this fraction is mainly present in protein-rich organic matter, although an unknown, but probably small proportion is ammonia nitrogen "fixed" in clays. There is a distinct maximum in particulate nitrogen in the top 30 m of the lake during the freshet (Fig.55). In the top 10 m, the concentrations range from 20 to 30 µg l^{-1} and are presumably in the form of detrital organic matter and clay-fixed ammonia from the flooding river.

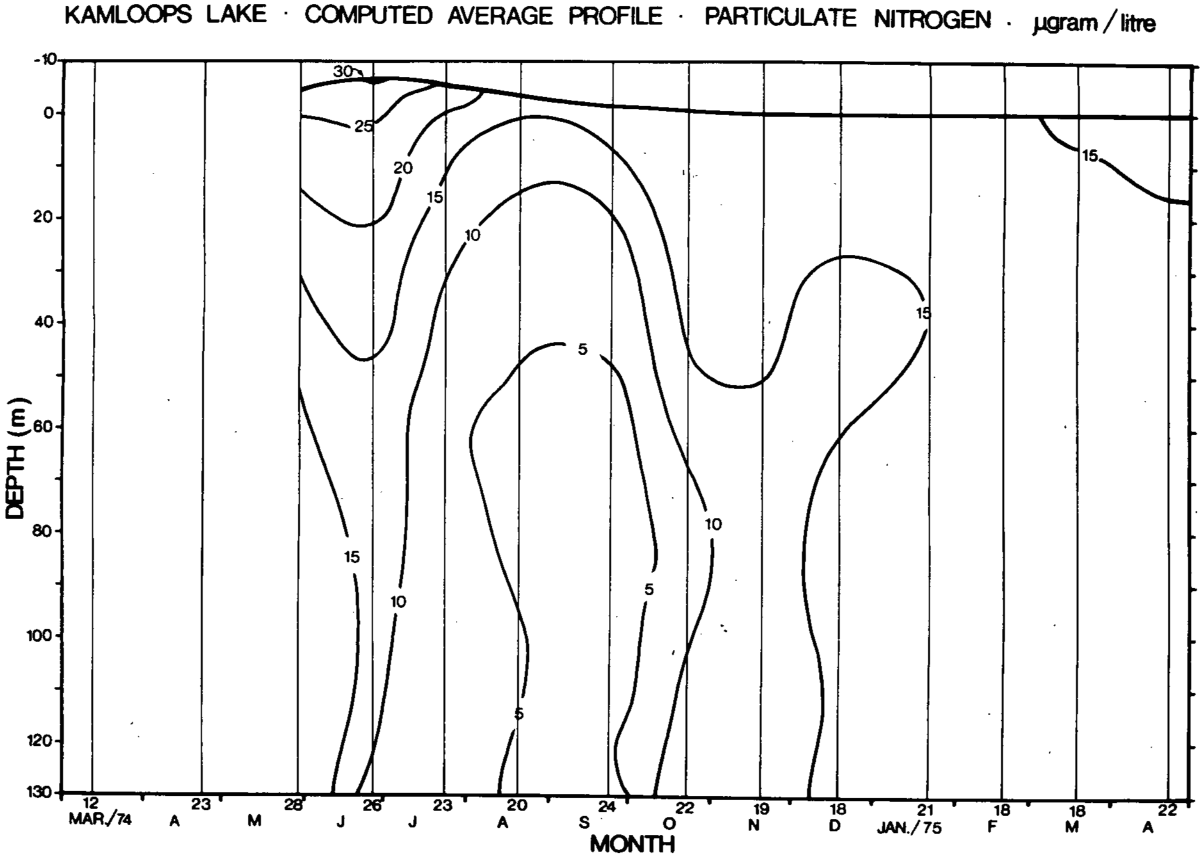


Figure 55. Annual isopleths of particulate nitrogen from the monthly computed average profiles in Kamloops Lake, 1974-75.

The minimal concentrations of particulate nitrogen occur in the hypolimnion during mid-summer when the processes supplying particulate nitrogen to the hypolimnion were presumably the least active. The epilimnion is also low in particulate nitrogen at this time (Fig.55). Biological uptake of dissolved nitrogen probably accounts for the increases seen in the epilimnion during late September and October. The supply of particulate nitrogen from the river increases during autumn and winter reaching a maximum in March (Fig.56). Hence the water column concentrations of particulate nitrogen remain high over the winter due both to high supply rates and to turbulence which inhibits settling. The reasons for the increased concentrations of particulate nitrogen in the inflow river during this period are unclear, although the peak concentration in March could have been benthic algal fragments originating in the North and South Thompson Rivers. These winter inputs of particulate nitrogen possibly settle to the sediments after the thermocline forms in spring and then serve as the primary source of the nitrogen generated from the sediments in September and October.

e) Nitrogen Budget

The difference between the annual input and output of each nitrogen component represents either its net retention in the lake, its loss to the atmosphere above the lake, or both. When the loadings, retentions (IWD Report, 1976), and average contents are plotted diagrammatically, the relative magnitudes of the processes are apparent (Fig.57). The lake system retains only 23% of the total nitrogen input annually. Since the annual input loading is 6.7 times the annual average content of the water column, the crude residence time for total nitrogen in the lake is *ca* 55 days.

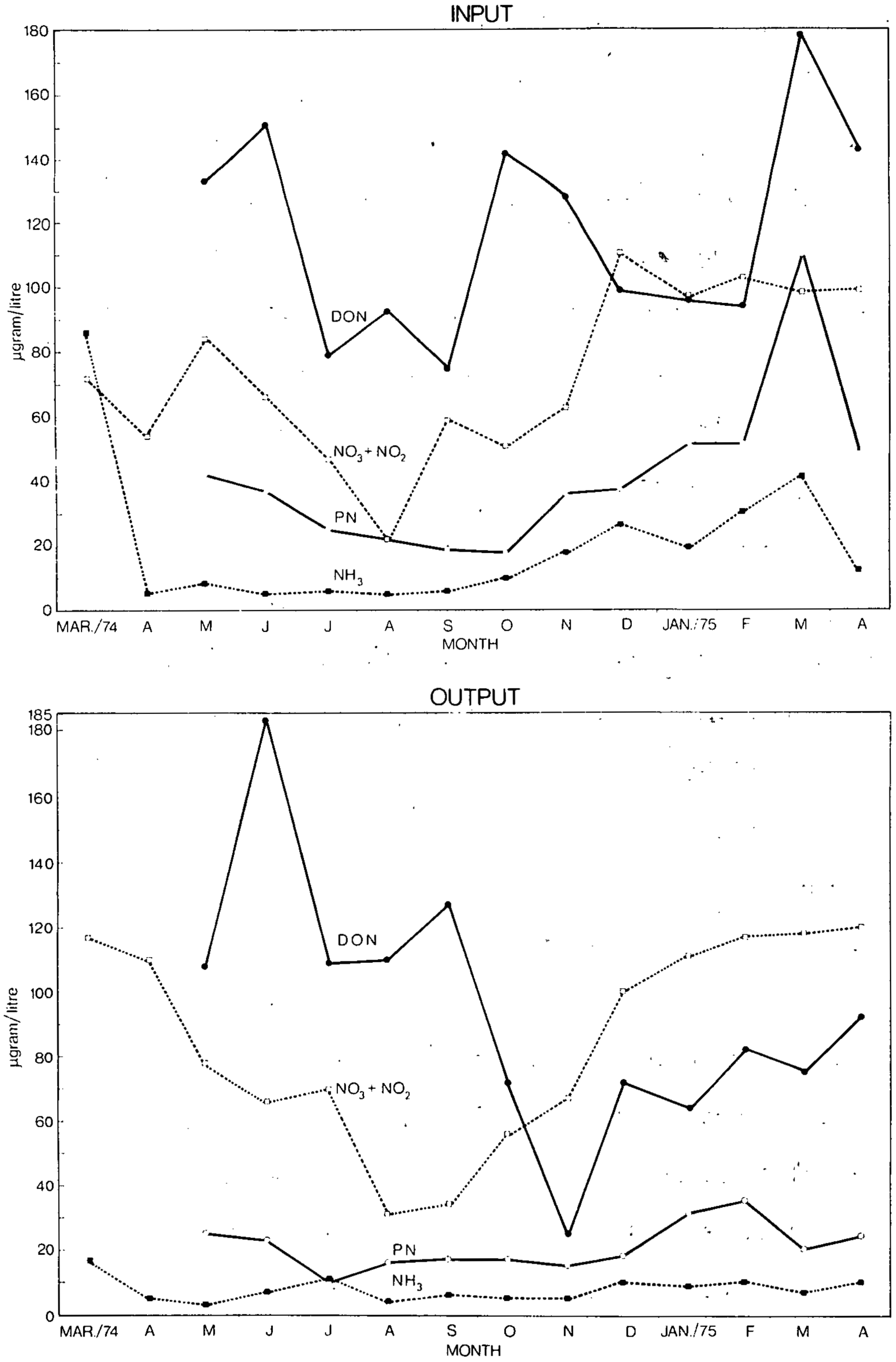


Figure 56. Monthly concentrations of the nitrogen fractions in the inflowing and outflowing rivers (Stations 1 and 24). Dissolved Organic Nitrogen (——•——), Nitrate Nitrogen (·····○·····), Particulate Nitrogen (——○——), Ammonia Nitrogen (·····•·····).

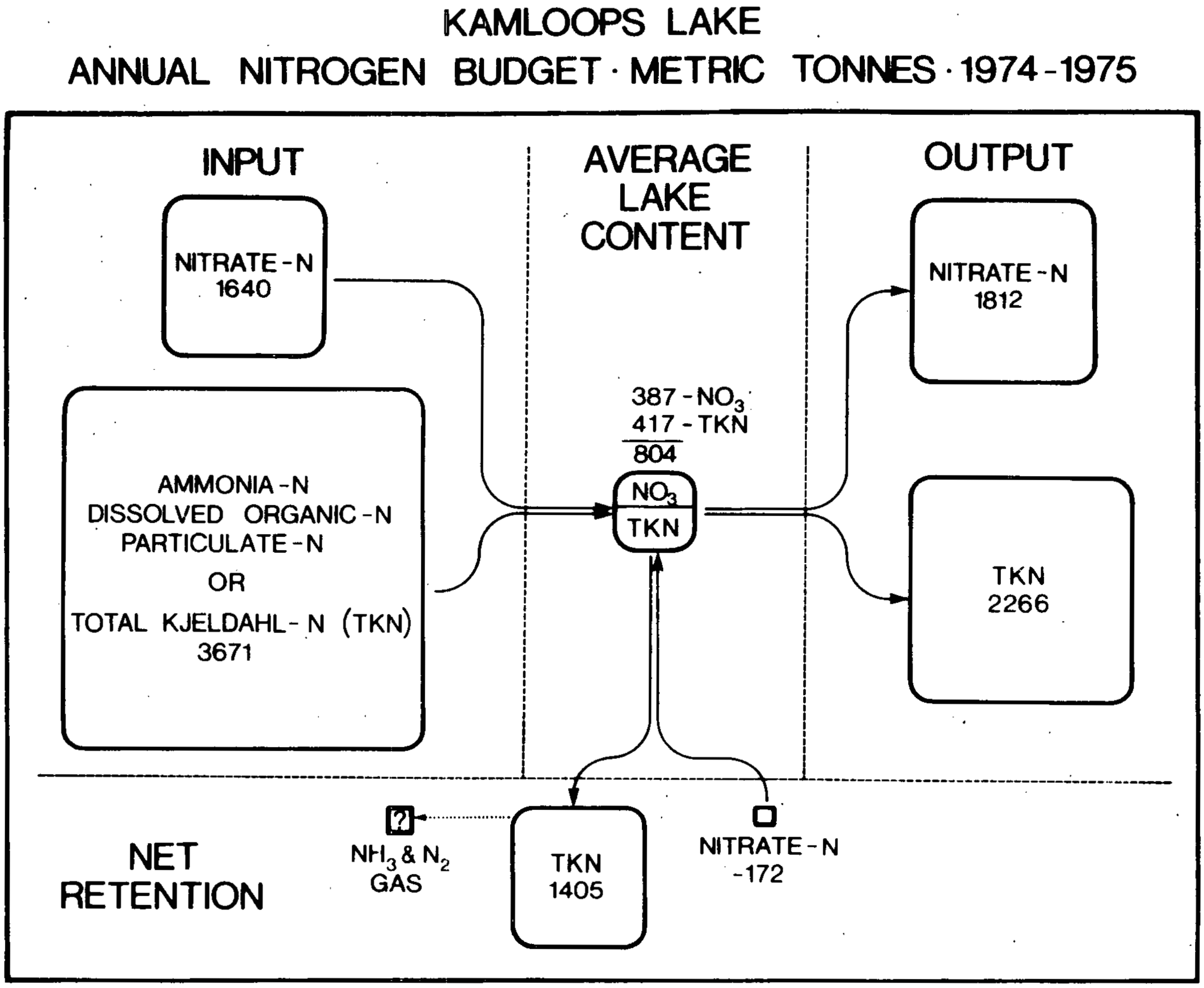


Figure 57. Annual nitrogen budget for Kamloops Lake.

4.2 Phosphorus

a) Seasonal Distributions

Phosphorus analyses were performed on two aliquots of the water sample, one of which was filtered in the field immediately after the bottle cast was complete. Dissolved phosphorus was then analyzed on the filtered sample while total phosphorus was determined on the unfiltered sample. The dissolved phosphorus was not analyzed for its component fractions of organic and inorganic phosphorus compounds, the most important of which is the algal nutrient, orthophosphate. Orthophosphate concentrations can, therefore, range from zero up to 100% of the dissolved phosphorus total.

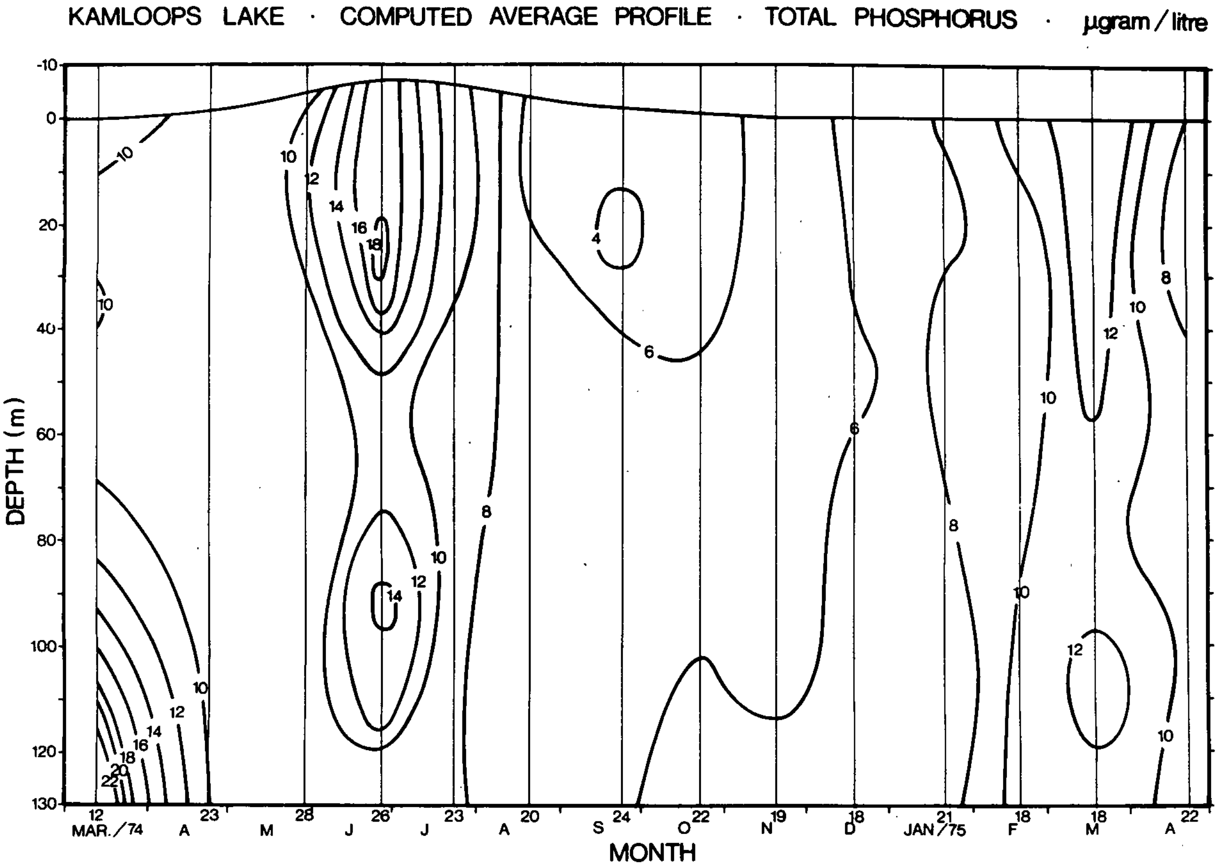


Figure 58. Annual isopleths of total phosphorus from the monthly computed average profiles in Kamloops Lake, 1974-75.

The seasonal isopleths of the total, dissolved, and particulate phosphorus fractions are plotted in Figures 58, 59 and 60, respectively. Concentrations range from 3 to 23 μg l^{-1} for the total phosphorus; from 3 to 11 μg l^{-1} for the dissolved phosphorus; and from 1 to 20 μg l^{-1} for the particulate phosphorus. For comparison, most of the Okanagan Valley lakes, which range from oligotrophic to eutrophic in status, have greater concentrations (Stockner and Northcote 1974) whereas Babine Lake (an oligotrophic lake in north central B.C.) has lower concentrations (Stockner and Shortreed 1974).

The seasonal distribution pattern of total phosphorus shows two maxima; one during the freshet (May-June-July), and the other in late winter (March). The freshet maximum consisted almost equally of particulate and dissolved fractions in the top 40 m but was mostly particulate between 7 and 100 m. The dissolved phosphorus maximum occurred at the average depth of the river plume during this period. Although some of this dissolved phosphorus was mixed down into the upper levels of the hypolimnion, as seen in the profile of July 23 (Fig.59), the majority of the dissolved freshet phosphorus was washed out of the epilimnion and progressively replaced by the influx of river water phosphorus which dropped from 11 to 4 μg l^{-1} between the peak flood and mid-August (Fig.61). Presumably the deeper area of higher particulate phosphorus concentrations during the freshet came about either by settling from the river plume or by resuspension of bottom materials due to river plume turbulence on the delta face.

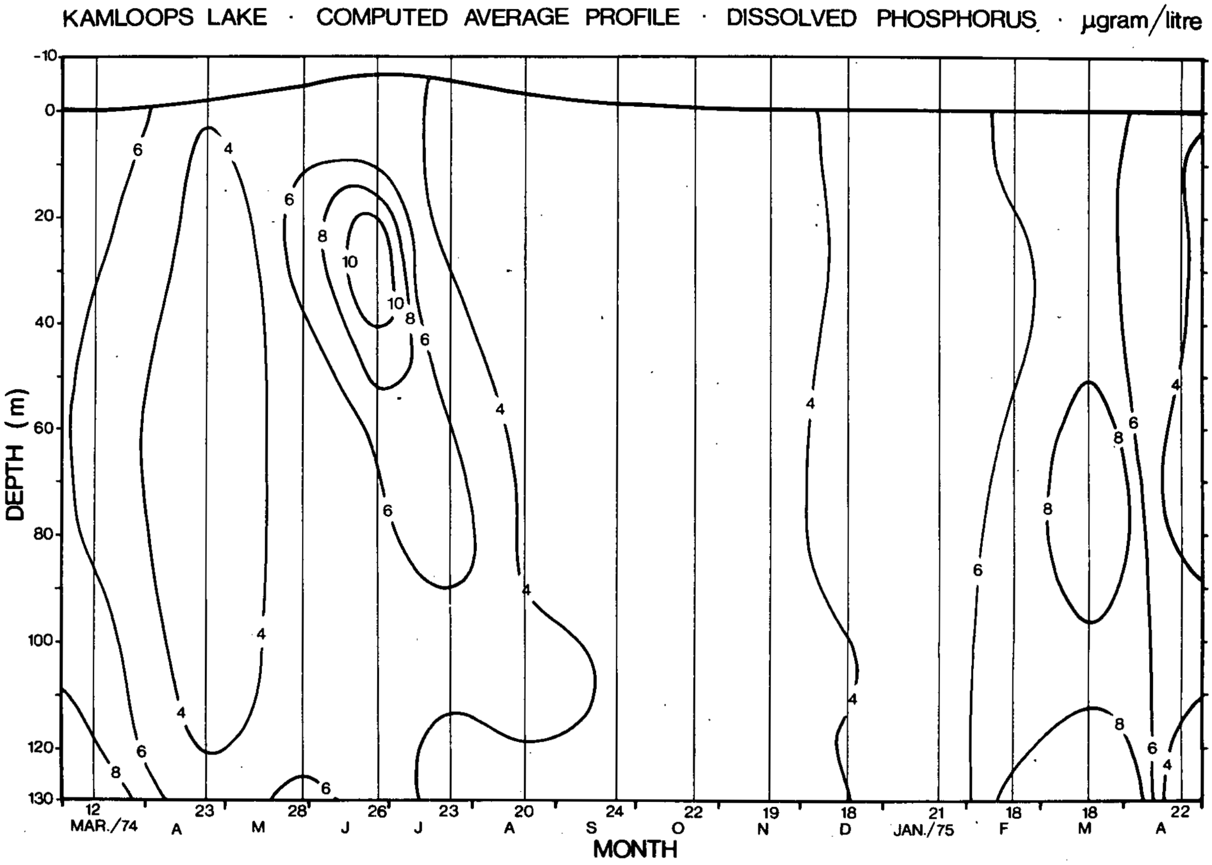


Figure 59. Annual isopleths of dissolved phosphorus from the monthly computed average profiles in Kamloops Lake, 1974-75.

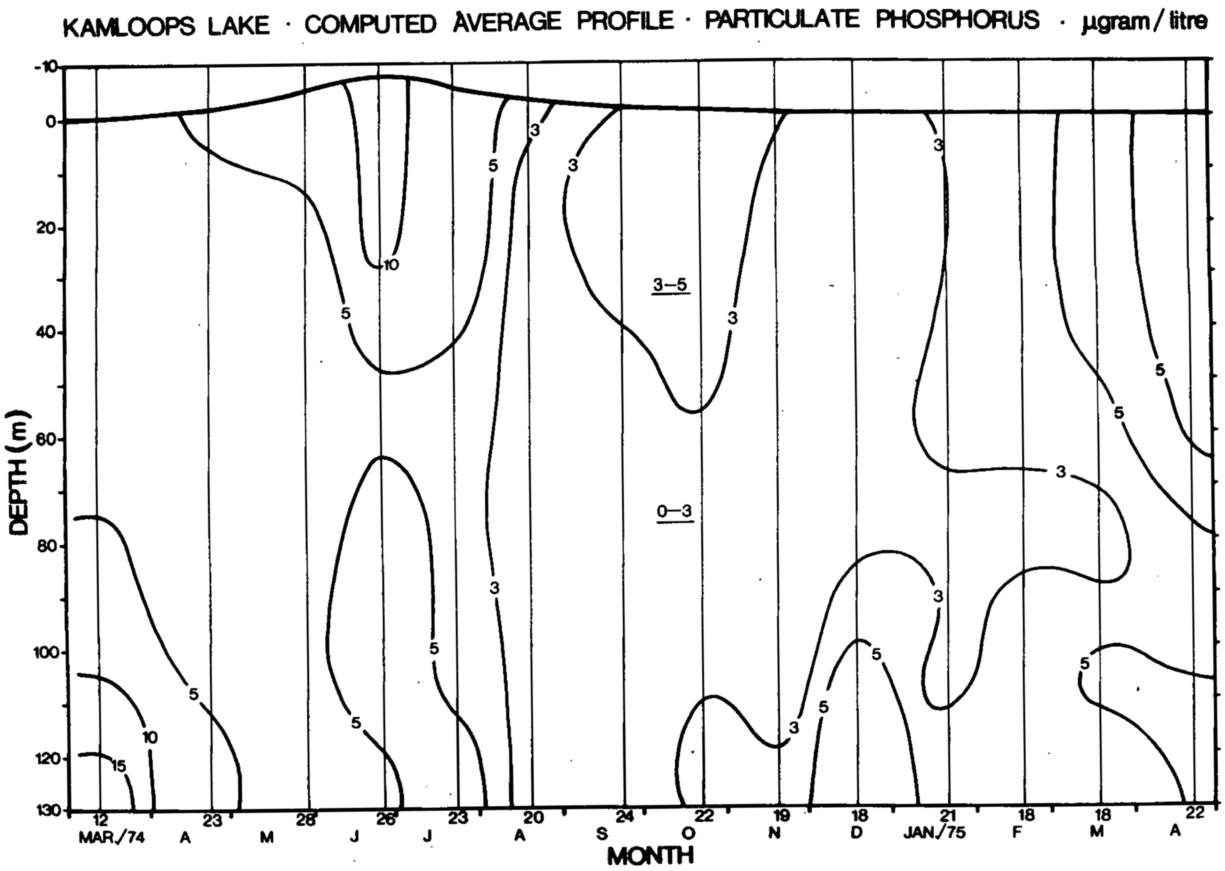


Figure 60. Annual isopleths of particulate phosphorus from the monthly computed average profiles in Kamloops Lake, 1974-75.

The late winter maxima of 1974 and 1975 differed in their relative proportions of dissolved and particulate phosphorus. On both occasions the dissolved phosphorus concentrations in the entire water column were generally double the fall overturn values. On the other hand, particulate phosphorus concentrations increased dramatically below 80 m in March, 1974 but not in March, 1975. A turbidity current, caused by a slump on the delta face several days before sampling, may possibly have carried resuspended particulate phosphorus into the hypolimnion and along the bottom in March, 1974. Particulate and dissolved phosphorus increased to 24 and 17 µg l^{-1}, respectively, in the inflow in March, 1975 and mixing of the river water with the lake water resulted in the March maximum (Fig.61). The increased concentrations in the inflow

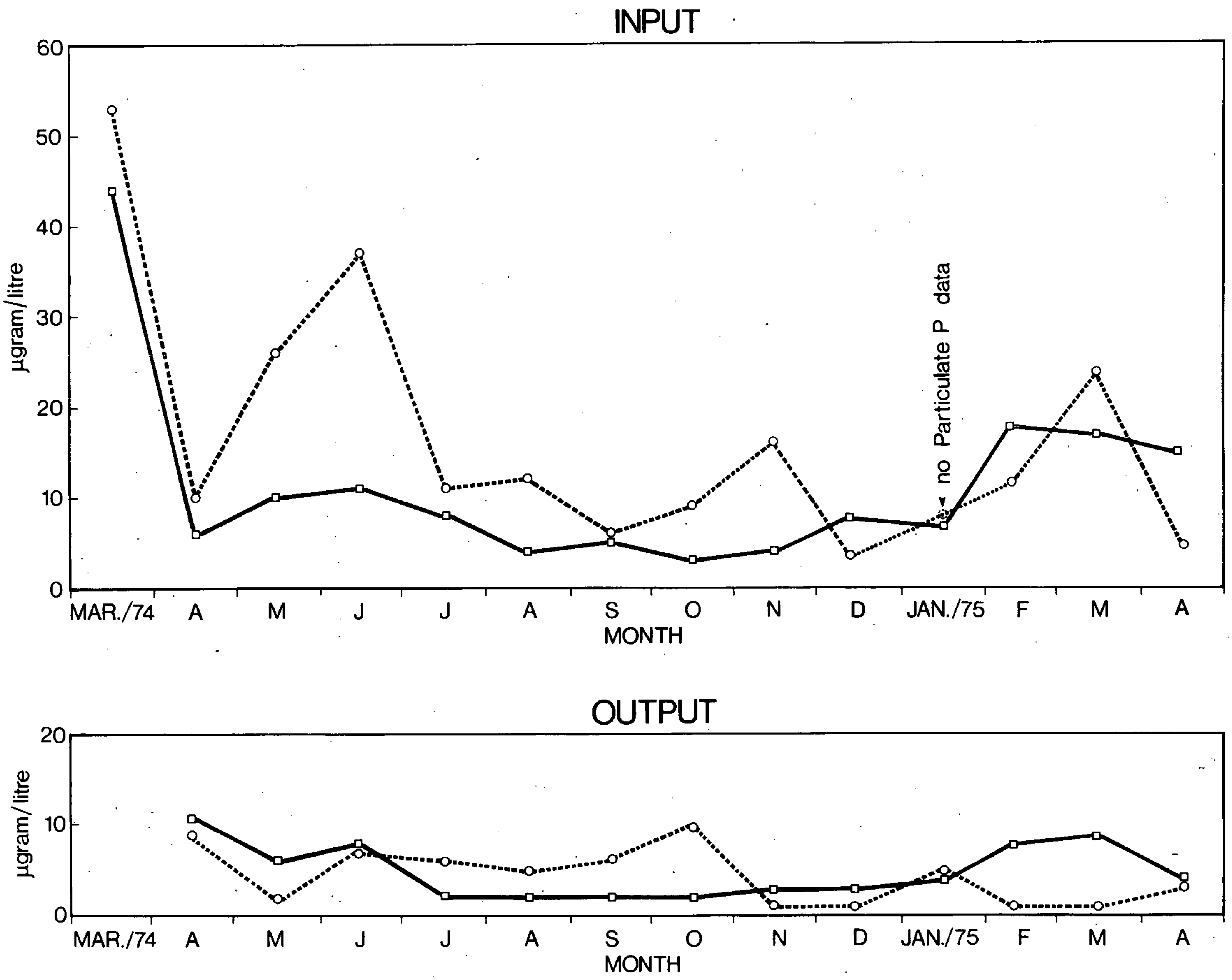


Figure 61. Monthly concentrations of the phosphorus fractions in the inflowing and outflowing rivers of Kamloops Lake, 1974-75. Particulate Phosphorus (····○····), Dissolved Phosphorus (—□—).

resulted when river flows decreased and hence did not dilute to the same extent the constant concentration point source effluents and the natural diffuse sources of phosphorus.

A slight increase in particulate phosphorus was observed in the epilimnion between August and the September-October period (Fig.60). This may have been partly due to algal uptake from the dissolved pool of phosphorus.

b) Phosphorus Budget

On an annual basis, Kamloops Lake is a sink for particulate phosphorus but not for dissolved phosphorus. The annual load (Fig.62) of total phosphorus was approximately 1190 metric tonnes (IWD Report 1976),assuming direct atmospheric inputs to the lake were insignificant. Of this total, 118 metric tonnes was dissolved phosphorus. In comparison, the net retention of particulate and dissolved phosphorus was approximately 896 and 7 metric tonnes, respectively. Therefore, 84% of the particulate phosphorus input and 6% of the dissolved phosphorus load were retained in the lake, giving a total phosphorus retention of 76%. Our independent geochemical estimate of the amount of phosphorus sedimented annually was 1000 metric tonnes (Section 2.7) which is 11% greater than the net retention of total phosphorus reported by IWD. The greater value would be expected because the measurement of net retention by IWD did not take into account the bedload transport of phosphorus-containing sediment which is included in the geochemical calculations.

The high annual retention of total phosphorus coupled with the short hydrologic residence time (Section 3.1) of Kamloops Lake is quite unusual. Kirchner and Dillon (1975) have found that higher areal water loadings (a calculation which combines both flushing rate and lake surface area) are usually associated with low total phosphorus retentions. Using their empirical relationship, Kamloops Lake, with an areal water load of 436 m, has a predicted phosphorus retention of 0.1%, which is much lower than the measured retention

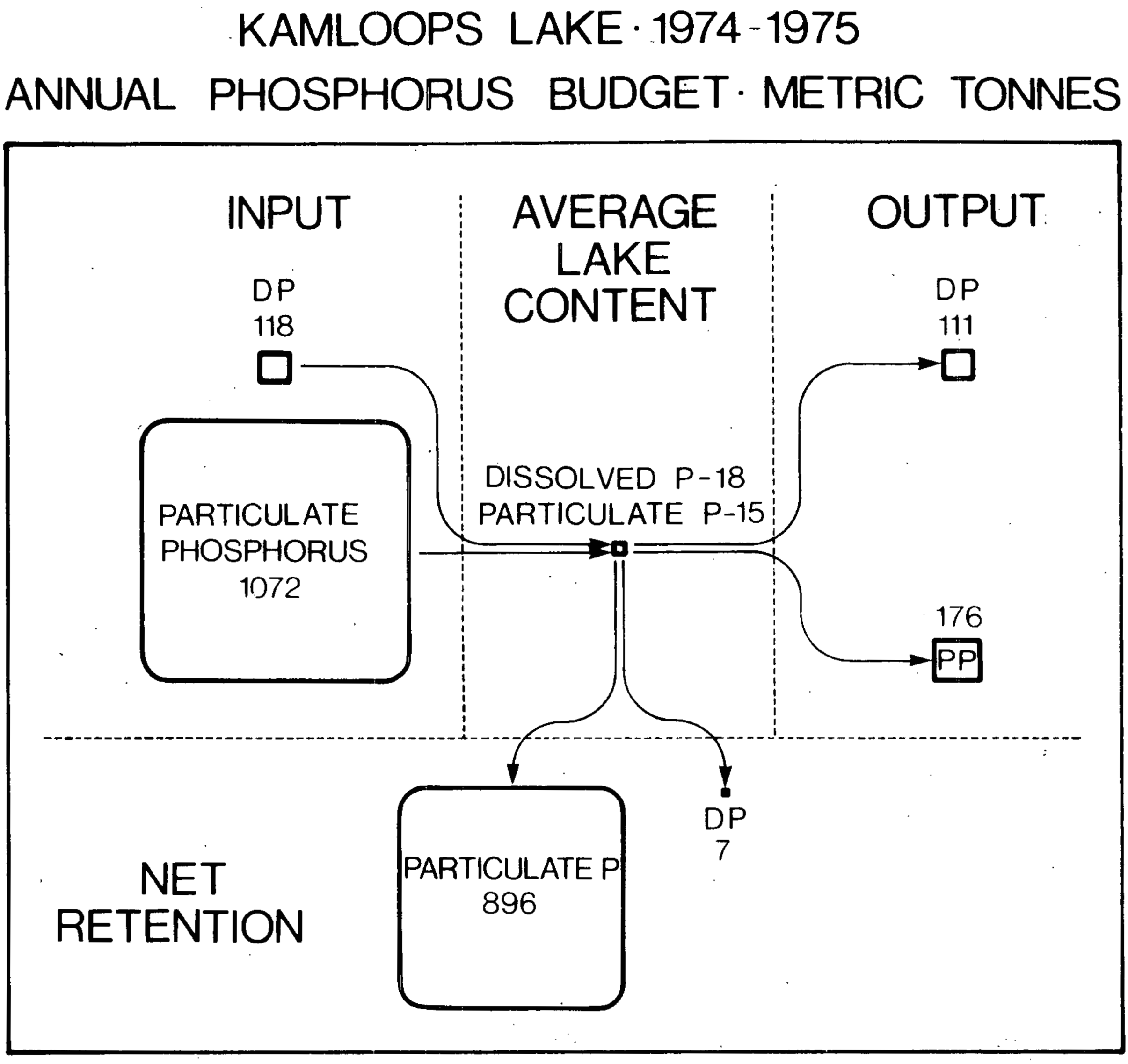


Figure 62. Annual phosphorus budget of Kamloops Lake, 1974-75.

of 76%. This large discrepancy is probably due to the fact that most of the load into the lake is particulate phosphorus (Fig.62), of which up to 80% is mineralogic apatite (Section 2.6). The latter is converted to dissolved phosphorus at a much slower rate (if at all) than is particulate organic phosphorus.

From the annual loading of particulate and dissolved phosphorus and their average lake contents, an estimate of average annual residence times in the water column can be calculated. The average content of particulate and dissolved phosphorus was 14.6 ± 8.1 and 17.5 ± 6.2 metric tonnes, respectively. By dividing the annual content by the annual input, a crude measure of the bulk residence time is obtained. Thus, on an annual basis, the particulate phosphorus had a residence time of 5 days while the dissolved phosphorus had a residence time of 54 days. The short "turnover" time for particulate phosphorus indicates that rapid sedimentation is keeping its content low. The residence time for dissolved phosphorus, however, is surprisingly close to the 60 day annual mean water residence time. Flushing rate is probably, therefore, controlling the fate of dissolved phosphorus in this system.

The specific areal loading of total phosphorus is very high at 22.8 g P m^{-2} yr^{-1}, but the dissolved phosphorus loading is only 2.3 g P m^{-2} yr^{-1}. Even though the dissolved phosphorus loading is higher than the specific total phosphorus load in all the Okanagan lakes except Vaseux (Stockner and Northcote 1974), and is also twice the specific load of total phosphorus to eutrophic Lake Erie (Vollenweider *et al* 1974), Kamloops Lake exhibits the characteristics of an oligotrophic lake. The obvious importance of the flushing rate in holding down the algal production in the lake is further discussed in Section 5.

Although the annual nutrient budgets are important in relating Kamloops Lake to other waters, the details of the budget in the winter months is of more crucial importance because is it during this period that the nuisance growth of attached algae are observed in the Thompson River immediately below Savona. From December through March, the river flows are at their lowest and are almost equal in the input and output rivers, thus maintaining a constant lake level. During these same months, the concentration of dissolved phosphorus in the river near Overlander Bridge (Kamloops) was increased, on average, from 4.3 μg l^{-1} to 8.4 μg l^{-1} (IWD Report 1976) [14 μg l^{-1} CCIW-EPS estimate] by the wastewater phosphorus loadings of the Weyerhaeuser pulp mill and the Kamloops City sewage lagoons. The lake concentrations responded more slowly but had doubled in concentration by mid-March, 1975. Outflow concentrations at Savona increased from an average of 3.7 $\mu g\ l^{-1}$ (IWD Report 1976) [2.4 $\mu g\ l^{-1}$ CCIW-EPS] during the September through December period to an average of 5.7 $\mu g\ l^{-1}$ (IWD Report 1976) [7.0 $\mu g\ l^{-1}$ CCIW-EPS] during the months of January through March. A mathematical expression was developed which successfully approximated these outflow concentrations of Kamloops Lake during the constant river flows of winter (Appendix V). This formula was applied to simulated dissolved phosphorus concentrations in the lake at autumn overturn as well as to simulated inflow concentrations that could reasonably be expected in the absence of point source phosphorus loads. Since the fall overturn concentration is approximately 4 $\mu g\ l^{-1}$ under present conditions, it was assumed that without the point sources, concentrations of 2-3 $\mu g\ l^{-1}$ would be probable in the lake and that possible inflow concentrations from January 1 to March 31 would be from 4 to 5 $\mu g\ l^{-1}$. Under these conditions, the concentration in the outflow after three months was predicted to range from 2.5 to 3.5 $\mu g\ l^{-1}$.

Of the total available phosphorus (i.e. that utilizable for biological growth) exported from the lake in winter, an estimated 40-90% is attributable to pollution sources, as the following calculations show. In the December to March period, the average dissolved phosphorus load of the Upper Thompson River increased between the Overlander Bridge and Tranquille by 46 kg day^{-1} (IWD Report 1976). Taking into account the relative phosphorus contributions of the pulp mill and sewage lagoons and the fact that 10-90% of the mill effluent and 20% of the sewage effluent is particulate in form (B.C. Pollution Control Branch unpublished data), it can be calculated that the average total phosphorus load (dissolved plus particulate) entering the lake from point sources in winter is approximately 50-80 kg day^{-1}. A very large percentage of these point source inputs is biologically available (Lewin 1973). Approximately 135 kg of total phosphorus exits the lake per day during the months of January, February and March (IWD Report 1975). Therefore, the pollution phosphorus, if it transits the lake unutilized, constitutes 40-60% of the total exported phosphorus (Fig.63). However, only a portion of this total export load is biologically available since up to 80% of the natural phosphorus (total minus point source phosphorus) in the lake probably consists of inert apatite in suspension (Section 2.6). If the daily rate of total phosphorus export is cor-

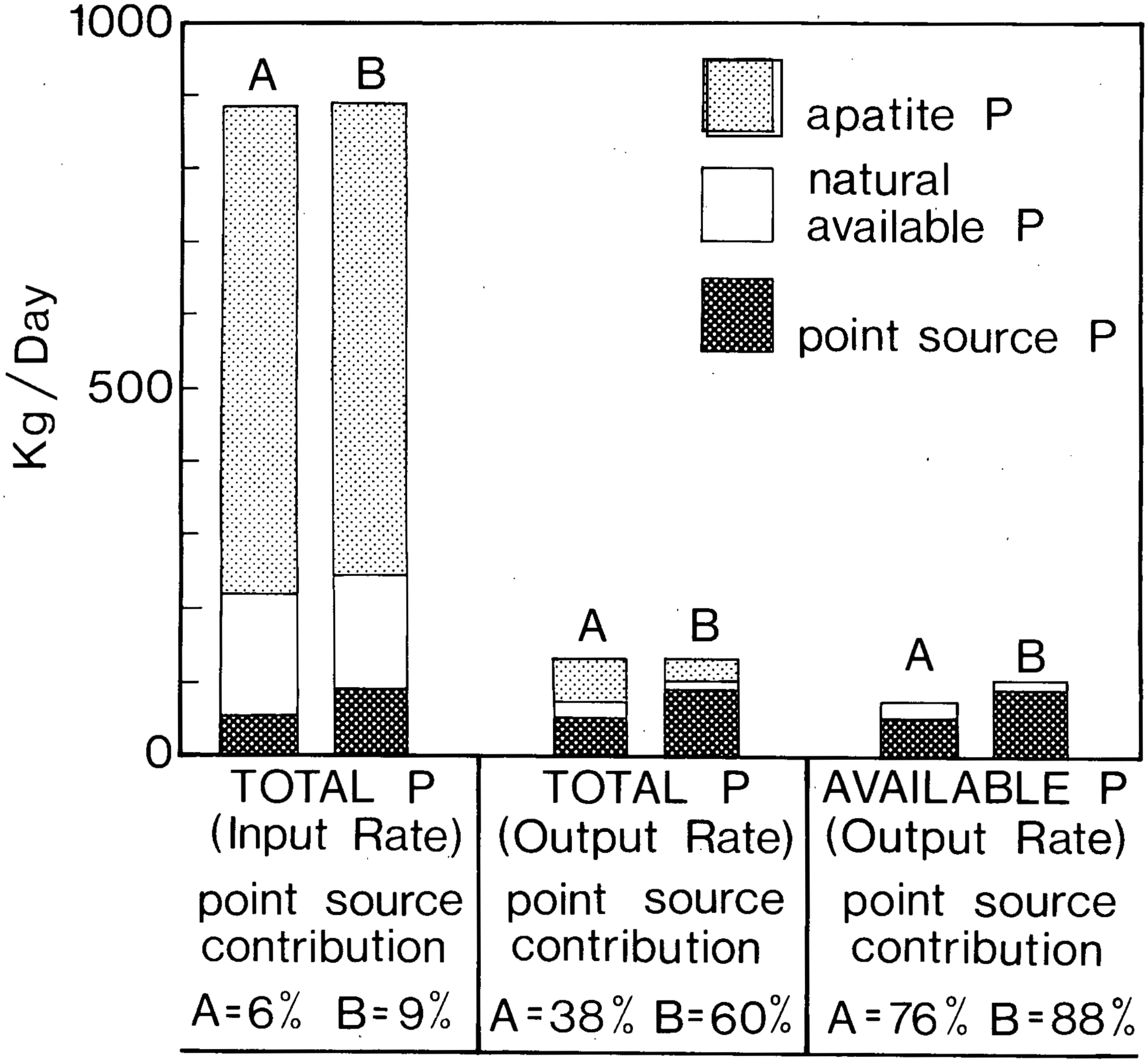


Figure 63. Comparison of average natural and point source phosphorus inputs from January 1, 1975 to March 31, 1975 for Kamloops Lake. A - a minimum calculation based on a 10% particulate phosphorus content in pulp mill effluent. B - a maximum calculation based on 90% particulate phosphorus content in pulp mill effluent.

rected for apatite phosphorus, an export value for total available phosphorus of 68-93 kg day^{-1} is obtained. Of this, 75-90% would then be derived from point sources. Hence, point sources contribute a minimum of 40% (if 100% of the natural phosphorus is biologically available) and a maximum of 90% (if only 20% of the natural phosphorus is biologically available) of the biologically available phosphorus that is exported from Kamloops Lake in winter. Either value is, of course, quite high.

A final inference can be drawn from the foregoing two sections of nutrient data concerning the significance of apatite phosphorus in Kamloops Lake. The ratios of particulate nitrogen to particulate phosphorus range between 1 and 4 in the water column. Such values are unusually low in comparison to most lakes where N:P ratios vary between 7 and 20. This observation lends further support to our earlier conclusion (Section 2.6) that a large proportion of the total phosphorus in the Kamloops Lake water column is suspended apatite. Thus a nitrogen-free, particulate phosphorus component, such as apatite, must be present to reduce the N:P ratios below those seen in other lakes which are presumably dominated by detrital organic phosphorus.

4.3 Dissolved Oxygen

Dissolved oxygen maxima of 11-12 mg l^{-1} occurred at autumnal and spring overturn (Fig.64). The minimal concentrations occurred in the epilimnion and the lower hypolimnion, especially below 120 m. The epilimnetic decreases were a response to higher temperatures and the attendant decreases in oxygen solubility, whereas concentrations in the hypolimnion decreased as a result of respiration in the water and sediments. The lowest value attained was 8.3 mg l^{-1} at the bottom of Station 6 in October. At the prevailing temperature of 4.5°C, this concentration represented 70% saturation. The lowest level of dissolved oxygen detected by Ward (1964) was also in the deepest part of the lake at Sta-

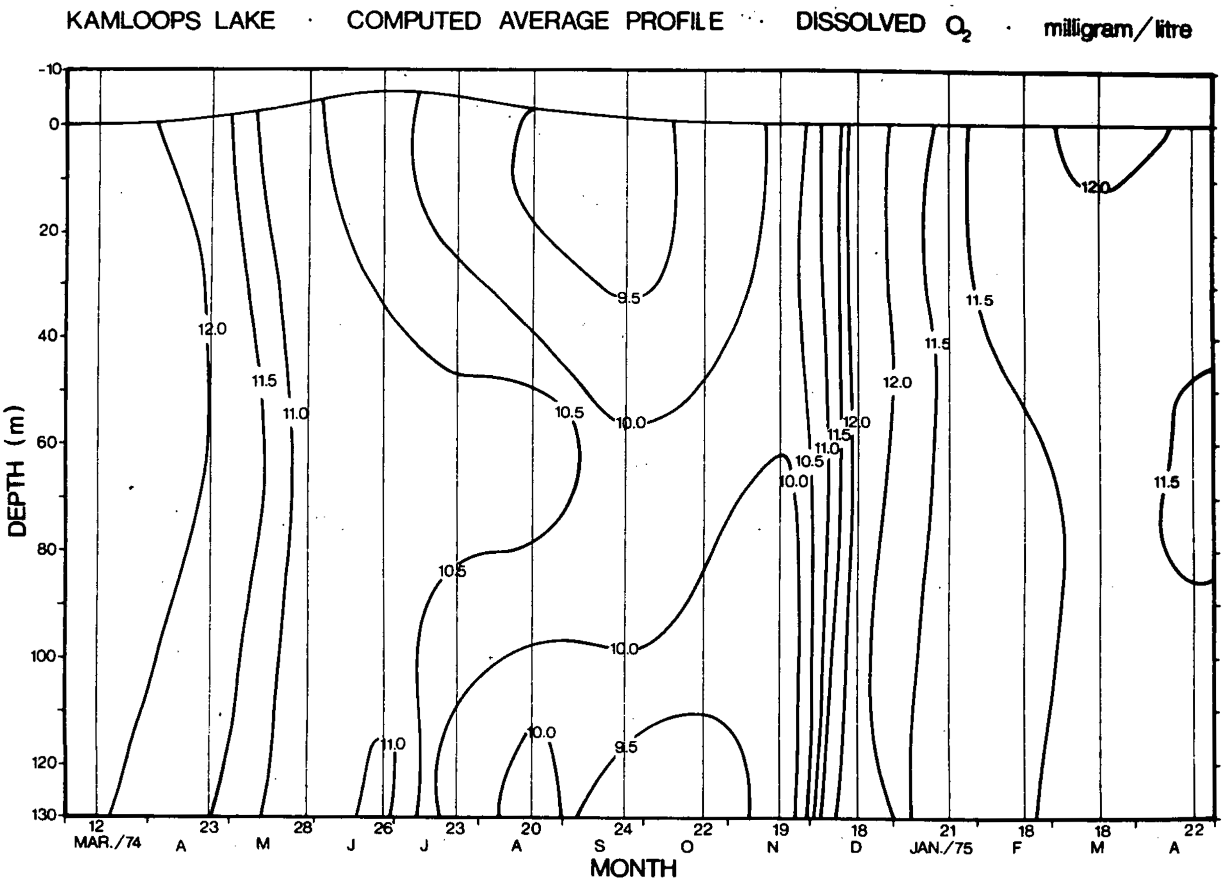


Figure 64. Annual isopleths of dissolved oxygen from the monthly computed average profiles in Kamloops Lake, 1974-75.

tion 6 (Ward's Station C-2) and the concentrations were similar. The Thompson River probably deposits a large quantity of its biodegradable detritus in the immediate area of the delta and hence the colonization of the detritus by bacteria and their resultant respiration in the hypolimnion could reduce the oxygen tension. Since our lowest observed concentration was the same as eleven years ago, it seems probable that the amount of biodegradable particulate organic matter has not increased dramatically during this time. Attempts were not made to ascertain whether the particulate matter is naturally produced or is the result of some man-related land use that was in existence before the 1964 study.

The areal oxygen depletion rate of the hypolimnion has often been related to a lake's trophic status. Eutrophic lakes generally have areal depletion rates greater than 1.5 mg O_2 cm^{-2} $month^{-1}$ (Hutchinson 1957) which are often sufficient to completely deplete oxygen in the hypolimnion. The areal depletion rate of the hypolimnion in Kamloops Lake was calculated to be 3.3 mg O_2 cm^{-2} $month^{-1}$. This figure was obtained by subtracting the dissolved oxygen content per unit area below 44 m on May 28, 1974 from that below 63 m on October 22, 1974 and dividing the result by the time interval (4.86 months). Although the Kamloops Lake value would appear to be very high, there are two major reasons why it is misleading to relate the areal oxygen deficit to trophic status in all lakes (Hutchinson 1957). First, lakes with depths greater than 50 m exhibit high sediment surface areas relative to the surface area of the top of the hypolimnion, especially in narrow, steep-sided lakes like Kamloops. Since the major site of hypolimnetic respiration is the sediment-water interface, the division of oxygen deficit values by the area of the hypolimnion "lid" results in an apparent areal depletion rate that is higher than would be obtained if sediment surface area were used. Second, the rate of incorporation of allochthonous organic matter from the drainage basin into the hypolimnion is unrelated to the production of autochthonous organic matter in the epilimnion. Hence, mineralization of allochthonous materials increases the areal depletion rate. The concentrations of particulate carbon in Kamloops Lake were highest in the freshet and in winter when the production of particulate carbon by algae and bacteria is at a minimum, suggesting that the carbon was mostly allochthonous (Fig.65). Even with the very high depletion rate, the oxygen content of this deep hypolimnion is large enough to be only slightly affected.

In contrast to areal depletion rates, the comparison of volumetric depletion rates in lakes of similar depth may be more suitable. The volumetric depletion rate in the Kamloops Lake hypolimnion was calculated by dividing the difference between the average dissolved oxygen concentrations in the hypolimnion

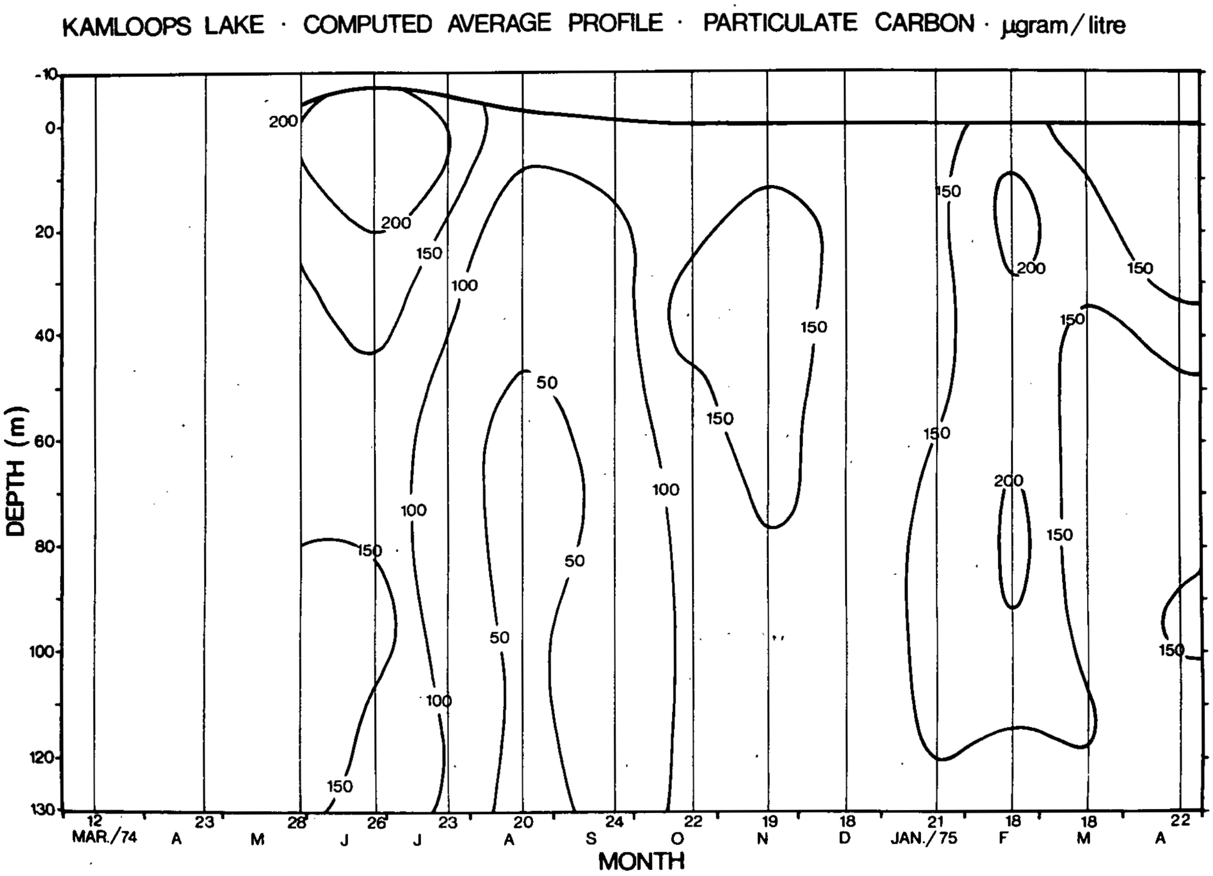


Figure 65. Annual isopleths of particulate carbon from the monthly computed average profiles in Kamloops Lake, 1974-75.

on May 28, 1974 and October 22, 1974 by the time interval (146 days). The average concentrations were calculated in turn by adding the dissolved oxygen contents of 20 m intervals in the hypolimnion and dividing the sum by the total volume of the intervals. The upper boundary of the hypolimnion occurred at 44 m in May and 63 m in October. The mean concentration change was only 0.9 mg l^{-1} so that the net volumetric depletion rate was 0.006 mg l^{-1} day^{-1}. This rate is lower than in other oligotrophic lakes of similar morphometry (eg. Kalamalka Lake, 0.009 mg l^{-1} day^{-1}; Okanagan Lake, 0.015 mg l^{-1} day^{-1}; Stockner and Northcote 1974). It should be noted, however, that turbulence caused by the movement of the river plume over the "surface" of the hypolimnion may mix oxygenated water downward into the hypolimnion. If so, our measured (net) depletion rate will considerably underestimate true absolute rates. The oxygen depletion rate in the bottom 5 m at Station 6 was substantially faster at 0.015 mg l^{-1} day^{-1}.

4.4 Specific Conductance

Specific conductance is a measure of the dissolved ion concentration. The amount of dissolved ionic matter in milligrams per litre in a freshwater sample may be estimated by multiplying the specific conductance by an empirical factor, varying from 0.55 to 0.9 depending on the ionic compounds (inorganic salts and organic salts) in solution. A unit decrease in specific conductance then indicates a decrease in the dissolved ion concentration within the limits of 0.55 to 0.9 mg l^{-1} (Golterman and Clymo 1969).

Specific conductances in Kamloops Lake varied between 65 and 116 μmhos cm^{-1} while the input and output rivers exhibited values between 66-160 and 68-112 μmhos cm^{-1}, respectively. The lowest values occurred during the freshet peak and the highest values occurred in late winter in both the lake and rivers. The smaller range of values in the lake demonstrates the lake's ability to moderate the concentration extremes of the input river. This is especially true in the winter when the entire lake volume is mixing to some extent with river water. Using the above conversion factor, the dissolved solids concentrations varied between 36 and 104 mg l^{-1} over the year. In comparison, the dissolved solids concentrations are from 2 to 6 times higher in the Okanagan lakes which have similar drainage basin characteristics but much higher water residence times than Kamloops Lake. The hydrologic regime of Kamloops Lake thus appears to inhibit the concentration increases resulting from evaporation in lakes with long residence times.

The annual distribution of specific conductance was homogeneous with depth during the winter months, but developed observable gradients during the spring and summer (Fig.66). The minimum levels were seen in the epilimnion

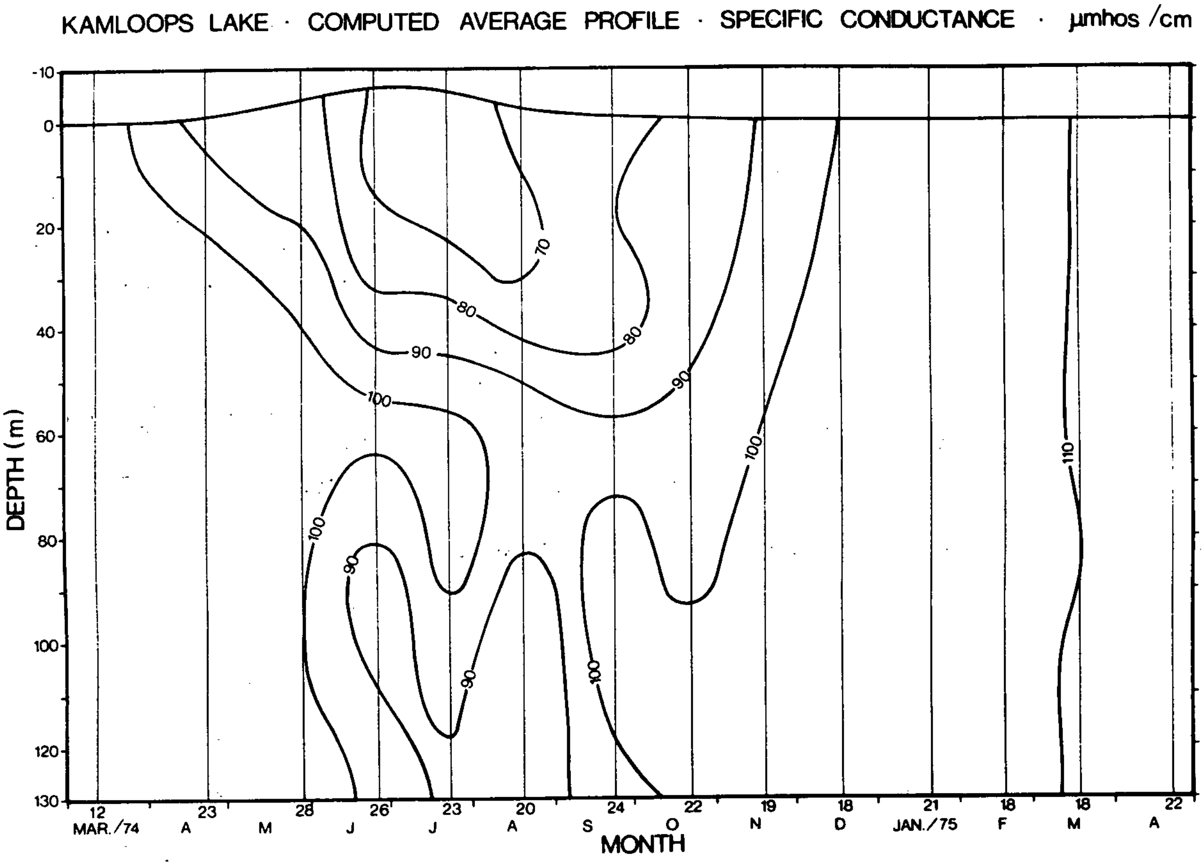


Figure 66. Annual isopleths of specific conductance from the monthly computed average profiles in Kamloops Lake, 1974-75.

during June, July and August when the conductance decreased from the winter maximum of approximately 100 μmhos cm^{-1} to below 70 μmhos cm^{-1}. During this period, the inflow river reached its minimum concentration of dissolved ions and had a specific conductance of 66 and 67 μmhos cm^{-1} on June 25 and July 23, respectively. The river plume apparently did not mix to any great extent with the hypolimnion waters as it transited the lake since the specific conductance of the outflow river in July was only 2 units higher than the inflow river. During mid-summer, the conductance also decreased in the hypolimnion by about 15 μmhos cm^{-1}. Transect profiles indicate that water of low specific conductance accumulated at the western end of the lake in May and moved slowly along the bottom towards the eastern end reaching Station 6 by August (Fig.67). This bottom flow is not well understood but may have occurred in response to a westward current induced in the upper hypolimnion by the viscous drag of the transiting river plume. In other words, the bottom flow was moving eastward to replace the water transported westward in the upper hypolimnion. Whatever the mechanism, water with properties similar to the freshet water is injected into the hypolimnion. As a result, some of the hypolimnetic concentrations increased (Fe, Mn, NH), most decreased, while dissolved phosphorus was unchanged.

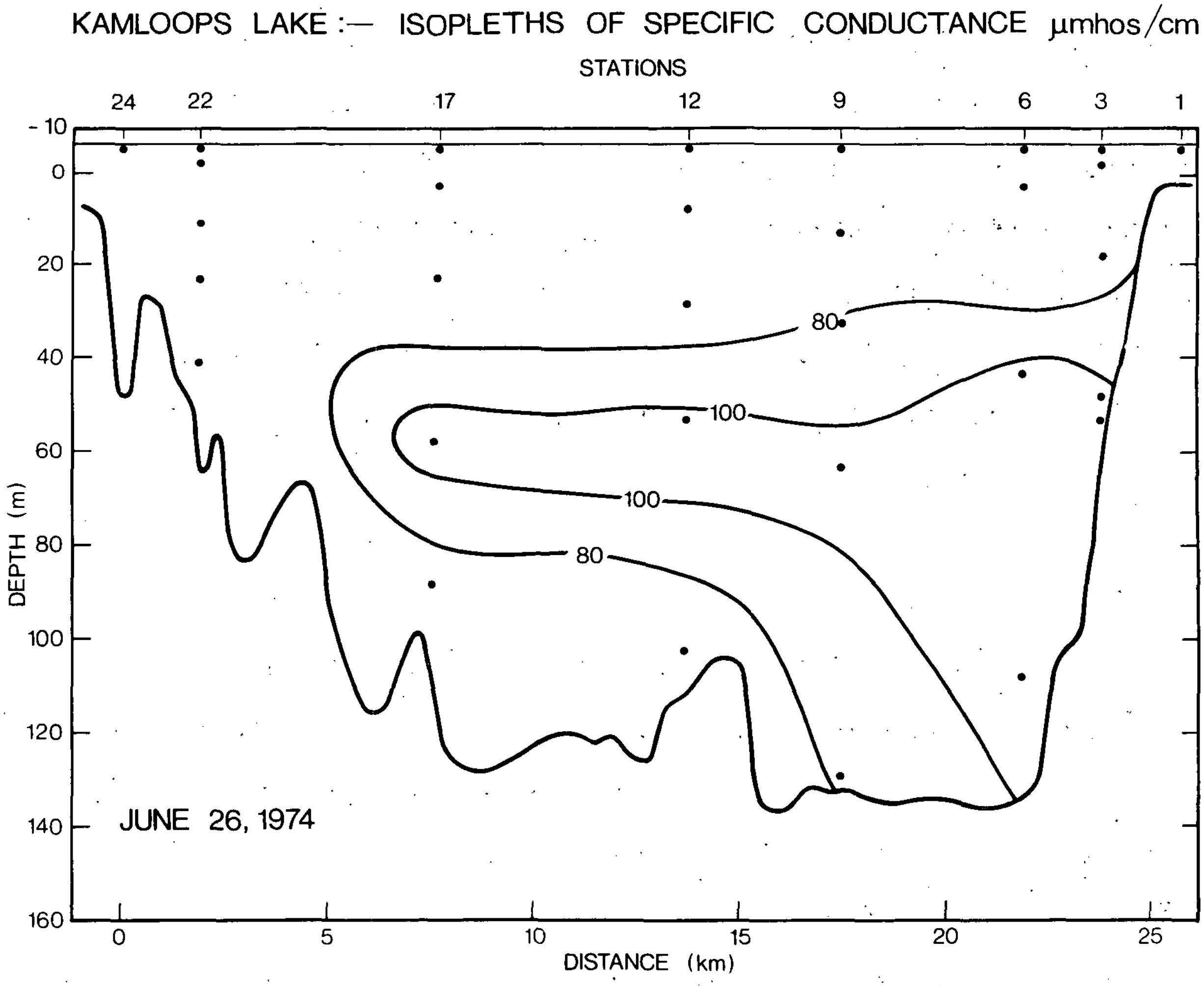


Figure 67. Spatial isopleths of specific conductance in Kamloops Lake on June 26, 1974.

During autumn, vertical mixing became effective to greater depths and the concentrations of dissolved ions in the inflow river increased. These two processes caused the specific conductance to increase and become homogeneous with depth. The specific conductance increased to a greater value in the spring of 1975 than in 1974. This was probably due to the lower flow rates of the winter of 1975 causing less dilution of the input of dissolved ions. Although all the major cation and anion concentrations approximately doubled in the inflowing river between freshet and late winter, the sodium and chloride concentrations increased approximately 8 and 12 times, respectively. The predominant salt of the Weyerhaeuser pulp mill effluent collected in January was sodium chloride, the concentrations of sodium and chloride being 220 and 300 mg l^{-1}, respectively. This point source loading rate could account for approximately half the increase. Another source of chloride ion could have been the road salt, calcium chloride, used by the Department of Highways. However, the calcium concentrations do not show disproportionate increases relative to the other major cations, so this source is probably insignificant. Chloride has increased from less than 0.5 mg l^{-1} in March, 1963 (Ward 1964) to 4 mg l^{-1} in March, 1975.

4.5 Metals

The concentrations of acid extractable iron (Fe), lead (Pb), copper (Cu), zinc (Zn), and chromium (Cr) were analyzed on all the monitors to test for possible metal pollution. Total mercury (Hg) was measured initially but concentrations were too low for accurate measurement (<0.05 μg l^{-1}) and the analyses were discontinued. Acid extractable metals included the dissolved metals, the metals adsorbed on particulate matter and the acid soluble metal minerals. In Kamloops Lake in April, 1974, most extractable metal concentrations were greater than 90% of the totals. The numbers of metals and samples analyzed precluded the more time-consuming total metal analyses.

The nature of the metal distributions in the lake have not been sufficiently analyzed to warrant full discussion. Although the concentrations are below toxic levels, the ranges of values observed are of descriptive interest (Table 4). In general, the concentrations of metals were lower in the outflowing river than the inflowing river, suggesting that the lake is a "sink" for metals.

Table 4. Concentration ranges of extractable metals in Kamloops Lake and the inflowing and outflowing rivers March, 1974 - April, 1975.

Extractable Metal	Concentration Range ($\mu g\ l^{-1}$) Inflow	Outflow	Lake
Iron	70 - 680	20 - 200	2 - 530
Manganese	7 - 50	2 - 40	1 - 50
Copper	<1 - 9	<1 - 7	<1 - 23
Lead	<1 - 15	<1 - 4	<1 - 6
Zinc	1 - 22	1 - 23	<1 - 24
Chromium	0.4 - 6	0.8 - 3	<0.2 - 5.2

4.6 Colour

Kamloops Lake acts to buffer the concentrations of colour entering the lake. The colour values range from 5 to 45 units in the input and from 5 to 15 units in the output river between September and March. In the lake, colour varied between 5 and 10 units during spring and summer and between 10 and 20 units during autumn and winter. Although the reduction in colour between the input and output may only be due to dilution with cleaner lake water which is replenished every summer, the possibility that coloured materials are degraded within the lake cannot be dismissed.

Table 5. Concentration ranges of chemical variables for Kamloops Lake March, 1974 - April, 1975.

Variable	Range
Chemical Variables (mg l^{-1})	
Calcium	9.2 - 16.6
Magnesium	0.8 - 3.8
Sodium	1.0 - 5.0
Potassium	0.5 - 1.1
Bicarbonate	28.2 - 52.4
Sulphate	4.9 - 12.7
Chloride	0.3 - 5.2
Silica	4.0 - 6.9
Total Inorganic Carbon	4.9 - 11.3
Total Organic Carbon	0.7 - 9.5
Particulate Carbon	0.027 - 0.38
Tannins and Lignins	0.16 - 0.68
Nitrate + Nitrite Nitrogen	0.012 - 0.202
Ammonia Nitrogen	<0.001 - 0.032
Dissolved Organic Nitrogen	0.028 - 0.164
Particulate Nitrogen	<0.001 - 0.038
Total Phosphorus	0.003 - 0.039
Dissolved Phosphorus	<0.002 - 0.015
Particulate Phosphorus	<0.001 - 0.027
Dissolved Oxygen	8.33 - 12.70
% Saturation	69 - 118
Specific Conductance (μmhos cm^{-1})	57.9 - 122
pH	7.2 - 8.0
Colour (True Apparent Colour Units)	<5 - 40

4.7 Miscellaneous

A table was prepared which summarizes the concentration ranges observed in the lake for all the analyses of the chemical monitor program (Table 5). Further interpretation of the data will be reported in subsequent publications.

5. MICROBIOLOGICAL LIMNOLOGY

The biological program focused exclusively on the primary autotrophs and heterotrophs of Kamloops Lake. This approach was chosen, within the context of the Federal-Provincial Thompson River Task Force, because photosynthetic production rates and levels of algal biomass are both sensitive and quantitative measures of the extent of lake eutrophication. In addition, both the population size and photosynthetic rates of algae are intimately related to, and thus help to characterize, nutrient fluxes within lakes. Accordingly, annual patterns of primary production, algal and bacterial biomass, and algal species composition were determined for Kamloops Lake. Some information on zooplankton and fish populations is available in other reports of the Thompson River Task Force and in Ward (1964).

5.1 Phytoplankton Biomass

Spatial and temporal changes in phytoplankton biomass were determined indirectly from conventional measurements of chlorophyll *a*. Water samples (1 litre) were collected monthly during the chemical monitor and stored in darkness until membrane-filtered, usually within 24 hours, by the Environmental Protection Service (EPS). Frozen filters were analyzed by the EPS Laboratory, Vancouver, according to the extractive spectrophotometric method of Strickland and Parsons (1972). With the 1.0 cm cuvettes used, this procedure had a detection limit, for 1 litre water samples, of 0.25 mg chlorophyll *a* (assuming no extract concentrating) and a sensitivity of ±30%.

Chlorophyll *a* concentrations increased progressively from a mid-winter low of 0.08 mg m^{-3} (1.0 mg m^{-2}) through spring and summer to a single peak of 3 mg m^{-3} (30 mg m^{-2}) in early October, then declined rapidly again to the winter minimum by early January (Fig.68). This clear annual pattern was apparent

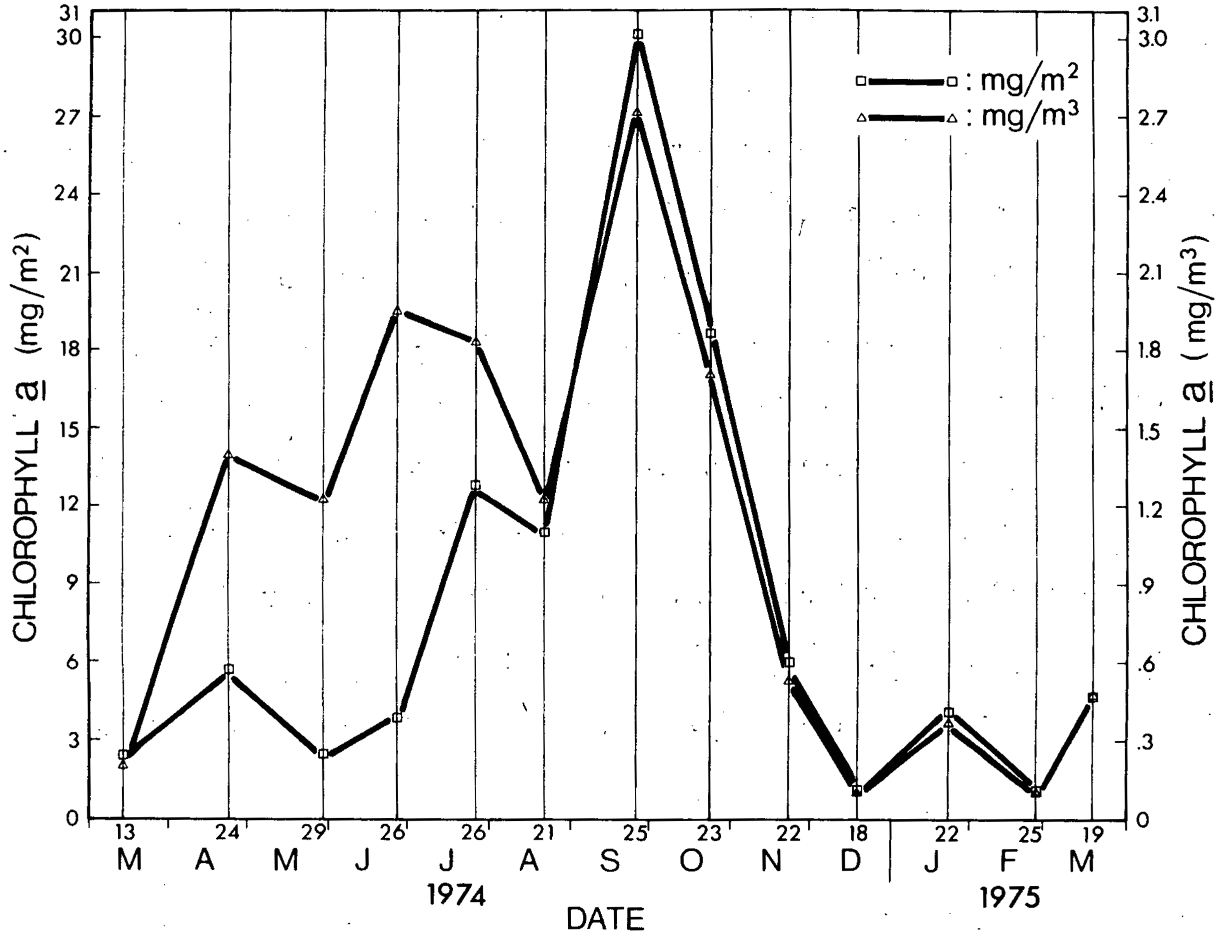


Figure 68. The chlorophyll *a* concentration on an areal (squares) and volumetric (triangles) basis in Kamloops Lake, 1974-75.

despite the fact that the ambient chlorophyll concentrations were usually near the lower detection limit for the EPS procedure.

Horizontal variations in phytoplankton biomass were low. Despite significant differences between regions on some individual sample dates, the annual means of chlorophyll *a* for the western (Fig.51, Stations 3 and 6), central (Stations 9 and 12), and eastern (Stations 17 and 22) zones of the lake were 3.2, 3.2, and 3.5 mg m^{-2}, respectively. The average annual chlorophyll content of the euphotic zone for all stations, determined by integration of Figure 68, was 3.3 mg m^{-2} (1.1 mg m^{-3}), a low value for temperate lakes (Wetzel 1975).

For comparison purposes, several estimates of phytoplankton biomass were obtained by direct microscopic enumeration and measurements of phytoplankton cell volumes. Samples were preserved in Lugol's acid fixative and counted with an inverted microscope. Aliquots (10 ml) were settled overnight in a counting chamber and observed under phase-contrast with a Wild M40 inverted microscope. Large species were counted in a 50 mm^2 area at 200X magnification while, for small forms, two complete transects were counted at 400X magnification. Preliminary diatom identifications were done on separate samples pretreated with nitric acid (Patrick and Reimer 1966). To identify all other groups, samples were concentrated onto (0.45μ Millipore) membrane filters, the filters cleared with Cedarwood oil and permanent slides prepared (McNabb 1960). Cell volumes (mm^3 m^{-3}) were calculated from geometric formulae using direct microscopic measurements from individual Kamloops Lake specimens. Finally, total phytoplankton carbon biomass (mgC m^{-3}) was calculated from an assumed cell density of 1 g ml^{-1} and a carbon content of 2.5% of wet weight for diatoms and 5% for all other groups.

Algal carbon concentrations ranged from a low of 10 mg m^{-3} in midwinter to 89 mg m^{-3} in September in very rough proportion to chlorophyll concentration (Table 6). Thus the chlorophyll content of the phytoplankton ranged

Table 6. Selected chlorophyll *a* and algal carbon concentrations (mg - m^{-3}) in Kamloops Lake, 1974-1975.

Date	Algal Biomass (mgC m^{-3})	Chlorophyll *a* (mg m^{-3})	Chlorophyll Content (%)
18 July	38.4	1.8	4.6
16 September	89.5	3.7	4.2
2 December	47.1	0.27	0.7
8 March	10.2	0.10	1.0

between 1 and 4% of algal carbon. Such chlorophyll:carbon ratios are average for phytoplankton.

Table 7. The relative species composition and dominant genera of Kamloops Lake phytoplankton, 1974-1975.

	Percentage Composition by Volume				
Algal Group	18 Jul	16 Sep	2 Dec	8 Mar	Dominant Genera
Cyanophyta	0.2	0.6	7.5	6.4	*Chroococcus* *Gomphosphaeria* *Microcystis*
Cryptophyta	14.0	54.1	10.4	6.9	*Chroomonas* *Cryptomonas*
Diatoms	54.9	34.2	54.6	63.9	*Tabellaria* *Fragilaria* *Melosira*
Chrysophyta	10.9	8.2	11.9	14.4	*Chromulina* *Mallomonas* *Ochromonas*
Chlorophyta	19.9	2.8	15.6	8.4	*Botryococcus* *Chlorella*

Diatoms dominated the phytoplankton of Kamloops Lake (Table 7), exceeding 50% by volume at all times except during the peak biomass period in early fall (34%). The principal genera of diatoms were *Tabellaria*, *Fragilaria* and *Melosira*. Two cryptophytes, *Chroomonas* and *Cryptomonas*, were dominant in the September sample (54%) and constituted about 10% of the population on the remaining dates. Chlorophyta were next in abundance with a maximum in midsummer (*Botryococcus*) and a minimum during September, while Chrysophytes (principally *Chromulina*, *Mallomonas*, and *Ochromonas*) comprised about 10% of the population at all times. Blue-green algae (*Chroococcus*) were the least abundant of the major groups reaching a maximum of only 6-7% in mid-winter, when total algal biomass levels were very low.

5.2 Phytoplankton Productivity

As a measure of the carbon fixation capability of Kamloops Lake, photosynthetic rates were determined by the C-14 procedure (Vollenweider 1969). Each month at three stations (Fig.51, Stations 6, 9 and 17) and six depths in the euphotic zone, duplicate experimental bottles (125 ml) were incubated with 2 to 10 μCi of $NaH^{14}CO_3$ and suspended from plexiglass holders for 4-5 hours over the mid-day period. Control bottles, fixed at zero time with Lugol's solution, were also prepared. Within 24 hours of retrieval and fixation, 10 ml portions of the samples were acidified and bubbled to remove inorganic bicarbonate. Aliquots (3 ml) were then placed in scintillation vials with 20 ml of Bray's solution and counted by liquid scintillation spectrometry (Schindler *et al* 1972). Lastly, depth profiles of productivity (in mgC m^{-3} hr^{-1}) were integrated and day-rates calculated according to Vollenweider (1965).

Vertical primary production profiles were similar in shape throughout the year, with a surface minimum (usually ascribed to light inhibition) and a mid-depth maximum followed by a progressive decline to zero at zero light intensity (Fig.69). Both the compensation depth (where photosynthesis and respiration are equal and hence net carbon assimilation is zero) and the depth of the primary production maximum varied with season depending on the intensity and depth extinction of sunlight.

Pronounced seasonal changes were apparent in mean primary production rates (Fig.70). Photosynthesis rose progressively from an early March minimum of *ca* 10 mg m^{-2} day^{-1} to a single peak of *ca* 200 mg m^{-2} day^{-1} in August and September, then declined again to the winter minimum by early December. Areal and volumetric production rates showed similar seasonal patterns (Fig.70). The fall peak in primary production was not coincident with the chlorophyll *a*

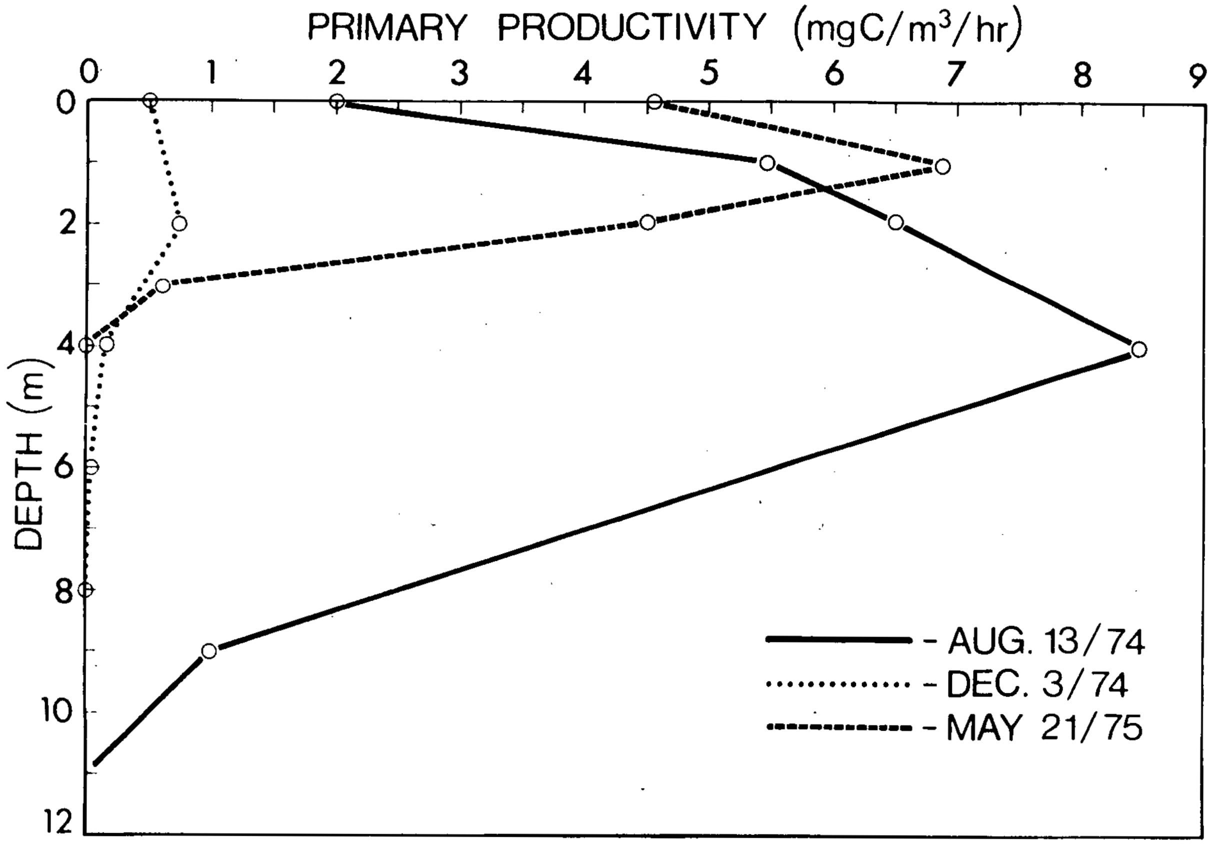


Figure 69. Typical photosynthesis - depth curves in Kamloops Lake, 1974-75.

peak (Fig.68), but preceded it by about a month. In consequence, assimilation numbers (ϕ, mgC mg^{-1} chlorophyll *a* day^{-1}) declined irregularly from 190 to 45 throughout the fall.

From area calculations of Figure 70, the mean annual primary production rate for Kamloops Lake was found to be 32 gC m^{-2} yr^{-1}, or an average daily rate for the year of 88 mgC m^{-2} day^{-1}. Such levels are low and typical of oligotrophic lakes (Wetzel 1975).

The foregoing estimates of productivity are complicated by the strong influence of the Thompson River on circulation patterns in Kamloops Lake. Production measurements based on *in situ* incubations at fixed depths will best approximate the actual rates <u>only</u> if the depth of the well-mixed epilimnion is equal to or slightly less than the depth of the euphotic zone. Under such cir-

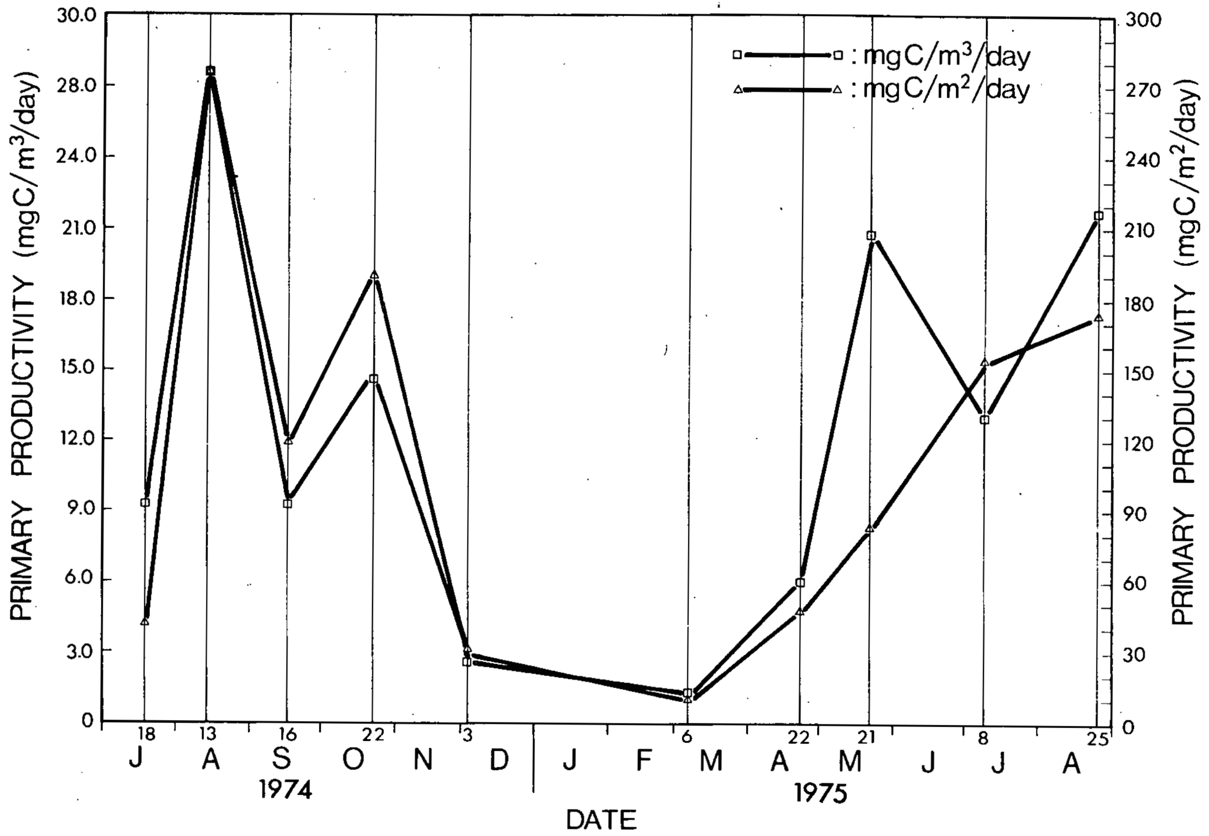


Figure 70. Phytoplankton primary production on an areal (squares) and volumetric (triangles) basis in Kamloops Lake, 1974-75.

cumstances, the natural algal populations are maintained within the euphotic zone by turbulent mixing. Bottle estimates for a given depth will, therefore, approximate the true average rates of carbon fixation of the algae being mixed through that depth at any instant in time. However, during the growing season in Kamloops Lake, the mixing depth greatly exceeds that of the euphotic zone due to the turbulence of the Thompson River flowing through the lake at intermediate depths (Section 3.7). This is best seen by a comparison (Fig.71a) of light compensation depths (=1% of surface light) and the depth of the relative maximum in lake stability (Section 3.4). The latter depth represents the lower boundary of an "epilimnion" that is stirred both because of classical wind-induced mixing near the surface and turbulence resulting from the deeper interflow of the Thompson River water. During summer stratification the epilimnion

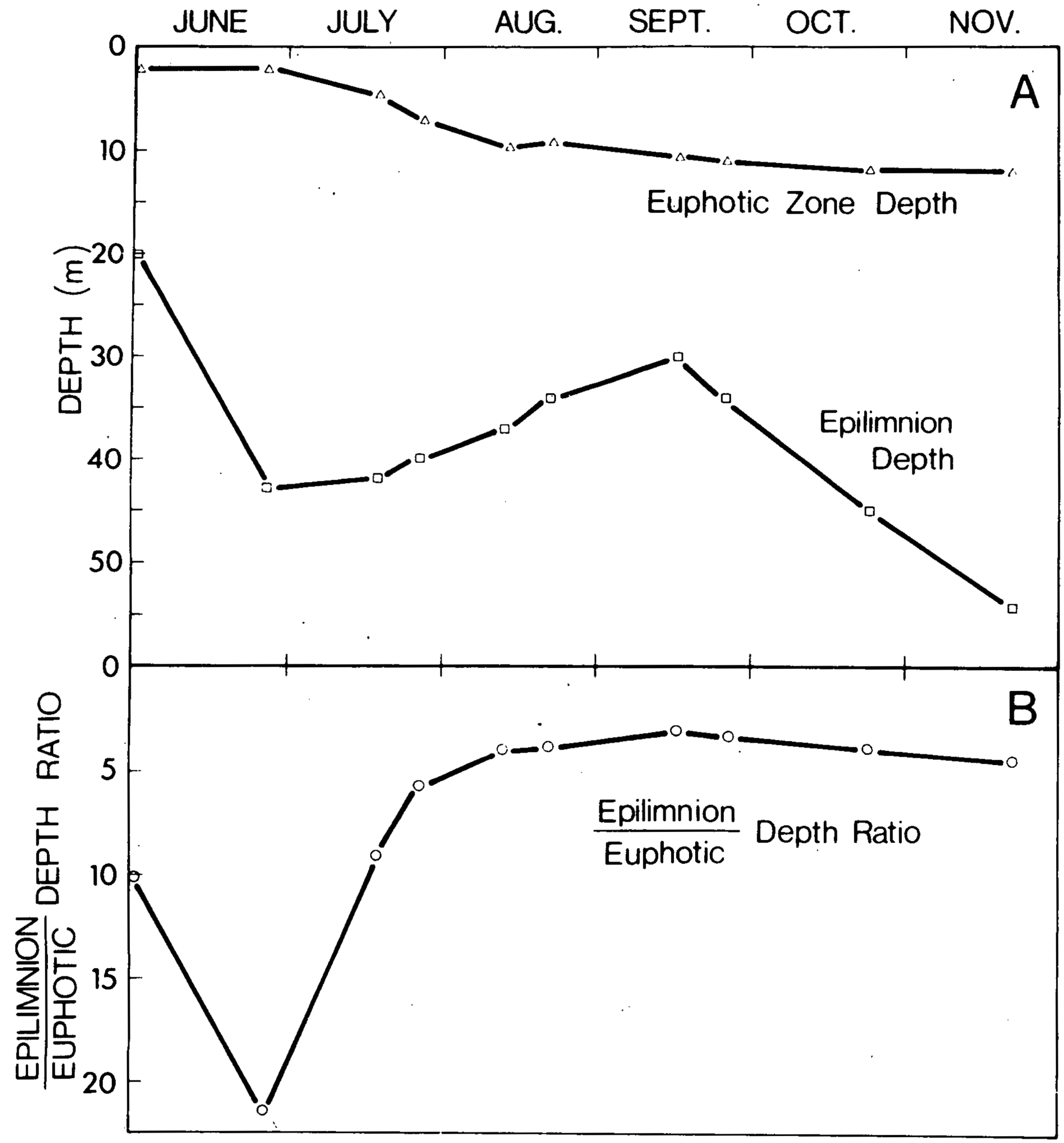


Figure 71. The depth of the euphotic zone (A), depth of the epilimnion (A), and the epilimnion:euphotic zone depth ratio (B) in Kamloops Lake, 1974-75.

depth is 3 to 21 times the light compensation depth (Fig.71b). Hence algal cells are constantly being mixed downward into darkness where photosynthesis is prevented.

The large depth ratios of epilimnion to euphotic zone have two important consequences. First, fixed bottle production measurements overestimate true areal production rates. Second, and of greater significance, algal growth rates will be lower in Kamloops Lake than in comparable systems lacking the pronounced influence of river turbulence. With a perfectly mixed epilimnion in Kamloops Lake, photosynthesis and growth would be reduced in direct proportion to the mixing depth:light compensation depth ratio (on an average, 7). However, weak but complex stability gradients exist near the surface of the epilimnion throughout summer (Section 3.4). Thus, photosynthesis will not have been reduced to this maximum extent, but to some intermediate level. The exact relative reduction cannot be calculated from available data.

5.3 Bacterial Biomass

The approximate magnitude of heterotrophic mineralization processes in Kamloops Lake was determined from estimates of total bacterial numbers. A modification of the direct epi-fluorescence microscopic enumeration procedure using acridine orange (Francisco *et al* 1973) was developed for this study. Procedural details are given in Daley and Hobbie (1975).

Bacterial numbers in the epilimnion were highest in summer and lowest in winter, as with the algae, but the changes were less dramatic (Fig.72). Cell numbers increased from $3.5\text{x}10^5$ cells ml^{-1} in winter to $7.1\text{x}10^5$ cells ml^{-1} in summer. No obvious October peak matching that of the algae was observed. Small coccoid forms ($<1\mu$) dominated the bacterial assemblage throughout the year, but a small percentage of large ($1\text{-}4\mu$) rods were also regularly observed. Filamentous bacteria, perhaps of terrestrial origin, appeared during the first half of the spring freshet.

On a volumetric basis, bacterial biomass was generally low in comparison to the phytoplankton. Assuming an average carbon content of $1.8\text{x}10^{-8}$ g cell^{-1} (Rublee 1975), the bacterial biomass in the epilimnion ranged from

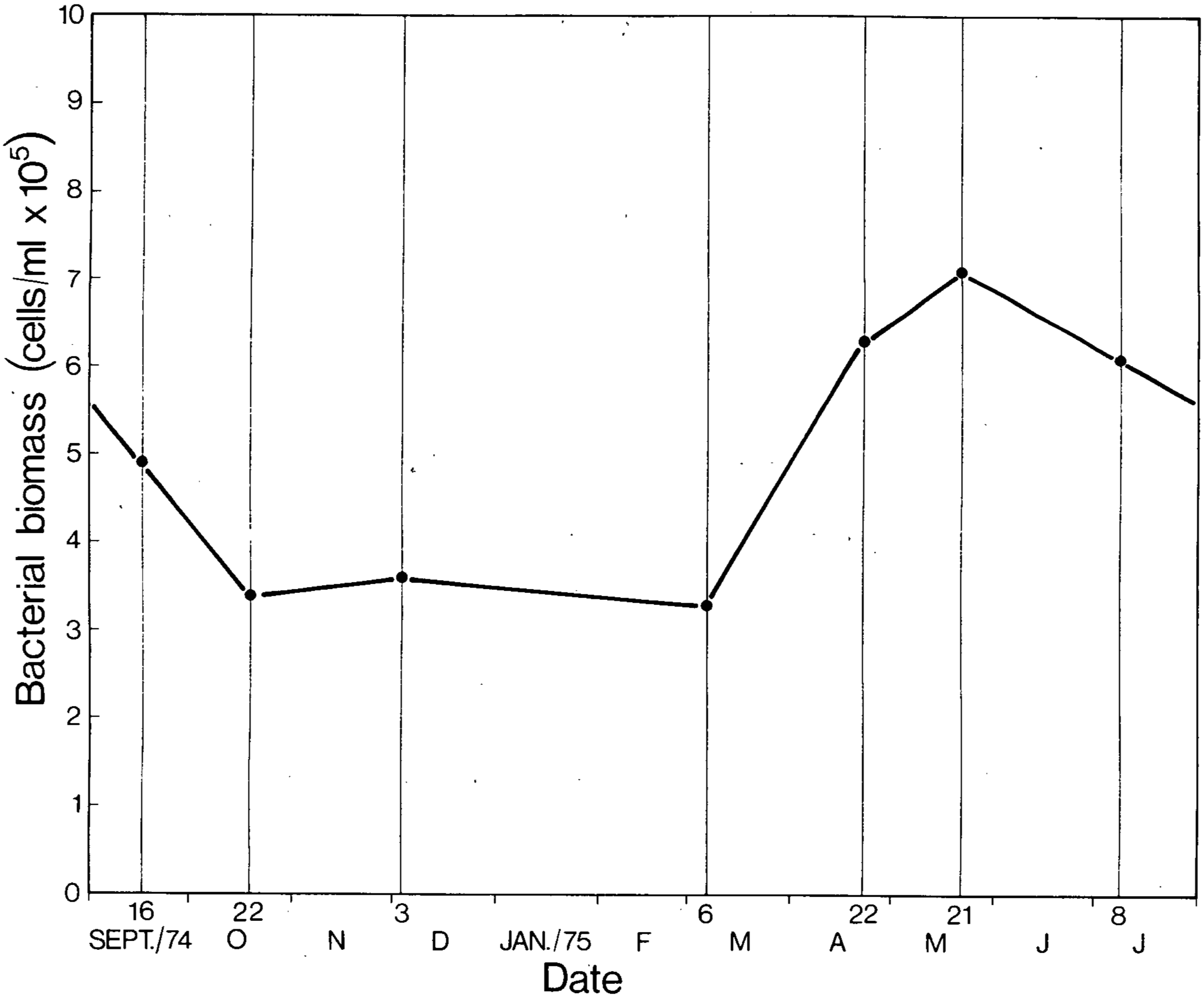


Figure 72. Total numbers of bacteria in the epilimnion of Kamloops Lake in 1974-75 determined by epi-fluorescence counting.

6 to 13 mg m^{-3}, or on average, less than 10% of phytoplankton biomass. Areal biomass estimates are very much higher, of course, because living cells are present throughout the water column. From a complete profile taken on October 22, 1974, it was estimated that 190 mg m^{-2} of bacterial carbon were present, or *ca* 6 times the biomass of the epilimnetic phytoplankton on the same date.

6. DISCUSSIONS AND RECOMMENDATIONS

In this section, the major limnological processes that determine the response of Kamloops Lake to pollution are identified. We demonstrate that the physical characteristics and circulation patterns established by the inflow of the Thompson River serve, in effect, to buffer the lake's response to pollutants. At the same time, however, these physical processes significantly increase the pollution sensitivity of the Thompson River downstream of the lake. A number of recommendations are then given which, if implemented, should enhance the environmental condition of the Kamloops Lake-Lower Thompson River system.

The analysis is conveniently presented in three parts: the current environmental status of Kamloops Lake; its degree of tolerance to future pollution pressures; and its effects on the water quality of the Lower Thompson River. A summary of this discussion together with recommendations derived from it have been incorporated into the general Summary Report of the Thompson River Task Force (1975).

6.1 Current Trophic Status of Kamloops Lake

It is well known that lakes undergo eutrophication as nutrient inputs to the lake basin increase with increased cultural activities (Vollenweider 1971). Phytoplankton populations rise dramatically, nuisance algal species (especially blue-green algae) form large surface blooms in summer, and benthic algae and macrophytes may proliferate. In addition, oxygen is often depleted in deep waters and commercial and sport fisheries decline. The gross effects of eutrophication have been well documented and a number of diagnostic parameters have been developed to characterize the trophic status of individual lakes (Vollenweider 1971).

All of the conventional criteria evaluated in this study clearly demonstrate that Kamloops Lake has undergone little, if any, eutrophication. In conventional terminology, it is said to be oligotrophic as opposed to eutrophic.

Both the composition and activity of the Kamloops Lake phytoplankton are typical of oligotrophic systems (Table 8; Report of EPS 1976). The mean biomass and productivity of the algae (3.3 mg chlorophyll *a* m^{-2} and 88 mg C m^{-2} day^{-1}, respectively) fall well within the oligotrophic range and are very low in comparison to typical eutrophic lakes. In the latter systems, chlorophyll levels of 100 mg m^{-2} and carbon production values of 1500 mg C m^{-2} day^{-1} are not uncommon. The dominance of diatoms together with the virtual absence of blue-green algae are also typical of unproductive systems (Hutchinson 1967 and Table 8). The few blue-gleen algae in the lake are small, non-filamentous winter species which do not form nuisance blooms. Benthic algal populations in near-shore areas, although not studied quantitatively, also appeared to remain at low levels during the study period.

Another indirect line of evidence for oligotrophy comes from an assessment of the phosphorus loading status of Kamloops Lake. Many limnological studies (eg. Eutrophication: Causes, Consequences, Correctives 1969; Dillon and Rigler 1974; Vollenweider and Dillon 1974) as well as the International Eutrophication Programme of the Organization for Economic Co-operation and Development (Vollenweider 1971;1975) have revealed a relationship among annual phosphorus input to lakes, their mean depths and water residence times, and their trophic status. On a log-log plot (Fig.73) of annual total phosphorus load (L_p) versus the ratio of mean depth ($\bar{z}$) to flushing time (τ_ω), empirical lines can be drawn which separate lakes into oligotrophic, mesotrophic and eutrophic classes. The lower line of Figure 73 that separates oligotrophic and medotrophic lakes is termed the "permissible loading", since it represents the maximum load for a given depth and flushing time under which oligotrophic

Table 8. Comparison of phytoplankton primary productivity, biomass, and related characteristics of Kamloops Lake to typical ranges for lakes of different trophic categories[†]

Lake Trophic Type	Mean Primary Productivity ($mgC \cdot m^{-} day^{-}$)	Chlorophyll *a* ($mg\ m^{-3}$)	Dominant Phytoplankton	Total Organic C ($mg\ l^{-1}$)	Total P ($\mu g\ l^{-1}$)	Total N ($\mu g\ l^{-1}$)	Total Inorganic Solids ($mg\ l^{-1}$)
Kamloops Lake	88	1.1	*Bacillariophyceae*	1 - 4	4 - 10	150 - 250	60
Oligotrophic lakes	50 - 300	0.3 - 3.0	*Bacillariophyceae* *Chrysophyceae* *Cryptophyceae*	<1 - 3	<1 - 5	<1 - 250	2 - 100
Mesotrophic lakes	250 - 1000	2 - 15	Variable	<1 - 5	5 - 30	250 - 1000	100 - 500
Eutrohpic lakes	>1000	10 - 500	*Cyanophyceae* *Chlorophyceae* *Bacillariophyceae*	5 - 30	30 - >1000	1000 - >10,000	400 - 60,000

[†] modified from Wetzel (1975) and Likens (1975)

conditions can be maintained. The upper "critical loading" line represents, in turn, the minimum above which eutrophic conditions would prevail. In most cases, lake trophic status predicted from this plot matches the observed status as measured, for example, by transparency, chlorophyll concentration, hypolimnetic oxygen deficit, and occurrence and frequency of algal blooms. This basic relationship strongly implies that most lakes are phosphorus limited.

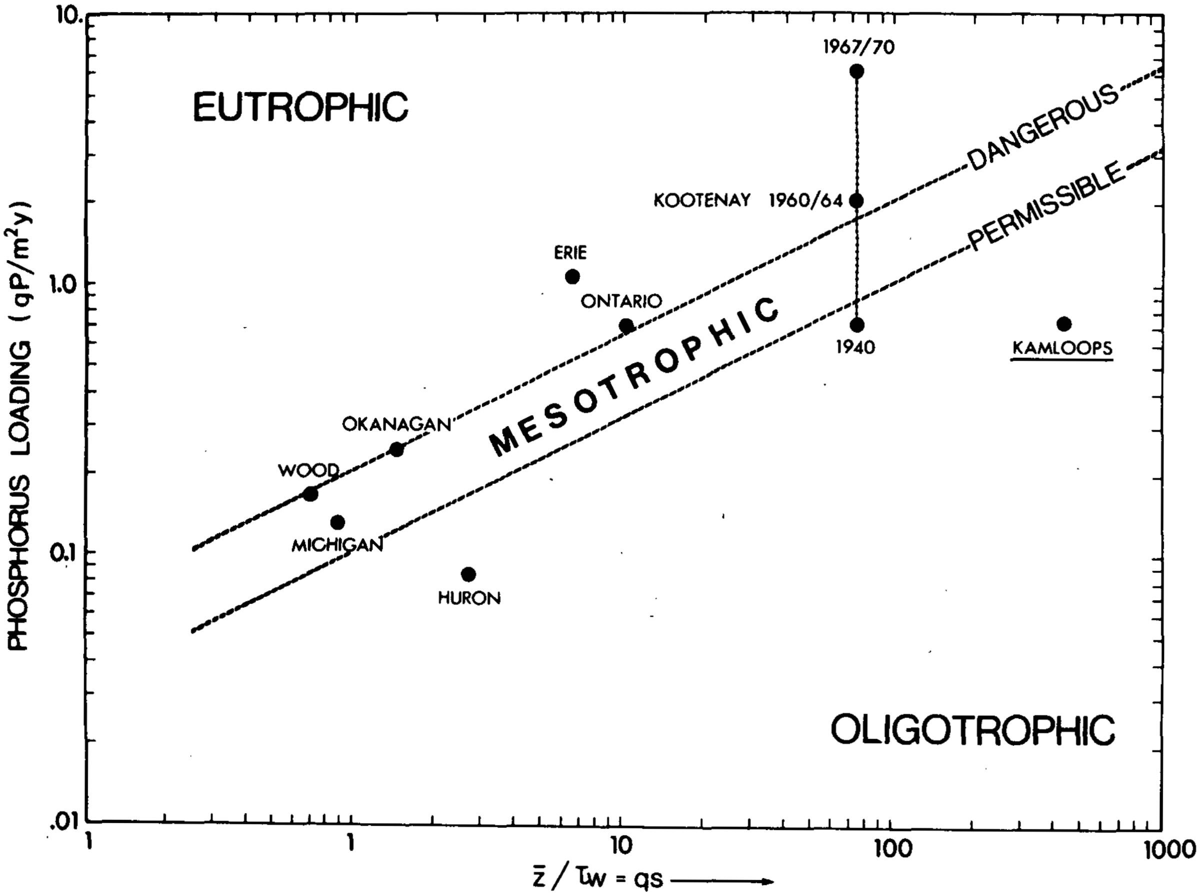


Figure 73. The relationship between annual phosphorus load and the mean depth/flushing time ratio for Kamloops Lake in comparison to various Canadial lakes of differing trophic status (modified from Vollenweider and Dillon 1974).

In attempting to apply this analysis to Kamloops Lake data, difficulties arose with the calculations of both flushing rates and annual phosphorus loadings. Calculations of residence time are complicated by the variable hydrologic regime of the lake. Not only do bulk residence times vary 20-fold over the year, from 18 to 340 days (Section 3.1), but at times the river can pass through the lake with relatively little mixing, thus reducing actual residence times even further. The loading difficulties on the other hand are related to the chemical forms of phosphorus entering and leaving the lake and to their measurement. Unlike most situations, up to 80% of the particulate phosphorus load in Kamloops Lake waters is probably in the form of mineral apatite (Sections 2.6, 4.2). Over its normal exposure time in Kamloops Lake, this mineral is almost certainly biologically unavailable and thus should not be included in the loading estimates. It was also not possible to estimate directly what fraction of the dissolved phosphorus pool was available for use by the microflora. Thus, in Figure 73, we have chosen to use the mean annual bulk residence time (60 days) for τ_ω and the sum of the net loads of particulate, non-apatite phosphorus, and total dissolved phosphorus (0.75 g m^{-2} y^{-1}) for L_p. Both of these values will somewhat overestimate the trophic state of the lake. Nevertheless, on the loading diagram (Fig.73) it can be seen that Kamloops Lake falls well below the "permissible loading" level, despite the large absolute phosphorus load, thus corroborating the experimental evidence cited earlier for its oligotrophic status. It appears that on an annual basis the high loading levels of utilizable phosphorus are counteracted by the great depth and high flushing rates through the lake.

It should be noted parenthetically here that the conclusions in this report concerning apatite phosphorus are new. It has usually been assumed, when considered at all, that apatite phosphorus is quantitatively insignificant in most lakes or, if present, is quickly lost to the sediments. Under such circumstances only analyses of phosphorus totals are needed for the loading calculations used in evaluating lake trophic status. For Kamloops Lake, however, the random horizontal distributions of sediment phosphorus, fluorine and lanthanides, the uniform sediment apatite concentrations, the anomalously high phosphorus retention estimates and the low particulate N:P ratios strongly suggest that a large percentage of the particulate phosphorus in the water column is (biologically inert) apatite. If confirmed to any significant extent in other lakes, these observations may help to explain some of the variability found in the "Vollenweider" loading relationships and in past estimates of lake recovery rates. The presence of significant amounts of water column apatite would also necessitate improvements in the analytical phosphorus procedures currently used in nutrient loading studies. Since a great many North American lakes lie in glaciated regions containing apatite-bearing source materials, it is not inconceivable that apatite is a major contributor to the phosphorus loadings of many systems. Attempts will be made to verify the present tentative conclusions by direct analysis of colloidal apatite in the water column of Kamloops Lake.

Hypolimnetic oxygen depletion rates are also frequently used in assessing lake trophic status. Areal oxygen depletion rates were very high in Kamloops Lake and would seem to suggest, in contradiction to the foregoing discussion, that Kamloops Lake is eutrophic. As pointed out earlier (Section 4.3), however, the great depth (and thus the great hypolimnetic sediment surface area) of Kamloops Lake together with the effects of allochthonous carbon inputs invalidates the use of areal depletion rates for such a purpose. In contrast, volumetric oxygen depletion rates were lower than other oligotrophic lakes in the area and the hypolimnetic oxygen content remained high throughout the summer. These facts suggest that sedimentation rates of easily-degraded carbon were low. In fact, the biomass of mineralizing bacteria in the water column was also low - total numbers of 0.5×10^6 ml^{-1} are 5 to 6 times less than those of eutrophic systems (Fig.72).

6.2 Pollution Sensitivity of Kamloops Lake

a) Nutrient Eutrophication

Kamloops Lake may be expected to respond at a slow rate to future increases in nutrient loadings. Unfortunately, with the present incomplete understanding of eutrophication (Vollenweider 1971), quantitative predictions of the eutrophication rate for Kamloops Lake cannot be given. Thus an ongoing, longer-term physical, chemical and biological monitor of the lake is of paramount management importance.

If Kamloops Lake is to undergo further eutrophication, nutrient concentrations must first increase in the epilimnion during the summer growing period and phytoplankton must then be capable of responding to the nutrient increase. It is concluded, for the following reasons, that neither of these conditions can be expected in the near future in Kamloops Lake (assuming the hydrologic regime in unaltered).

i/ Flushing rates are high. Hence, biologically available nutrients can only accumulate very slowly within the lake basin. With a mean annual bulk residence time of only 60 days, the lake cannot act as a nutrient sink to the same extent as can Okanagan Lake, for example, with a residence time of 60 years (Section 4.2). Thus phytoplankton growth in any one year will be primarily a function of nutrient inputs for that, or at most, the several previous years, and will be controlled more directly by the relative timing of annual physical and chemical cycles.

ii/ Very little of the point-source nutrients that accumulate in the lake during winter are available for phytoplankton growth in summer. As detailed in Sections 4.1 and $.2, point-source nutrient loadings (which enter the lake at a constant rate throughout the year) increase in proportion to natural loadings as river flows decline in winter. While the increase in nitrate is insignificant in comparison to the natural load, winter phosphorus concentrations are as much as doubled in the lake by the point source inputs. If all of this phosphorus were later to be made available to the algae in the summer epilimnion, a considerable enhancement of phytoplankton growth might occur. However, less than 20% of the lake's volume and phosphorus load is destined to enter the epilimnion following summer stratification. Furthermore, during the freshet much of this winter phosphorus is rapidly replaced by river water with a higher phosphorus content. During peak flows, partial residence times in the river interflow may be as low as 24 hours. Thus, summer uptake of wastewater phosphorus accumulated over the previous winter is effectively prevented.

iii/ Point source nutrients in the summer epilimnion are insignificant in comparison to natural loadings, so that very large increases in pollution nutrients would be required to elicit even small increases in phytoplankton. From June to October the epilimnion consists principally of river water. If point source phosphorus levels were high in this water, increased algal growth might result. However, during this period, it is calculated that wastewater phosphorus inputs comprise less than 5% of the total. Even if phytoplankton growth was phosphorus limited and directly proportional to phosphorus concentrations, an approximate 8-fold increase in wastewater phosphorus inputs would be required to double the algal biomass in the lake. In other words, to raise algal biomass 100-fold to levels typical of bloom conditions in eutrophic lakes would require as much as an 800-fold increase in wastewater phosphorus inputs, assuming, of course, no decreases in loadings from the North and South Thompson Rivers.

iv/ It is quite probable that phytoplankton growth rates are limited, or at least their response to nutrients modified, by factors other than nutrients. Two separate mechanisms are involved, both related to the summer movement of Thompson River water through the epilimnion.

The first involves light effects on algal photosynthesis. Areal production rates are strongly influenced by the relative depths of the epilimnetic mixing layer and the euphotic zone (Section 5.2). The deeper the mixed layer relative to the illuminated layer, the less time the algae spend in light, the lower the average light intensity "seen" by the algae, and thus the lower their net rates of photosynthesis and growth. Conversely, the shallower the mixed layer and the higher the light intensity, the greater the likelihood that photosynthesis will be limited by some factor other than light (usually nutrients). In most lakes with low flushing rates, where the epilimnion is formed by surface heating and where light attenuation is a function of water colour and seston, mixing depths are normally equal to, or less than, the depth of the euphotic zone. Limitation by nutrients, usually phosphorus, is thus more frequent. Such a situation does not exist in Kamloops Lake. First, the high suspended load of the Thompson River, especially in May and June, results in light compensation depths well below that expected on the basis of colour alone (<1 m). Second, the interflow of Thompson River water at intermediate depths during summer results in a mixed layer on the average 40 m deep. The net effect of turbidity and river turbulence is to produce ratios of epilimnion to euphotic zone depths that average 7 throughout the summer. Respiratory losses of the phytoplankton are thus high in comparison to photosynthesis and growth rates are considerably reduced.

The second process that slows the rate of accumulation of phytoplankton is their rapid horizontal transport out of the lake. Little river water is exchanged with the hypolimnion during summer because of temperature stratification. Hence flushing rates in the epilimnion are even higher than indicated by the short bulk residence times (Fig.26). Epilimnetic residence times range from 24 hours to 24 days between June and October, with a mean of 10 days. With such very rapid horizontal water movement, newly-produced algae are rapidly transported out of the lake, thereby slowing the accumulation of algal standing crop.

Limitation of algal growth by light could not be tested directly, but several simple observations hint at its probably importance in comparison to nutrient effects. Potentially available phosphorus concentrations in the epilimnion throughout summer were relatively high and matched river inflow concentrations (Section 4.2), suggesting (but not proving) that an ample supply of phosphorus was available for algal growth. Moreover, despite the rapid flushing rate, both primary production and phytoplankton biomass increased during summer while epilimnetic phosphorus concentrations declined. Finally, photosynthetic rates, both on an areal and on a per unit chlorophyll basis, generally increased with increases in both compensation depth and epilimnetic residence times.

There is no reason to believe that benthic algal populations in the lake will increase more rapidly in the future than the phytoplankton. The same proportion of wastewater to natural phosphorus is available to them as to the phytoplankton, and while not subject to the same washout effects as the pelagic algae, they do undergo submergence (causing light limitation) during the spring freshet and dessication as water levels fall during the rest of the year.

Assuming no major hydrologic changes, we conclude that cultural eutrophication of Kamloops Lake will occur very slowly, if at all, due to the moderating effects of intermittent light limitation, high flushing rates, and high summer levels of background nutrients. Further, neither the lake's present condition nor its future pollution potential would along appear to justify nutrient removal from the Kamloops sewage treatment plant or the Weyerhaeuser mill. However, as stressed below, the opposite conclusion is drawn for the Lower Thompson River.

b) Colour and Toxicity of the Weyerhaeuser Effluent

While there is little doubt that the effluent from the Weyerhaeuser pulp mill increases the water colour of Kamloops Lake (Section 4.6), it is our judgement that such discolouration is primarily an aesthetic problem and has little effect on light-dependent biological processes. There are several reasons for this conclusion. Colour increases due to the effluent are greatest in autumn and winter (Section 4.6) when algal production is already low for other reasons. In addition, the highly coloured winter water is flushed rapidly through the lake in spring before it can have any light-reducing effects on the phytoplankton. In summer, the effluent is diluted by high river flows and by cleaner lake waters to levels which are insignificant in comparison to the light-limiting effects of river turbidity and turbulence. Finally, as with the nutrients, the high flushing rates of the lake prevent colour concentrations from accumulating within the lake to levels exceeding those of the input water. In the absence of dramatic increases in effluent loadings, it is thus unlikely that lake discolouration will increase beyond present levels.

Unlike the coloured materials, any toxic substances released into the lake from the Weyerhaeuser effluent cannot be viewed as biologically insignificant. Other studies of the Thompson River Task Force have demonstrated tainting of both resident and migratory fish populations by the pulp mill effluent (Southern Operations Branch Report, Fisheries and Marine Service 1975). Like colour, effluent toxicants are highest in concentration in winter and highly diluted by river flow in summer. Nevertheless, it cannot be assumed *a priori* that dilution has rendered the toxic compounds ineffective towards the lake's biota. The toxicity of kraft mill effluent to phytoplankton varies with the source and concentration of effluent and species composition of affected organisms (eg. Rainville *et al* 1975).

Further general toxicological study of pulp mill effluents in B.C. is urgently required. Direct evidence for toxic effects of Weyerhaeuser effluent on Kamloops Lake algae was not obtained in this study because of the complexity and cost of experimentation at *in situ* concentrations. Without a comprehensive statistical study, it is difficult to differentiate between the direct effects of toxic substances on photosynthesis and the confounding effects of colour, nutrient utilization and heterotrophic bacterial activity in the raw effluent. Given the large size and pollution potential of the British Columbia wood pulp industry, it it important that a major, intensive investigation of these effects be undertaken. During such work, attempts should be made to isolate and identify all compounds inhibitory to algae, bacteria, zooplankton or fish and to establish the degree of toxicity in relation to toxicant concentration and to the size, composition, and temporal distribution of the affected organisms. Without such knowledge the microbiological effects of pulp mill effluent in lakes such as Kamloops cannot be understood. Only when such detailed information is at hand can rational cost-benefit analyses of urgently needed toxicant removal programs be carried out

6.3 The Effects of Kamloops Lake on the Pollution Sensitivity of the Lower Thompson River

A comparison of the present study with others of the Thompson River Task Force indicates that the lake and Lower Thompson River differ considerably in their general environmental condition and in the timing of biological cycles. For example, benthic algal growth was generally much higher downstream of the lake than in either the North or South Thompson Rivers (Souther Operations Branch Report, Fisheries and Marine Service 1975) and, unlike the phytoplankton (Section 5.1), reached a peak in early spring just prior to the freshet. The diversity of macroinvertebrates was lower, and the relative abundance of pollution-tolerant aquatic insects higher below the lake than above it (Southern Operations Branch Report, Fisheries and Marine Service 1975; International Pacific Salmon Fisheries Commission Report 1975). Declines in the sport fishery in the Lower Thompson River have also been reported (Fish and Wildlife Branch Report 1975). The Lower Thompson River thus appears to be relatively more polluted at present than Kamloops Lake.

While no direct work on the Lower Thompson River was done in the present limnological study, these results indicate that physical, chemical and biological processes within Kamloops Lake itself are indirectly responsible for the nuisance algal growths and enhanced pollution sensitivity of the Lower Thompson River. The principal reason for this effect is related to the very short residence times of Kamloops Lake. Incoming toxic substances and biologically available nutrients are generally transferred to the lower river before they can be utilized or degraded within the lake. Thus the very same physical processes that serve in a positive way to buffer the lake against rapid eutrophication (Section 6.2a) also increase the potential pollution rate of the outflow river. Since the lake is prevented from acting as a soluble nutrient sink, the pollution problems are, in effect, "transported" downstream.

The susceptibility of the Lower Thompson River to environmental degradation varies throughout the year, with the greatest response to pollution inputs occurring in late winter and early spring. For several reasons, algal growth is severely mimited between April and October. Both natural and point source nutrient concentrations are relatively low. Turbidity is high and hence light intensities are reduced. River flows are also high and the resultant scouring of the river bed removes accumulated algae. Finally, dessication of the algae as a result of declining river levels is severe. In late winter, on the other hand, the flushing rates in the North and South Thompson Rivers are at the seasonal low and point source nutrients are less diluted as they enter Kamloops Lake. Winter river water is less dense than the ambient lake water and thus tends to accumulate in the upper layers of the lake (Section 3.9). As a result the outflow into the Lower Thompson River during early spring is drawn from lake surface water exhibiting "winter" properties. At the same time, water transparency is high and the river level low and constant. In view of these relatively favourable circumstances, the occurrence of the benthic algal biomass maximum in early spring, when light intensity is increasing, is not unexpected.

It is concluded that nuisance growths of benthic algae in the Lower Thompson River have resulted from increases in phosphorus loadings from the Kamloops Sewage Lagoons and the Weyerhaeuser pulp mill. This conclusion has been reached by the following indirect process of elimination. Direct proof of nutrient limitation in benthic algae is currently very difficult, if not impossible, to obtain.

Biologically active (toxic or stimulatory) substances from the pulp mill outfall together with the nutrients from both the pulp mill and sewage lagoon effluents are the two principal classes of wastewater pollutants currently discharged into the Thompson River system. The former group is almost certainly not the source of the benthic algal problem: there is little evidence for direct stimulation of algal growth by organic compounds in pulp mill effluent (as distinct from stimulation by associated inorganic nutrients) while potential toxic effects have been well documented (eg. Rainville *et al* 1975). On the other hand, there is broad limnological agreement that nitrogen and phosphorus are the two nutrients that almost always limit algal growth (see, for example, Eutrophication: Causes, Consequences, Correctives 1969; Schindler 1971; Schindler *et al* 1971), and there is nothing in our limnological data to suggest that this is not the case for the Thompson River system.

It is unlikely that increases in nitrate alone are responsible for the nuisance growths of benthic algae. Total nitrogen:phosphorus ratios are high at all times in comparison to the physiological requirements of the algae, thus suggesting limitation by phosphorus rather than nitrogen. Nitrate concentrations in the Lower Thompson River are increased by point source loadings at Kamloops and by internation generation of nitrate in both the sediments and water column in fall and winter, with some of the latter nitrate possibly derived from particulate wastewater nitrogen. However, these inputs are insignificant in comparison to the high natural loadings of nitrate and ammonia. The Kamloops wastewater inputs, for example, only increase the nitrate concentrations in the inflowing water by 8%. Furthermore, even assuming that all the nitrate generated within the lake originated from point source inputs of non-nitrate nitrogen such generation processes only increased lake water nitrate levels by 17%. In contrast, however, biologically available phosphorus concentrations in the Upper Thompson River during the critical winter period are as much as doubled as a result of point source discharges at Kamloops. These higher incoming concentrations of phosphorus are seen within a month in the Lower Thompson River as a result of river water transport across the lake surface (Section 4.2).

Control of phosphate rather than nitrate therefore appears to be the only available option to reduce benthic algal growth rates to pre-cultural levels. We thus recommend that discharges of biologically utilizable phosphorus from both the sewage lagoons of the City of Kamloops and the Weyerhaeuser Pulp Mill be reduced to as low a level as is technologically possible. Because of the extreme variation in annual river flows, it may be possible to vary the absolute point source loadings through the year as some function of the river flow rates and temperature, if such a management procedure was economically beneficial. This unusual option, together with suggestions for establishing phosphorus release rates in relation to the future growth of the City of Kamloops is discussed in Appendix VI.

The circumstantial nature of the foregoing arguments has a number of management implications and requires a final re-emphasis. Ideally, three facts should have been directly established by the Thompson River Task Force: that benthic algal populations in the Lower Thompson River have increased significantly from pre-cultural levels; that concentrations of phosphorus and not some other nutrient have increased significantly because of cultural activities in the watershed; and that the benthic algae in the lower river are, in fact, limited by phosphorus. It is apparent that the Task Force has directly established the second point, provided convincing but circumstantial evidence for the third point, but only subjective data for the first. These difficulties are common to all environmental studies in areas for which pre-cultural data are not available. In view of these difficulties, two important recommendations follow:

1. Multidisciplinary environmental surveys of British Columbia lakes and rivers are important and should be encouraged. Data from such surveys are necessary if meaningful assessments of the tolerance of these resources to environmental pressures are to be made.

2. A study should be undertaken of the physiology and nutrient energetics of benthic algal communities characteristic of British Columbia rivers. Such a program should attempt to develop short-term criteria of nutrient sufficiency and thereby, indirectly, the trophic status of rivers.

APPENDIX I

Turbidity Relationships in Kamloops Lake

Turbidity is a measure of the degree of decreased transparency due to the presence of suspended particulate material in the water column. The instrumentation system used by the IWD - CCIW Branch to monitor turbidity in Kamloops Lake measures the ratio between transmitted light and scattered light at a center angle of 20°. Ratio measurements of this type are more appropriate than direct transmitted light measurements for suspended solids studies because they suppress the effects of dissolved substances. The CCIW turbidimeter yields large signals for particles in the range of 0.7 μ to 7 μ. (Particles in this size fraction comprise about 32% of the sediment deposited in Kamloops Lake.) The instrument can be used to obtain approximate particle concentrations, aid in water sample positioning, and assist in water mass identification.

An attempt to calibrate turbidity measurements (in JTU) in terms of total particle concentration (in mg l^{-1}) was made in May, 1975, during the spring freshet. Concentrations of particulate matter were determined by samples retrieved with Van Dorn bottles while turbidity was measured at corresponding sample depths. Two one-litre samples were drawn from the bottles. Particles were filtered onto pre-weighed Whatman glass fibre filters (GF/C) which retain particles larger than 1 μ, and then dried at 110°C for 24 hours before reweighing. Particle concentrations were then compared to their corresponding turbidity readings.

The turbidity-suspended load relationship (Fig.74) can be approximated by two linear segments, or:

$$SL = 1.90Tu - 0.5, \quad Tu < 5 \text{ JTU}$$

and

$$SL = 0.64Tu + 5.4, \quad Tu > 5 \text{ JTU}$$

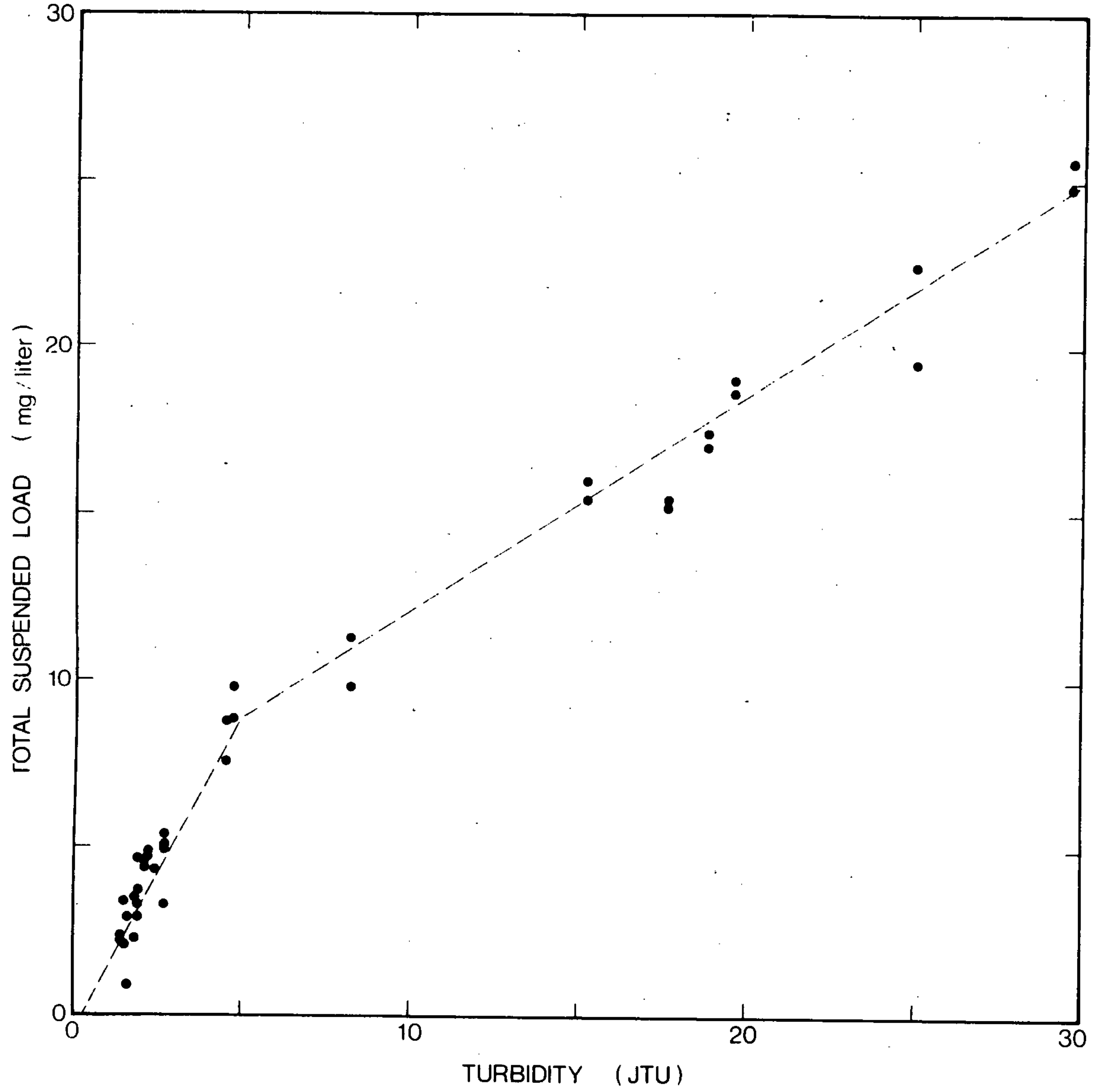


Figure 74. Plot of water turbidity versus suspended load.

where SL is suspended load and Tu is turbidity. The correlation coefficients for the above least-square fits are 0.91 and 0.98, respectively.

Assuming a mean density of 2.5 g cm^{-3} for suspended material, an excess density can be calculated from

$$\Delta\rho = \Delta SL(1.5\times10^{-6}) \text{ g cm}^{-3}$$

For example, water at T = 8°C and Tu = 5 mg l^{-1}, has a density excess of 7.5 $\times10^{-6}$ g cm^{-3}, or in fact is equal in density to water at T = 7.87°C and Tu = 0.

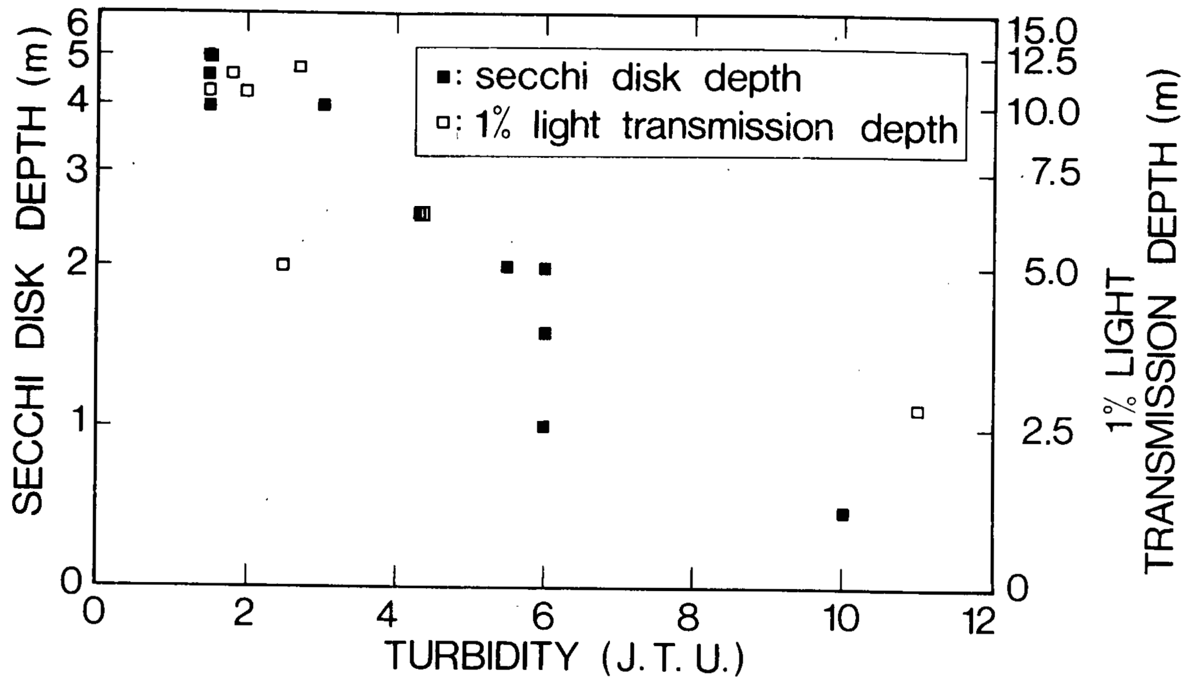


Figure 75. Plot of water turbidity versus the secchi disc depth and the 1% light transmittance depth.

The relationship between turbidity and light transmittance is of obvious biological importance. A comparison among surface turbidity, secchi disc depth, and the 1% light transmittance depth is shown in Figure 75. Although scatter is present, a definite logarithmic relationship is revealed between surface turbidity and light transmittance. The high values of turbidity observed in the early summer freshet correspond to 1% light level depths of 1.5 to 2.5 m. The lowest values of turbidity, characteristic of winter conditions, allow a 1% light level depth approaching 15 m.

APPENDIX II

Some Relationships Between Temperature and Density Affecting Spring and Autumnal Overturn in Kamloops Lake

Buoyancy forces in a fluid arise as a result of variations in density. When a light fluid overlies a heavier one, the stratification is said to be stable since buoyancy forces act against vertical displacements. On the other hand, when density decreases with depth, the stratification is unstable, and buoyancy becomes the source of energy for convective flow. In this section some of the properties of the equation of state of pure water that influence convection in lakes are reviewed.

The density of pure water depends on temperature (T) and pressure (P). Fine and Millero (1973) expressed this relationship in the empirical form

$$\rho = \frac{B}{A}\left(1 - \frac{P}{C + D - P + E - P^2}\right)^{-1}$$

where

$$A = 1 + 18.159725\text{x}10^{-3}T,$$

$$B = \sum_{n=0}^{5} B_n T^n, \text{ and}$$

$$C, D, E = \sum_{n=0}^{4} C_n D_n E_n T^n$$

The coefficients of B, C, D, and E are listed in Table 9. The unit for density is g cm^{-3}; for temperature, °C; and for pressure, bar.

The equation of state yields a parabolic-shaped curve of density versus temperature (Fig.76): as water is warmed from 0°C, it increases in density to a maximum of 1.000 g cm^{-3} at 4°C; above this temperature, expansion occurs at an increasing rate as the temperature is raised. It follows then that two parcels of water with different temperatures, one above 4°C and one below, can have equal densities, while their mixture is denser than either parent component.

Table 9. Coefficients of the four polynomials in temperature which appear in the equation of state for pure water.

n	$B = \sum_{n=0}^{5} B_n T^n$	$C = \sum_{n=0}^{4} C_n T^n$	$D = \sum_{n=0}^{4} D_n T^n$	$E = \sum_{n=0}^{4} E_n T^n$
0	0.9998396	19654.320	3.2891	6.245×10^{-5}
1	18.224944×10^{-3}	147.037	-2.3910×10^{-3}	-3.913×10^{-6}
2	-7.922210×10^{-6}	-2.21554	2.8446×10^{-4}	-3.499×10^{-8}
3	-5.544846×10^{-8}	1.0478×10^{-2}	-2.8200×10^{-6}	7.942×10^{-10}
4	1.497562×10^{-10}	-2.2789×10^{-5}	8.477×10^{-9}	-3.299×10^{-12}
5	$-3.932952 \times 10^{-13}$			

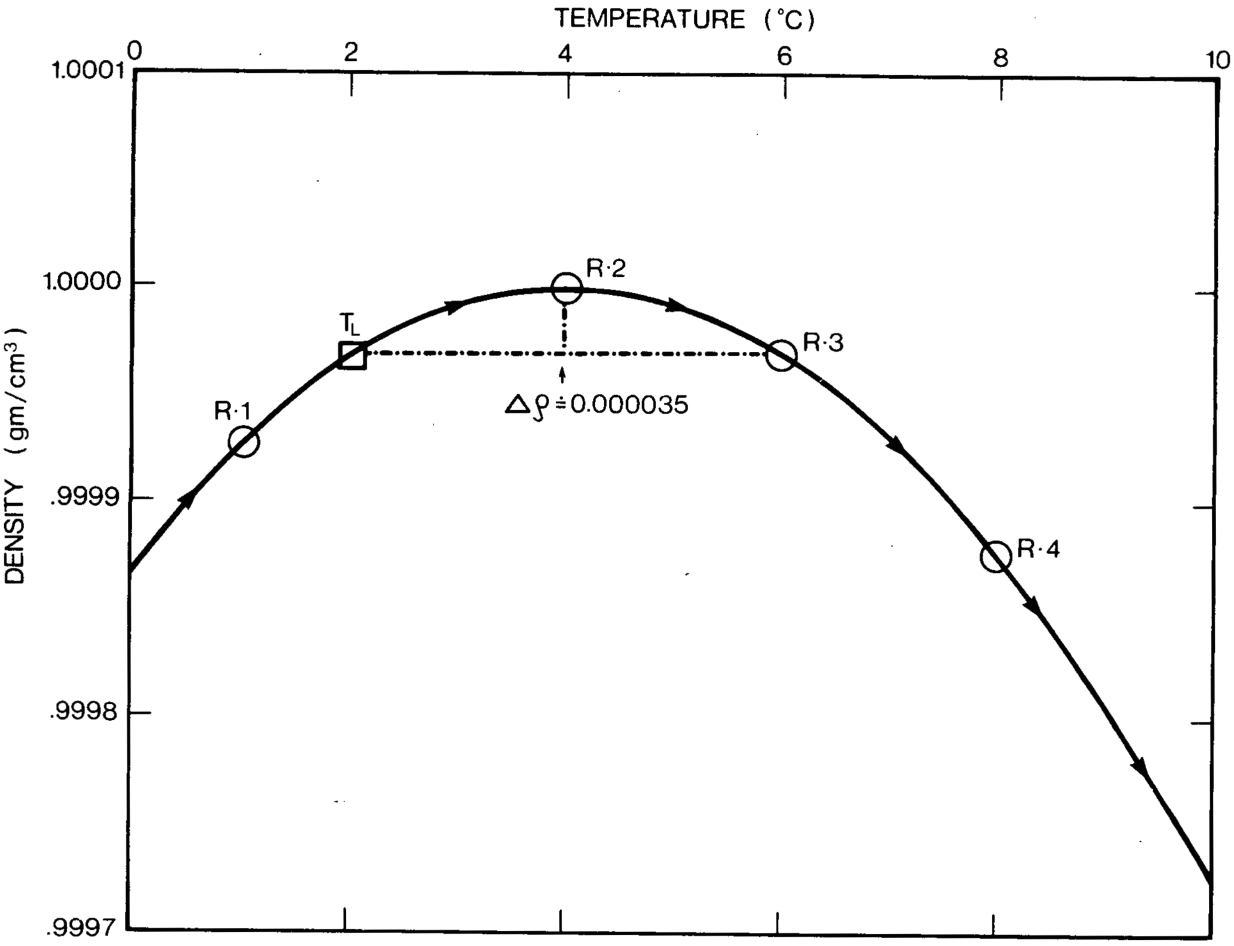


Figure 76. Relationship between water temperature and density.

This increase in density when dissimilar water types are mixed is commonly referred to as cabbeling.

Witte (1902) was evidently the first person to note the importance of cabbeling in the ocean. He proposed that when dissimilar water types of equal density were mixed, such as along the edge of an ocean current, a sharp boundary would be maintained by the continual sinking of the heavier mixtures. In physical limnology, cabbeling may be related to the so-called "thermal bar" phenomena described by Tikhomirov (1963) and Rodgers (1965). During spring, when the surface of a dimictic lake passes through the temperature of maximum density, warming proceeds outwards from the shore because mixing occurs through a shallower depth. Subsequently the "thermal bar" extends around the perimeter of the lake at a surface temperature near 4°C and separates the inshore region, where surface temperatures are above 4°C, from the open lake region, where surface temperatures are below 4°C. Being of maximum density, fluid within the thermal bar sinks. Surface flows from the inshore and open lake regions converge in the vicinity of the 4°C isotherm to replace the sinking water and mix (eg. cabbel) to form additional volumes of 4°C water.

In Kamloops Lake, however, the steep bottom configuration is not conducive to differential warming and "thermal bar" formation. Instead, convective overturn is primarily effected by the advected water of the Thompson River which responds more rapidly to seasonal temperature changes than the lake. The hypothetical example below explains some of the basic characteristics of the cabbeling mechanism during spring overturn.

As a reference, assume a <u>constant</u> lake temperature of 2°C (ρ = 0.99997 g cm^{-3}) and allow the inflow water to warm rapidly from 0°C to 8°C. We further assume that density is a function of temperature alone. At 0°C the density of the inflow (ρ = 0.99987 g cm^{-3}) is less than that of lake water, so it tends to remain on the surface. When the inflow warms to 2°C a condition of neutral stability is established. At 4°C, the inflow water reaches maximum density and thus tends to underflow the 2°C central lake water. Further warming of the inflow decreases its density until at 6°C the inflow is once again of a density equal to that of the lake water. At this time, however, cabbeling can occur since all mixtures of lake and inflow water are denser than either constituent.

In the final case, consider the juxtaposition of inflow water at 8°C (ρ = 0.99987 g cm^{-3}) and lake water at 2°C. The inflow is less dense than the lake water so it enters the lake as a surface overflow. All mixtures in the range $6 < T°C < 8$ are also less dense than the ambient lake water. Mixtures in the range $2 < T°C < 6$, however, are denser than either original constituent. Thus, two antithetical processes are operative: the first (in the $6 < T°C < 8$ range) is a condition of static stability that inhibits mixing; the second (in the $2 < T°C < 6$ range) is the cabbeling instability that promotes mixing.

The two mixing conditions combine to prevent 'new' inflow water from leaving the lake during convective overturn (Fig.77). As the inflow spreads across the surface of the lake and mixes with lake water, a dynamical boundary between river and lake water is established by the continual sinking of the heavier mixtures. Water within the sinking plume is comprised of nearly equal parts of river and lake water converging from either side of the sinking region. Through the cabbeling instability, new inflow water is thus removed from the surface by sinking, and retained within the lake basin. At the same time, mixtures warmer than 6°C, which are unaffected by the cabbeling instability, form an 'arrested' thermocline and act as a barrier to heat and mass transfer.

The thermal structure across the sinking plume during spring overturn in Kamloops Lake (Fig.78) reveals closely spaced isotherms in the range

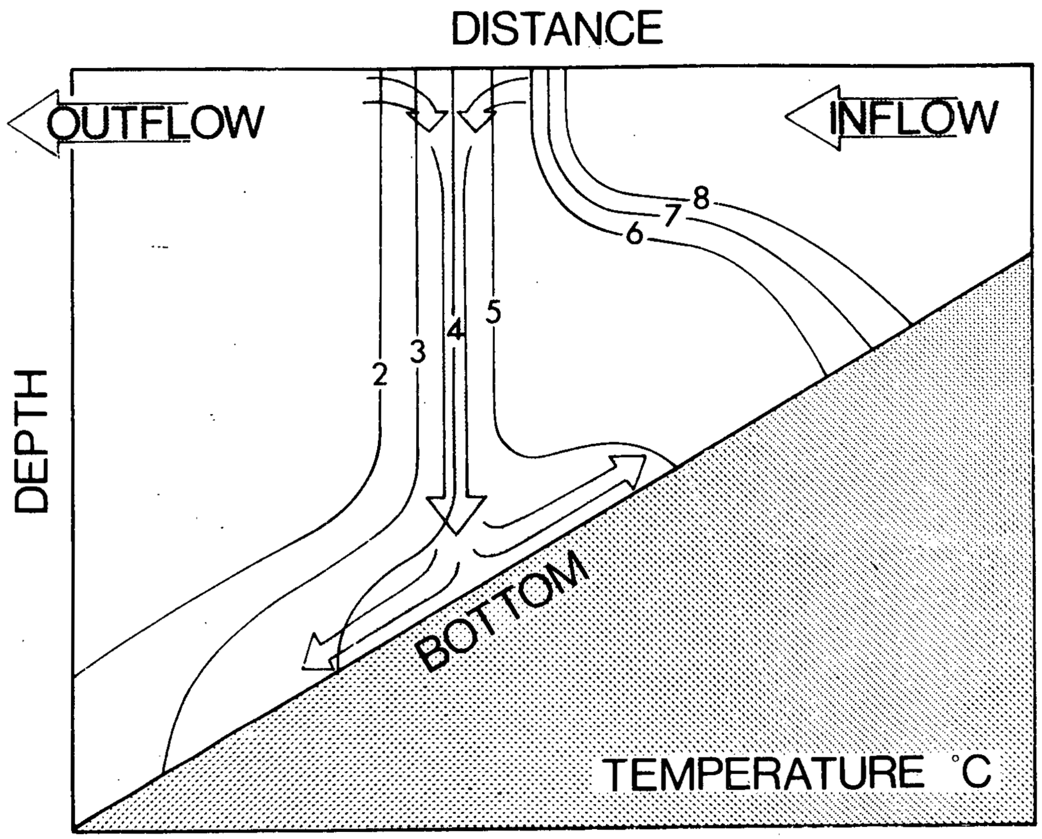


Figure 77. Schematic illustration of convective circulation during spring overturn.

3.4-5.2°C which includes the mixtures affected by cabbeling. Sinking is indicated by the vertical arrangement of isotherms near 4°C. Temperature gradients immediately inside the sinking zone are weaker, perhaps suggesting strong mixing. A second region of sharp temperature gradients coincides with the 'arrested' thermocline in the temperature range 5-6°C. Evidence that the sinking water is formed by mixing and cabbeling rather than by local heating of lake water is given by the temperature-turbidity correlation diagram (Fig.79) across the same sinking plume which shows the 4°C water to be a mixture of lake and river water.

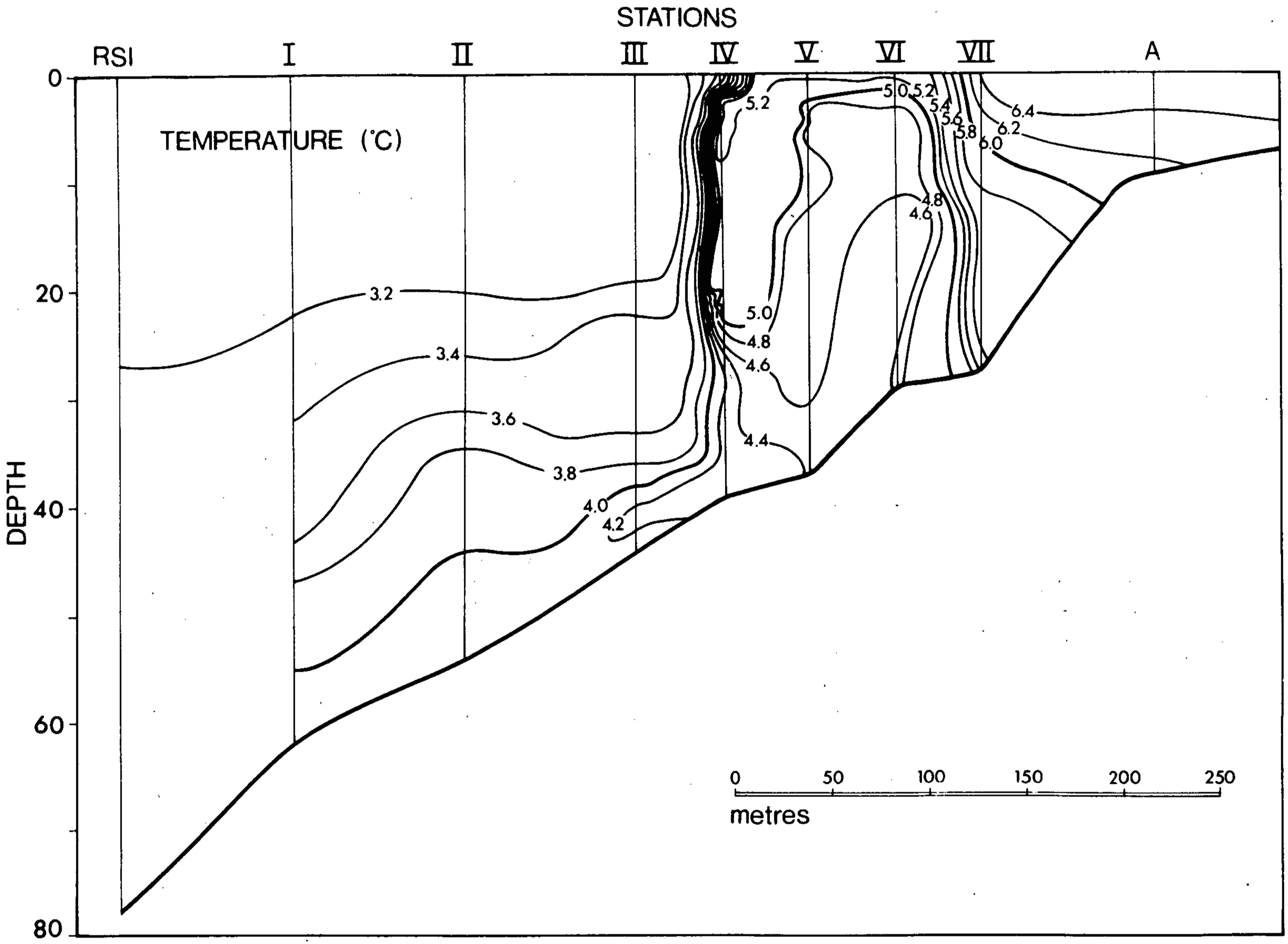


Figure 78. Section of temperature across the sinking zone during spring overturn.

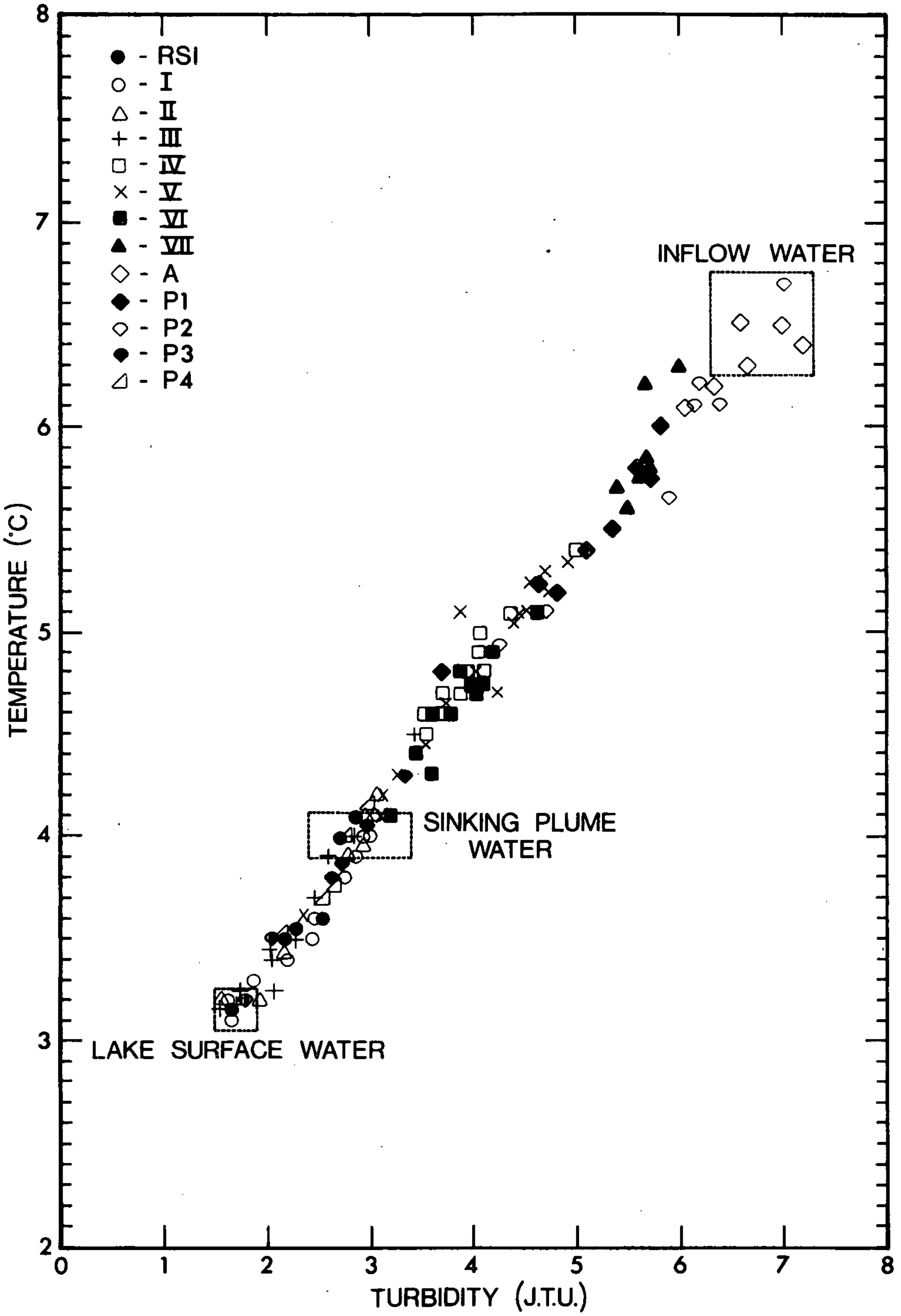


Figure 79. Temperature-turbidity correlation diagram for observations near the sinking zone during spring overturn.

APPENDIX III

The General Current Patterns of Kamloops Lake Obtained by the Drogue Technique

H. Y. F. Ng
Physical Limnology Section
Hydraulics Research Division
Canada Centre for Inland Waters-Burlington

a) Introduction

Currents have been measured by many investigators (Krauss 1963; Hamblin and Rodgers 1967; Blanton and Ng 1972) by tracking drogues set at predetermined depths which are marked on the surface by easily identifiable targets. From June through November, 1974, drogue measurements were conducted at various locations (Fig.80) on Kamloops Lake. Two position fixes were taken for each drogue during each measurement episode. One fix was made at launching, and the other fix was made at recovery. The distance between the first and last fix divided by the total time elapsed between the two fixes gives a vectoral average of drogue speed. All the data from the tracking of drogues from different episodes at 1, 13, 15, 20, 35, 40, 50 and 80 m of depth were grouped into three zones (Fig.80) according to initial launching location in the lake. The results of such groupings yield a simpler estimation of the predominant current speed and direction pattern over that zone. To determine the value for the current in a particular zone, individual drogue vectors from that zone were plotted about the compass rose and the resultant vectors at various depths for the same zone obtained by the U,V component relationship given by:

$$V = S \sin\theta \quad \text{and} \quad U = S \cos\theta$$

The resultant is

$$R = \sqrt{V^2 + U^2}$$

and the direction of the resultant drogue vectors is

$$\tan\theta = V/U$$

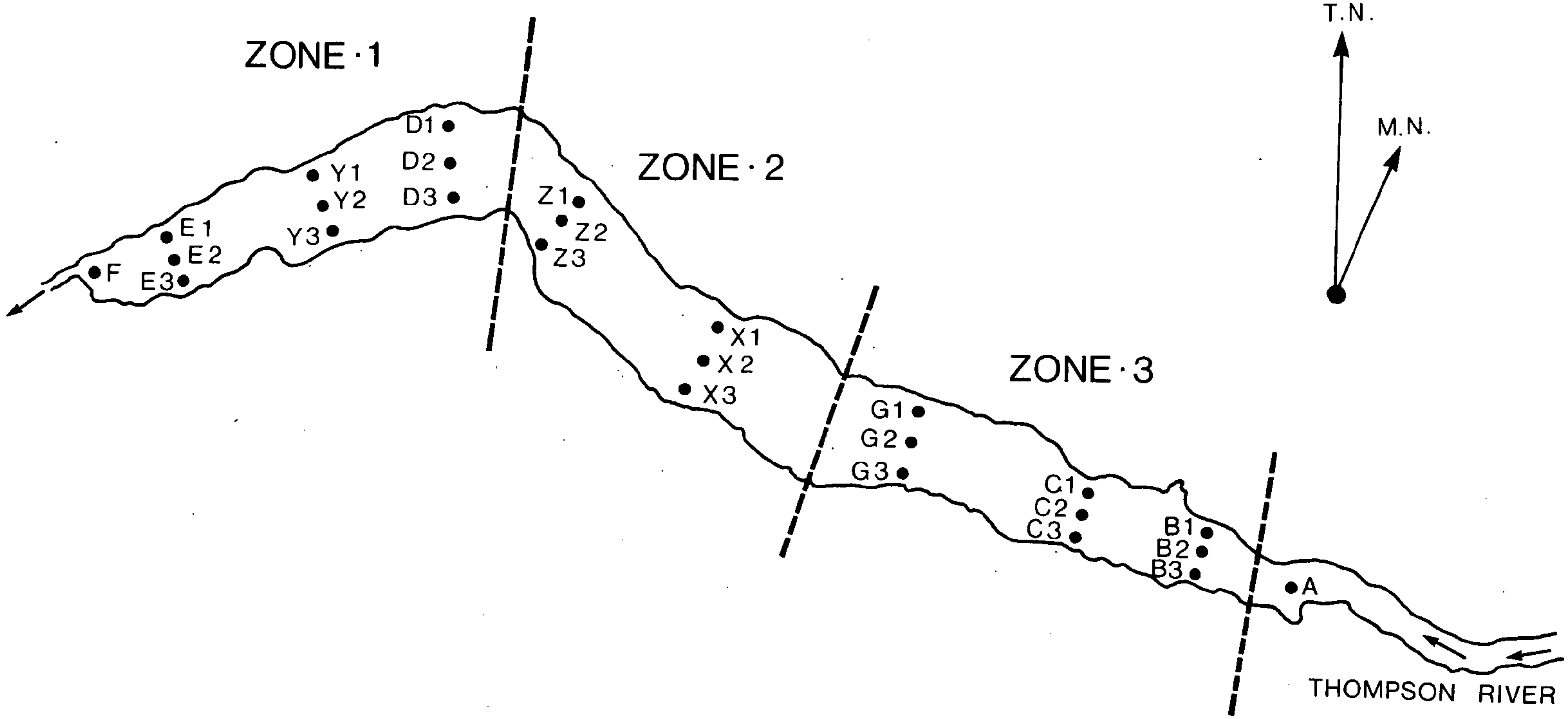


Figure 80. Locations and zones for drogue measurements in Kamloops Lake, 1974.

b) General Circulation

Vector patterns (Fig.81) in Zone 1 at depths of 1 and 20 m and Zone 2 at 20 and 35 m, suggest a predominantly westward current, while those of Zone 2 at 1 m and Zone 3 at 1, 20 and 35 m indicate a generally eastward current. The vector patterns of Zone 3 at 13 and 15 m also show a southwest current but of much greater magnitude than any of the above. Data from the drogue trackings at 40, 50 and 80 m levels were available for Zone 1 only and show current speeds in this zone decreasing with increasing depth.

The average drogue speed at each depth is shown in Figure 82. The average drogue speed over depth is 5.8 ± 4.3 cm sec^{-1}. Higher drogue speeds are indicated between 15 and 40 m depth. From the overall pattern of the drogue plots (Fig.81) it appears that current direction in Zones 1 and 2 tends to follow the longitudinal axis toward the downstream side of the lake. Current direction in Zone 3 indicates an opposite orientation, toward the upstream side of the lake.

The wind data from the same period as the drogue episodes are plotted in Figure 81. Wind speed is shown beside the vector arrow. No attempt has been made to establish the relationship between the wind and drogue movement in this study because time intervals between drogue position fixes are too short. However, there is some indication that the currents at 1, 15, 20 and 35 m depths in Zone 3 follow the wind direction.

In conclusion, based on the drogue plots, two types of current pattern are apparent in Kamloops Lake:

i) the current pattern in Zones 1 and 2 is subject to the influence of the Thompson River, and

ii) the current pattern in Zone 3 reflects the wind conditions.

c) Calculation of the Richardson Number

In connection with this drogue study the Richardson Number, Ri, (see

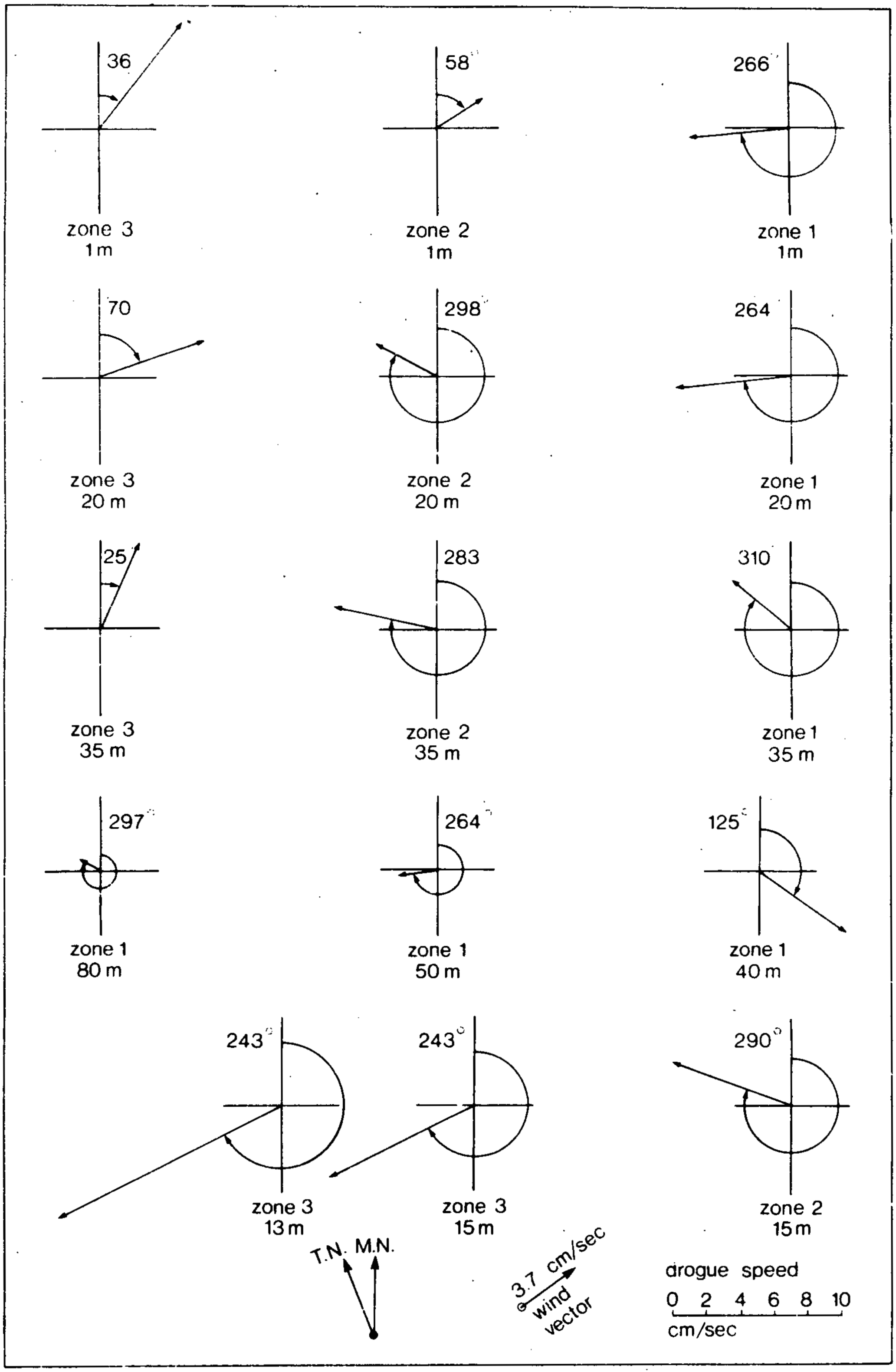


Figure 81. Drogue (resultant) vector patterns in various zones and at various depths in Kamloops Lake, 1974.

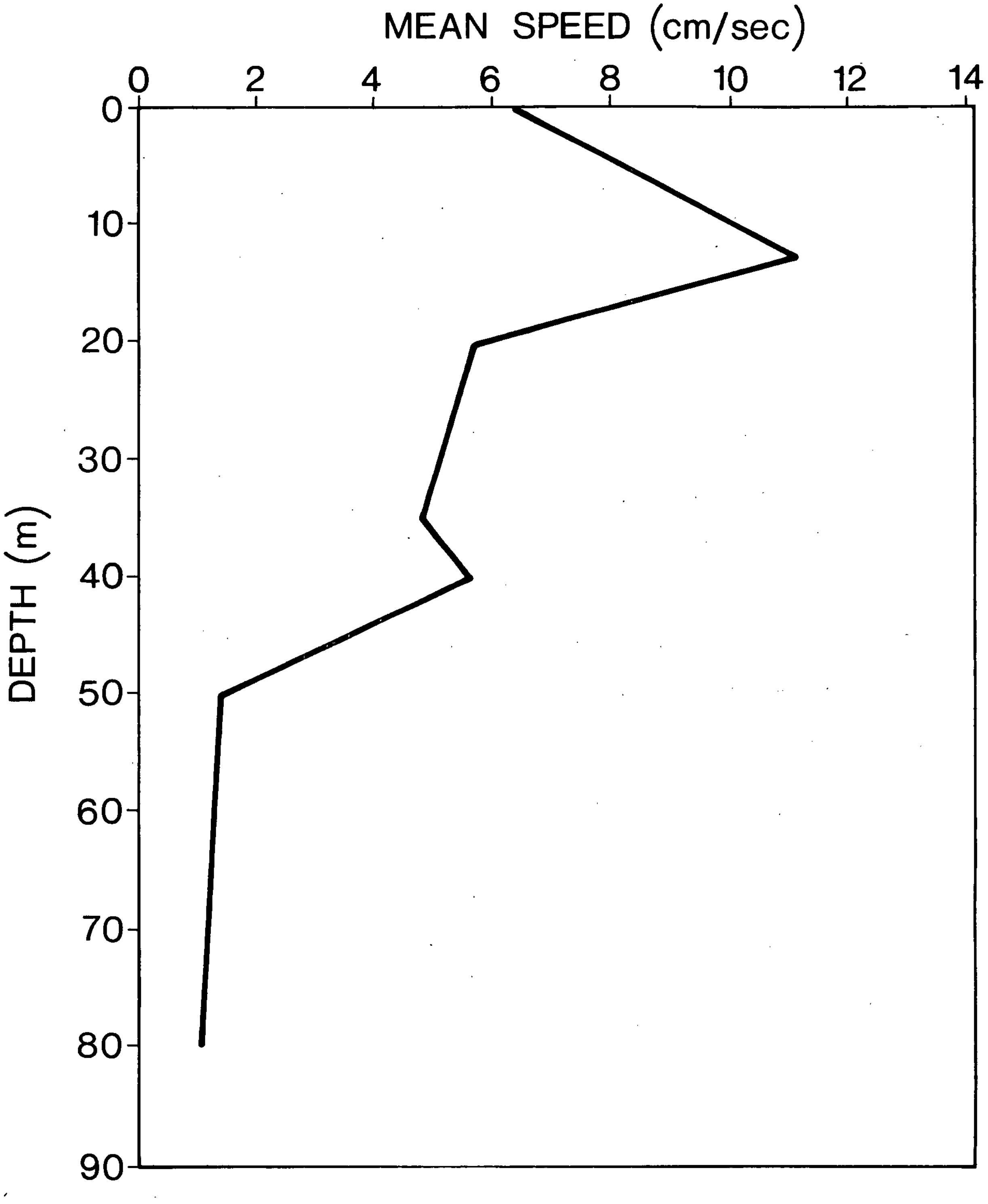


Figure 82. The relationship between average drogue speed and water depth in Kamloops Lake.

Hutchinson 1957 for discussion) describing the relationship between turbulence and stratification was calculated. The Richardson Number is defined as:

$$Ri = \frac{gE}{(\partial u/\partial z)^2}$$

where

g = the gravitational acceleration,

$E = \frac{1}{\rho} \cdot \frac{\delta\rho}{\partial z}$, the stability of stratification, where $\delta\rho/\partial z$ is the density gradient of the water column and ρ is the density in a given layer, and

$\frac{\partial u}{\partial z}$ = the velocity gradient.

Ri was calculated using drogue data and temperature data obtained from the monitor cruises, since no temperature measurements were made during the drogue experiments. Results of the Richardson Number calculation at different locations in the lake and at different times are shown in Table 10. A small value of the expression on the right-hand side indicates maintenance or increase of turbulence, whereas a large value indicates suppression or extinction of turbulence.

Table 10. Calculated Richardson Numbers for Kamloops Lake, 1974

Date	Location	Depth at (m)	Ri
21/6/74	B2	20-40	43
19/7/74	B2	20-35	80
19/7/74	C2	20-35	22
19/7/74	G2	20-35	276
19/7/74	X2	20-35	21
24/7/74	Z2	15-35	6
24/7/74	D2	15-35	3
24/7/74	Y2	25-35	48
24/7/74	E2	13-35	3
30/7/74	C1	20-35	13
30/7/74	G1	20-35	103
7/8/74	B3	20-35	1096
7/8/74	G3	20-35	848
8/8/74	X3	20-35	42
8/8/74	Z3	20-35	65
8/8/74	Z1	20-35	181
9/8/74	D3	20-35	77
9/8/74	D2	20-35	103
13/8/74	Y3	20-35	654
13/8/74	Y2	20-35	147
13/8/74	Y1	20-35	147
23/8/74	E2	15-35	448
23/8/74	E1	15-35	25
11/9/74	Y3	20-35	1274

APPENDIX IV

A Note on Internal Waves in Kamloops Lake

P. F. Hamblin
Physical Limnology Section, Hydraulics Research Division
Canada Centre for Inland Waters-Burlington

Internal motions and vertical displacements of the isotherms in Kamloops Lake are prevalent throughout the stratified period. For example, fluctuations in the depth of the 8° isotherm at the east and west ends of the lake are evident in the plots of Figures 83a and b.

The thermal unrest during the entire stratified period is summarized in Figure 84, in which the variability of the isotherms having the largest vertical displacement is resolved into a number of fluctuating components of periods ranging from 11.1 to 200 hours. The amplitude squared of each component during 7 episodes over the stratified period is also presented. The period of the maximum amplitude is 66 to 100 hours during May and June and decreases to 33 hours at the end of the summer period. (See also Table 11.) The amplitudes of the maximum decrease from a high of 5.2 m early in May to a low of 1.2 m in August. A test of the correlation between the fluctuations at the two ends of the lake indicates that the motions are highly synchronized; the maximum displacement at one end occurs at the same time as a minimum at the opposite end. The coherency value of 0.90 (Table 11) is taken as a significant correlation and a phase angle of 180° indicates opposite motion at the two ends of the lake.

Figure 84 also shows that motions having periods of fluctuation around 24 hours are also common in the lake, particularly in the spring, but also during the August episode. Table 12 summarizes the data for these thermal oscillations. It is evident that the "diurnal" waves have smaller amplitudes than the longer period fluctuation and are more poorly correlated between the ends of the lake.

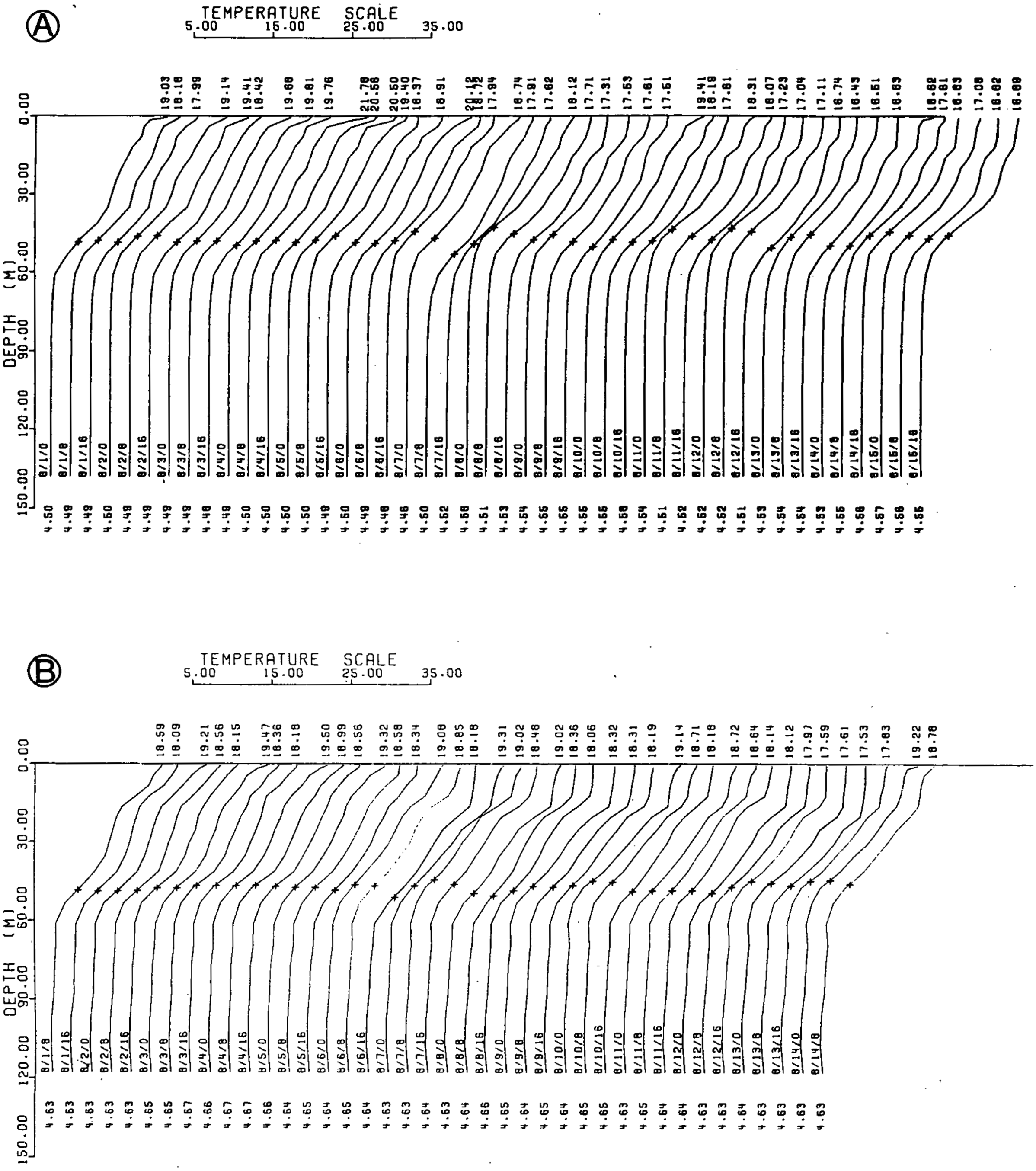


Figure 83. (A) Temperature profiles, August 1-15, 1974, west end. The depth of the 8° isotherm is denoted by *. (B) Temperature profiles, August 1- 5, 1974, east end Kamloops Lake.

In Figure 84 the internal wave structure appropriate to the thermal structure (Fig.85a) on August 3, 1974 is shown for the first internal mode (Fig.85b) through to the third internal mode (Fig.85c,d). The solid line in

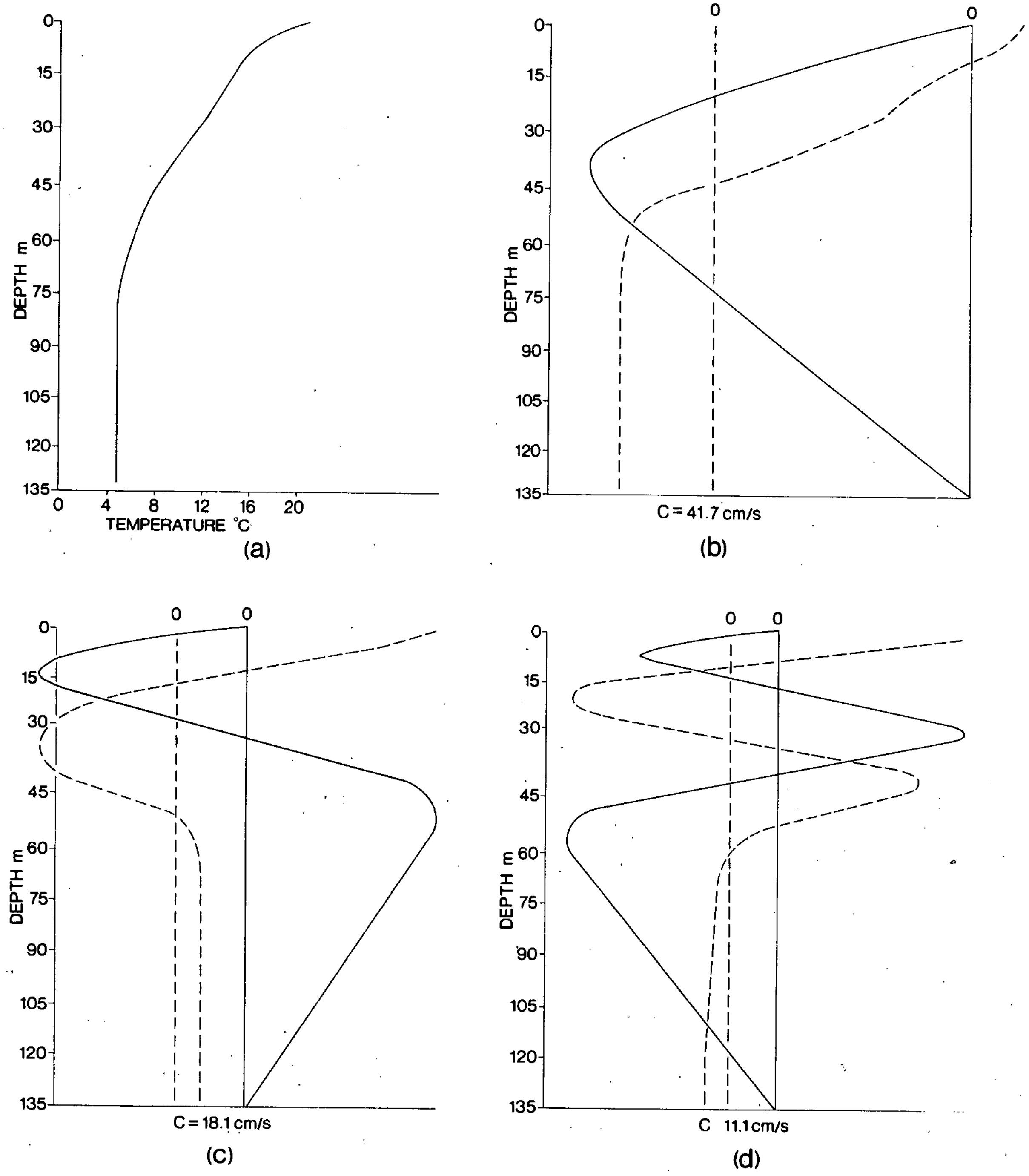


Figure 85. (a) Temperature profile from August 3, 1974, 0340 GMT, mid-lake station, Kamloops Lake; (b) associated vertical internal wave displacement and horizontal current for the first internal mode; (c) second internal mode; (d) third internal mode. The phase velocity, C, is shown for each mode.

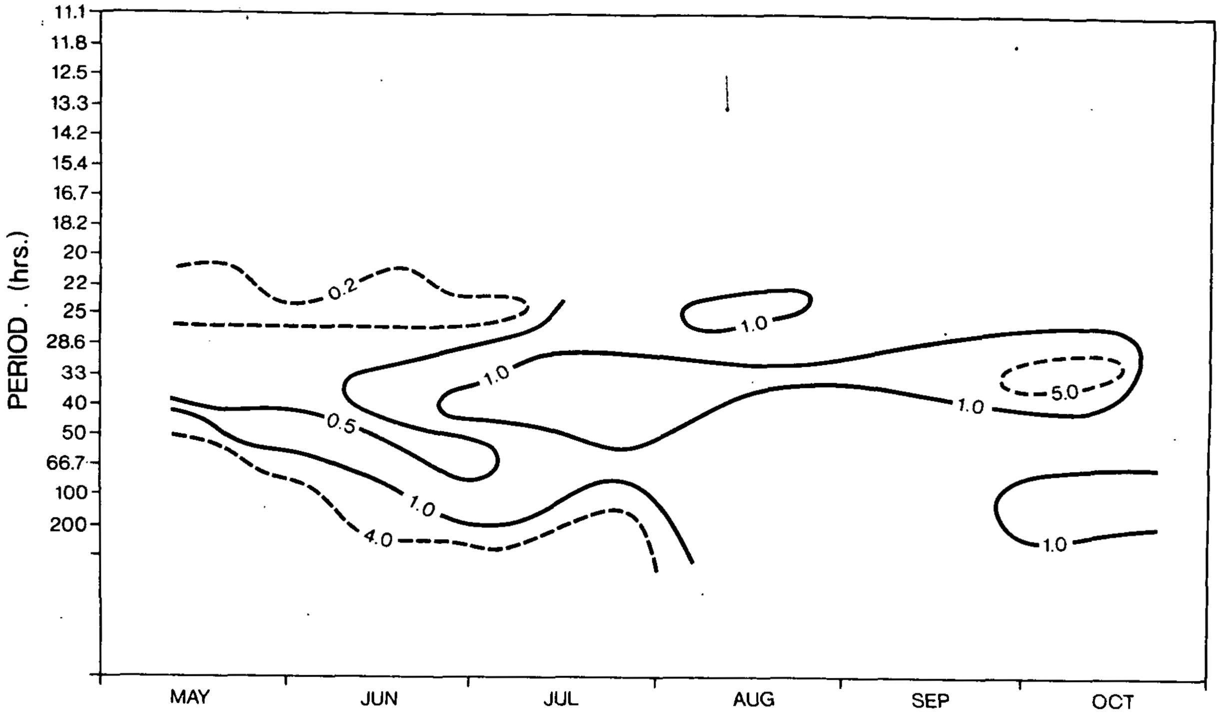


Figure 84. Spectral densities of the maximum isotherm displacement at the west end of Kamloops Lake as a function of period of oscillation and time.

Figure 85b is the isotherm displacement, which reaches a maximum at a depth of 40 m for the first mode and zero at the surface and bottom. This displacement is in agreement with Figure 83a and b. The maximum current is at the surface and, for a maximum thermocline displacement of 2 m, is 7 cm sec^{-1}. The corresponding hypolimnion current has an amplitude of 2.5 cm sec^{-1}. The maximum current shear is $2x10^{-3}$ sec^{-1}.

In conclusion, internal waves with the character of standing waves or seiches are prevalent in Kamloops Lake during the stratified period. The free periods of seiche oscillation are observed to range from 100 to 30 hours depending on the degree of vertical stratification. Minimum periods occur in August when the stratification is strongest. Also detectable are forced oscillations having a period of 24 hours which are thought to be attributed to differing wind regimes between day and night.

Table 11. Periods, amplitudes, coherency and phase for the east and west maximum isotherm displacements in Kamloops Lake. The period is associated with the internal seiche.

Episode	Period Long Internal Waves (hr)	Power Spectral Density E	Power Spectral Density W	Amplitude M E	Amplitude M W	Coherency	Phase
May 10-19	66	13.9	10.9	5.2	4.6	.96	155
May 21-31	66	9.1	2.7	4.3	2.3	.89	176
Jun 12-21	100	5.9	2.0	3.4	2.0	.96	170
Jun 23-Jul 2	40	1.5	0.7	1.7	1.2	.99	-175
Jul 18-27	50	3.3	4.1	2.5	2.9	.99	165
Aug 4-14	33	0.81	1.4	1.2	1.2	.99	-167
Sep 30-Oct 10	33	4.6	6.2	3.0	3.5	.99	155

Table 12. Amplitudes, coherence and phase between the east and west stations in Kamloops Lake for the 25 hour period of oscillation.

May 10-19		.21	.26	.65	.72	.86	85
May 21-31		.27	.73	.73	1.2	.98	55
Jun 12-21		.053	.275	.33	.55	.61	156
Jun 23-Jul 2		.29	.45	.76	.94	.51	101
Jul 18-27		.09	.03	.24	.24	.925	-91
Aug 4-14		.23	2.1	.67	2.0	.65	140
Sep 30-Oct 10		.5	.6	1.0	1.1	.96	155

APPENDIX V

A Mathematical Model for Predicting the Concentration of Dissolved Nutrients in the Outflowing Water of Kamloops Lake During Winter

As a first approximation, it was assumed that Kamloops Lake behaves as a continuously stirred reactor during the winter. The following assumptions were made:

a) the rate of water inflow equals the rate of outflow,

b) the inflow loading of dissolved constituent is instantly mixed,

c) the inflow concentration is constant over the period in question, and

d) the outflow concentration equals the lake concentration.

The following terms are used: C_i, C_ℓ, C_o - concentration of inflow, lake and outflow; f - rate of inflow and outflow; V - volume of the lake.

The mass balance equation is given by

$$\frac{C_\ell \cdot V}{dt} = C_i f - C_o f \tag{1}$$

Equation (1) can be integrated with respect to time giving equation (2). Substituting C_ℓ for C_o and integrating, one thus obtains

$$C_\ell = C_i - K e^{-(f/V)t} \tag{2}$$

where

K = the constant of integration

= $C_i - C_\ell$ at time zero, and

t = time

For Kamloops Lake in January, February and March

$f = 0.336$ km^3 month^{-1}, and

$V = 3.7$ km^3

Using these constants and the lake data for C_i and C_ℓ, the predicted lake concentrations of dissolved phosphorus for February and March were 5.3 and 7.2 µg l^{-1}, respectively. The actual computed average concentrations for the same period were 6.2 and 7.7 μg l^{-1} dissolved phosphorus. The lower predicted values might be expected if the effective mixing volume was smaller than the total lake volume. Using the actual concentration reached in the lake, the effective mixing volumes were calculated by equation (1) to be 1.5 and 2.4 km^3 for February and March, respectively, both of which are smaller than total lake volume (3.7 km^3). Since there is less thermal stratification in March than in February, the larger effective mixing volume in March is not implausible.

APPENDIX VI

On the Selective Release of Wastewater Phosphorus into the Thompson River-Kamloops Lake System

The present report has demonstrated that in Kamloops Lake and the lower Thompson River the relative proportion of natural to wastewater nutrients varies annually with the hydrological cycle. At the same time, physical interactions between the lake and inflowing river restrict pollution effects to the late fall, winter and early spring periods. In this section, these points are related to wastewater treatment in the Kamloops area and, in particular, draw attention to the possible option of selectively scheduling the release of wastewater dissolved phosphorus at a rate in proportion to the natural biological tolerance of the lake-river system throughout the year.

Briefly, the limnological year for Kamloops Lake can be divided into two periods on the basis of general sensitivity to nutrient loading:

a) From the beginning of fall overturn (November) through winter to the spring overturn (May) river flows are low, and thus the relative concentration of wastewater phosphorus in the system is high. The water level is low and constant and water transparency is high. Hence, when light conditions permit, benthic algal growth in the lower Thompson River occurs.

b) During limnological spring and summer, by contrast, the high river flows dilute the percentage of wastewater phosphorus in the system. Lake and river turbidity is comparatively high, as are the flushing rates of river water through the lake. Photosynthesis is thus reduced and benthic and pelagic algal cells are rapidly washed downstream. Consequently, algal production is low in both the lake and river. Only towards the end of this period, when progressively more of the inflowing river is mixed into the lake's hypolimnion, is wastewater phosphorus retained in the system for subsequent biological use.

In view of these conditions, we propose that a selective release schedule for wastewater nutrients be considered as an alternative to total control, should such an alternative prove to be economically beneficial.

In the fall-winter period, when all wastewater phosphorus entering the lake can directly aggravate pollution problems downstream, maximal removal of biologically utilizable phosphorus in wastewaters should occur. However, in the spring-summer period, when only that proportion of the wastewater phosphorus that is mixed into the hypolimnion can lead to excessive algal growth in the subsequent winter period, the phosphorus removal efficiency could be varied. Efficiency would increase from a minimum in early spring to the maximum in late summer according to a specific schedule related directly to the dynamics of lake circulation patterns.

The ideal situation for the autumn-winter period is absolute (100%) removal of wastewater phosphorus. Although it is possible that a lower phosphorus removal efficiency could be maintained without a significant increase in benthic algae above natural levels, the exact calculation of such removal efficiencies would require specific knowledge of the relationship between algal growth and phosphorus concentrations. As discussed earlier, this is not possible at present and the proposed study to provide such information will require a number of years to complete. Without such information there is no choice but to construct wastewater treatment facilities with phosphorus removal efficiencies as high as is technologically possible.

The most economical release schedule for the spring-summer period (assuming wastewater inputs remain at their present level) would simply be to suspend operation of treatment facilities. However, as pointed out above, this is probably unsound because of the progressive accumulation of river water in the hypolimnion of the lake throughout the summer. Instead, the removal efficiency should be gradually increased during late summer so that the accumulation of this remnant of wastewater phosphorus in the hypolimnion is negligible.

The removal efficiency curve shown in Figure 86 illustrates the above arguments for scheduled nutrient loadings. At the end of the spring overturn period (ie. when the temperature of the outflow water below Savona warms above 4°C), removal efficiency can be set to near-zero (A to B, Fig.86). During late summer, as the hypolimnion begins to deepen, the removal efficiency should

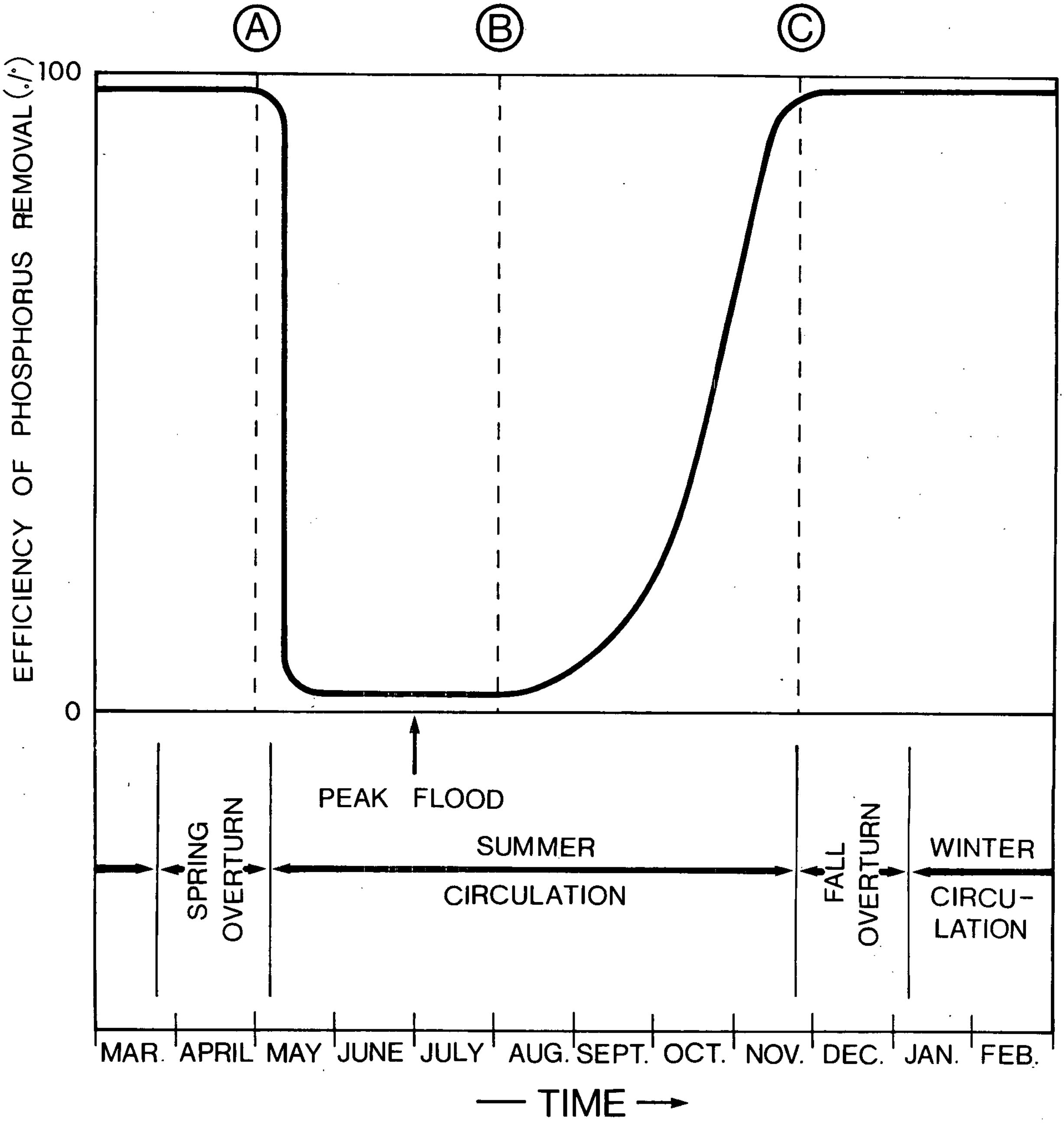


Figure 86. The general shape of the proposed phosphorus removal efficiency schedule for Kamloops Lake.

be increased gradually (B to C, Fig.86). Finally, at the onset of fall overturn, when the temperature of the inflow water falls below about 6°C, removal efficiency should reach a maximum (C, Fig.86).

The exact timing and shape of the removal efficiency curve is a function of river and lake temperatures and streamflow, all of which vary from year to year. Hence, an operational wastewater treatment schedule is best determined from numerical mixing calculations based on the physical dynamics of the lake. With the present understanding of circulation processes in Kamloops Lake, it is our opinion that such a calculation model can easily be constructed. Thus if this selective release option is chosen for implementation we recommend that the feasibility and form of an operational model then be determined either by contract or by a government agency that has the appropriate mandate and expertise.

Practical difficulties in obtaining the required monitor data for the operational model are unlikely. Only river flow rate, inflow and outflow temperatures, and a diagnostic lake temperature profile would be required. Sensor costs would thus be minimal. Adoption of such a phosphorus treatment schedule would increase the need for the ongoing biological-chemical monitor recommended earlier. Measurements of biologically available phosphorus (soluble reactive phosphorus), the dominant wastewater species, would be of special significance.

To prevent misunderstanding, the rationale behind this proposal for a variable phosphorus removal schedule for Kamloops Lake must be emphasized. In the past, inadequate nutrient treatment facilities have been constructed despite a clearly defined pollution problem because insufficient funds are freed for such purposes. Since so little is known about the biological response of the Thompson River algae to nutrients, it is crucial that phosphorus removal during the critical winter period be as efficient as possible. By removing phosphorus at less than maximum efficiency during the less critical summer period, the savings in operating costs may be sufficient to permit the initial capitalization of the more efficient treatment facilities required for the winter period.

REFERENCES

Bennett, E. B. (1975) Calculated relationships among temperature, density, pressure and depth useful for study of freshwater lakes. CCIW, unpublished manuscript.

Biscaye, P. E. (1965) Mineralogy and Sedimentation of recent deep-sea clay in the Atlantic Ocean and adjacent seas and oceans. Geological Society of America Bulletin 76:803-832.

Blanton, J. O. and Ng, H. Y. F. (1972) The physical limnology of the mainstem lakes in the Okanagan Basin, British Columbia. Okanagan Basin Study Committee Preliminary Report No.20, 34p.

Chang, S. C. and Jackson, M. L. (1957) Fractionation of soil phosphorus. Soil Science 84:133-144.

Cockfield, W. E. (1948) Geology and mineral deposits of Nicola map area, British Columbia. Geological Survey of Canada, Memoir 249, 164p.

Daley, R. J. and Hobbie, J. E. (1975) Direct counts of aquatic bacteria by a modified epi-fluorescence technique. Limnology and Oceanography 20:875-882.

Dillon, P. J. and Rigler, F. H. (1974) A test of a simple nutrient budget model predicting the phosphorus concentration in lake water. Journal of the Fisheries Research Board of Canada 31:1771-1778.

Environmental Protection Service Report. Kelso, B. W. and Derksen, G. A. (1975) Standing crop of plankton in Kamloops Lake, B.C., March 1974 - April 1975.

Eutrophication: Causes, Consequences, Corrections (1969), Proceedings of the Symposium of the National Academy of Science, Washington, D.C. October 1968, 661p.

Fine, R. A. and Millero, F. J. (1973) Compressibility of water as a function of temperature and pressure. Journal of Chemical Physics 59: 5529-5536.

Fish and Wildlife Branch Report. Cartwright, J. W. (1975) Fish and Wildlife Branch Thompson River Study, October 1975.

Foster, T. D. (1972) An analysis of the cabbeling instability in sea water. Journal of Physical Oceanography 2:294-301.

Francisco, D. E., Mah, R. A., and Rabin A. C. (1973) Acridine-orange epifluorescence technique for counting bacteria in natural waters. Transactions of the American Microscope Society 92:416-421.

Fulton, R. J. (1963) Surficial geology, Kamloops Lake, British Columbia. Geological Survey of Canada Map 9-1963.

Fulton, R. J. (1965) Silt deposition in late glacial lakes of southern British Columbia. American Journal of Science 263:553-570.

Fulton, R. J. (1969) Glacial lake history, southern Interior Plateau, British Columbia. Geological Survey of Canada, Paper 69-37, 14p.

Golterman, H. L. and Clymo, R. S. (1969) Methods for chemical analysis of freshwaters. IBP Handbook No.8, Blackwell Scientific Publications, Oxford and Edinburgh, 116p.

Hamblin, P. F. and Rodgers, G. K. (1967) The currents in the Toronto Region of Lake Ontario. Great Lakes Institute Publication No.29, University of Toronto, Toronto, Ontario.

Harris, E. A. and Lavkulich, L. M. (1972) Analytical methods used in pedology laboratory. Department of Soil Science, University of British Columbia, 47p.

Holland, S. S. (1964) Landforms of British Columbia: A physiographic outline. B. C. Department of Mines and Petroleum Resources Bulletin 48, 138p.

Hutchinson, G. E. (1957) A treatise on limnology, volume I. John Wiley and Sons, Inc., New York, 1015p.

Hutchinson, G. E. (1967) A treatise on limnology, volume II. Introduction to lake biology and the limnoplankton. John Wiley and Sons, Inc., New York, 1115p.

Inland Waters Directorate Report. Oguss, E. and Erlebach, W. E. (1975) Nutrient concentrations and loads in the Thompson River system.

International Pacific Salmon Fisheries Commission. Servizi, J. (1975) Thompson River macroinvertebrates and periphyton.

Kemp, A. L. W., Savile, H. A., Gray, C. B. J. and Mudrochova, A. (1971) A simple corer and a method for sampling the mud-water interface. Limnology and Oceanography 16:689-694.

Kirchner, W. B. and Dillon, P. J. (1975) An empirical method of estimating the retention of phosphorus in lakes. Water Resources Research 11:182-183.

Khomyakov, A. P. (1971) Geochemical mobility of lanthanides. Doklady Akademii Nauk SSSR, 200(5):1203-1206.

Kittrick, J. A. and Hope, E. W. (1963) A procedure for the particle size-separation of soils for x-ray diffraction analysis. Soil Science 96:319-325.

Krauss, J. A. (1963) Drogues and neutral-buoyant floats. In: The Sea, Vol. 2, Section III, M. N. Hill, ed., Wiley-Interscience, New York.

Lewin, V. H. (1973) Phosphates in sewage and sewage treatment. Water Research 7:55-67.

Likens, G. E. (1975) Primary production of inland aquatic ecosystems. In: The Primary Productivity of the Biosphere, H. Lieth and R. H. Whittaker, eds., Springer-Verlag, New York.

Mathews, W. H. (1944) Glacial lakes and ice retreat in south central British Columbia. Transactions of the Royal Society of Canada 38, Section IV:39-58.

McNabb, C. D. (1960) Enumeration of freshwater phytoplankton concentrated on the membrane filter. Limnology and Oceanography 5:57-61.

Patrick, R. and Reimer, C. W. (1966) The diatoms of the United States, exclusive of Alaska and Hawaii. I. Monographs of the Academy of Natural Science, Philadelphia, No.13, 688p.

Rainville, R. P., Copeland, B. J. and McKean, W. T. (1975) Toxicity of kraft mill wastes to an estuarine phytoplankton. Journal of the Water Pollution Federation 47:487-503.

Rodgers, G. K. (1965) The thermal bar in the Laurentian Great Lakes. Proceedings of the 8th Conference on Great Lakes Research, University of Michigan, Ann Arbor, Michigan, p358-363.

Rublee, P. A. (1975) Production of bacteria in a pond. M.Sc. thesis, North Carolina State University.

Schindler, D. W. (1971) Carbon, nitrogen, and phosphorus and the eutrophication of freshwater lakes. Journal of Phycology 7:321-329.

Schindler, D. W., Armstrong, F. A. J., Holmgren, S. K. and Brunskill, G. J. (1971) Eutrophication of Lake 227, Experimental Lakes Area, northwestern Ontario, by addition of phosphate and nitrate. Journal of the Fisheries Research Board of Canada 28:1763-1782.

Schindler, D. W., Schmidt, R. V. and Reid, R. A. (1972) Acidification and bubbling as an alternative to filtration in determining phytoplankton production by the ^{14}C method. Journal of the Fisheries Research Board of Canada 29:1627-1631.

Shepard, F. P. (1954) Nomenclature based on sand-silt ratios. Journal of Sedimentary Petrology 24:151-158.

Southern Operations Branch Report, Fisheries and Marine Service. Langer, O.E. and Nassichuk, M. D. (1975) Selected biological studies of the Thompson River system.

Stockner, J. G. and Northcote, T. G. (1974) Recent limnological studies of

Okanagan Basin lakes and their contribution to comprehensive water resource planning. Journal of the Fisheries Research Board of Canada 31:955-976.

Stockner, J. G. and Shortreed, K. R. S. (1974) Phytoplankton succession and primary production in Babine Lake, British Columbia. Fisheries Research Board of Canada Technical Report No.417,

Strickland, J. D. H. and Parsons, T. R. (1972) A practical handbook of sea-water analysis, 2nd edition. Fisheries Research Board of Canada Bulletin 167, 310p.

Tikhomirov, A. I. (1963) The thermal bar of Lake Ladoga. Izvestia Akademii Nauk SSSR Ser. Geogr.95:134-142, Translation AGU Soviet Hydrology Selected Papers No.2.

Vollenweider, R. A. (1965) Calculation models of photosynthesis-depth curves and some implications regarding day rate estimates of primary production measurements. Memoirie Instituto Italiano Idrobiologia 18 (Suppl):425-457.

Vollenweider, R. A., ed. (1969) A manual on methods for measuring primary production in aquatic environments. IBP Handbook No.12, Blackwell Scientific Publications, Oxford, 213p.

Vollenweider, R. A. (1971) Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication. Organization for Economic Co-operation and Development, Paris. DAS/CSI/68.27, 192p. Annex, 21p; Bibliography, 61p.

Vollenweider, R. A. and Dillon, P. J. (1974) The application of the phosphorus loading concept to eutrophication research. National Research Council Associated Committee on Scientific Criteria for Environmental Quality, NRCC#13690, 42p.

Vollenweider, R. A., Munawar, M. and Stadelmann, P. (1974) A comparative review of phytoplankton and primary production in the Laurentian Great Lakes. Journal of the Fisheries Research Board of Canada 31:739-762.

Vollenweider, R. A. (1975) Input-output models with special reference to the phosphorus loading concept in limnology. Schweizerische Zeitschrift für Hydrologie 37:53-84.

Ward, F. J. (1964) Limnology of Kamloops Lake. International Pacific Salmon Fishery Commission Bulletin 16.

Wetzel, R. G. (1975) Limnology. W. B. Saunders Co., 743p.

Wier, D. R., Chien, S. H. and Black, C. A. (1972) Transformation of hydroxyapatite to fluorapatite. Soil Science Society of America Proceedings 36:285-288.

Williams, J. D. H., Syers, J. K., Walker, T. W. and Shah, R. (1969) Apatite transformations during soil development. Agrochimica XIII(6):491-500.

Williams, J. D. H., Murphy T. P. and Mayer, T. (1976) Rates of accumulation of phosphorus forms in Lake Erie sediments. Journal of the Fisheries Research Board of Canada 33:430-439.

Witte, E. (1902) Zur theorie der stromkabbelungen. Gaea (Köln):484-487.