LIMNOLOGY OF THE GORDON RIVER BASIN, TASMANIA, AND ITS MEROMICTIC LAKES.

by

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ABSTRACT

In recent years the Gordon River Basin, south west Tasmania, has been the subject of considerable debate between conservationists and the Hydro-Electric Commission. A dam was built on the middle Gordon River and discharge from the power station commenced in October 1977. This development has had a severe impact on the wilderness area of the lower Gordon River. This thesis discusses the water chemistry of the Gordon River system, the limnology of a small holomictic lake elevated above the river and three riverine meromictic lakes, and the effects of the dam on this lower Gordon River area.

Those unregulated rivers of the Gordon River Basin whose catchments contain calcareous rocks display a fluctuation in major ion chemistry from alkaline earth bicarbonate dominance at low summer flow to sodium chloride waters at high winter flows. Because Gordon limestone also contains variable amounts of sea salts, the alkaline earth bicarbonate waters sometimes contain appreciable amounts of both sodium and chloride at low flows. Composition of rivers draining catchments not containing calcareous rocks are always similar to sea water.

Due to power station release, water chemistry and flow of the Gordon River have been significantly altered. Waters are now more dilute and ionic composition, principally that from Lake Gordon, varies little from that of sea water. High winter flows have been reduced, and most significantly, summer flows elevated, consequently river height during summer is much greater, reducing light penetration to the river bed. Power station discharge has further reduced temperature variability (lowered summer temperatures and raised winter temperatures).

Perched Lake is a small lake above the Gordon River near Butler Island, moderately dystrophic and acidic with water chemistry akin to sea water. It is warm monomictic, stratifying in summer and circulating freely in winter. Dissolved oxygen in the surface waters is mostly undersaturated. Late in the period of stratification oxygen in the bottom waters is reduced to about 20% of saturation. Phytoplankton biomass is sparse, dominated by one chrysophyte and two desmid species.

The three meromictic lakes occur behind river-deposited levee banks along the tidal section of the lower Gordon River. They are well protected from the prevailing westerly weather by surrounding rainforest. Meromixis results from salt input from the river to the lakes, producing a saline gradient within each of these lakes. The lakes are thermally stratified in summer and inversely stratified in winter. They have two isothermal periods, but do not circulate completely due to the saline gradient. Dissolved oxygen in the mixolimnia is mostly undersaturated, decreasing rapidly to zero in the chemocline. Large amounts of total dissolved sulphides occur in the monimolimnia. Surface waters are acidic to neutral, becoming basic in the monimolimnia. The waters are very dark and chemically akin to sea water. Large amounts of phosphorus are trapped in the monimolimnia.

A well developed bacterial plate is present in each lake, composed principally of green sulphur bacteria below an algal layer, including *Cryptomonas*. Light penetration is severely limited by dissolved organic material, and to a lesser extent by photosynthetic pigments, with blue light being deficient.

These lakes are amongst the shallowest meromictic lakes in the world, with the chemocline situated at depths of only 0.1 m in some cases.

Discharge from the Gordon Dam has flushed the salt wedge from the river, eliminating salt supply to these lakes. As a result, the halocline of one lake has been seriously eroded and the lake shows all signs of becoming holomictic. This is likely to have severe repercussions for the maintenance of meromixis in the other two lakes.

DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma in any University, except as stated herein, and, to the best of my knowledge, contains no copy or paraphrase of material previously published by another person, except where referenced in the text.

RONALD DAVID KING.

CONTENTS

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CHAPTER 1

Introduction

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INTRODUCTION

The Gordon River Basin, and more particularly the lower reaches of the Gordon River, has been of extreme interest ever since early European settlement in Tasmania (formerly Van Diemens Land). Aboriginals are known to have roamed the west coast of Tasmania long before intrusion into this area by the white man, but there is no evidence of them venturing up the Gordon River. James Kelly was probably the first white man to do this, and in 1818 Thomas Florance journeyed up the Gordon River in search of exploitable timber species, as well as land suitable for grazing (Gowlland and Gowlland 1975).

The highly prized Huon pine timber (*Dacrydium franklinii* Hook.f.) attracted many people to the lower Gordon River area, and this resource was actively exploited when a convict settlement was established on Sarah Island (at the mouth of the Gordon River in Macquarie Harbour) in 1821. The first known tramper across this south west area was James Goodwin, an escaped convict from the penal settlement, who headed east towards Hobart Town. By 1850 Huon pine became scarce, forcing many piners to move further afield (Gowlland and Gowlland 1975, Gee 1978). The only remaining evidence of these early days are remnants of some piners' huts and a lime kiln along the banks of the river. The history of the white man's activities in this south west Tasmanian wilderness, of which the Gordon River Basin forms a major part, has been discussed by Gowlland and Gowlland (1975) and Gee and Fenton (1978).

For nearly thirty years the Hydro-Electric Commission (HEC) has investigated the hydro-electric potential of the Gordon River Basin. A bitter battle raged between the Commission and conservation movements who lobbied to keep development out of this south west wilderness area. In 1967 the Tasmanian Government approved the construction of Stage 1 of the Gordon Power Development. Two major dams were constructed, one on the Gordon River (at The Knob - Figure 1), flooding vast areas of the middle Gordon River, and a second on the Serpentine River, flooding the original Lake Pedder, a lake of majestic splendour. This Serpentine impoundment was further contained by a minor dam in the upper Huon River.

Recently the Hydro-Electric Commission presented proposals for Stage 2 of the Gordon Power Development to the Tasmanian Government, recommending a major dam on the Gordon below Franklin, and diversion of the polluted King

River (Lake *et al* 1976) down the Franklin River. An alternative scheme was also proposed whereby a major dam would be constructed on the Gordon River above Olga, and several dams on the King River (Hydro-Electric Commission 1979b and c). Again the conservation battle raged, more fiercely than before. On this occasion the Government recognized the international wilderness value of the Franklin River, but unfortunately accepted the alternative development scheme (Hydro-Electric Commission 1979c). Although the decision to save the Franklin River from future development was welcomed by conservation movements, strong objection has been voiced to further development in the south west. The conservation battle continues, as the Olga scheme will make significant inroads into the wilderness area.

Very limited biological study accompanied the Hydro-Electric Commission's engineering investigation which led to construction of Stage 1, a fact which attracted considerable criticism from conservation movements. This led to an enquiry into the proposed flooding of the original Lake Pedder (Lake Pedder Committee of Enquiry 1974), and many warned that endemis species would become extinct if flooding occurred (Lake and Tyler 1974, Lake *et al* 1978). Unfortunately development proceeded and Stage 1 of the Gordon Power Development is now in full operation, at the expense of a unique wilderness area.

During the engineering investigations for Stage 2, limited physical data from the area was collected but no biological information existed (King 1977). The Hydro-Electric Commission therefore initiated an environmental survey of areas likely to be affected by the various engineering options for harnessing the power generating potential of the region. In 1974 an adviser was appointed to plan and direct the "Lower Gordon River Scientific Survey", which was to be a fact-finding study on which an Environmental Impact Statement could be based. The scientific survey was broadly based and a wide range of reports were prepared (Christian and Sharp-Paul 1979; see Appendix 10). The study area (designated by the Hydro-Electric Commission) covered 1500 km^2 west of the Gordon Dam (Figure 1), and comprised that section of the Gordon Basin likely to be flooded or otherwise directly affected by hydro-electric development (see Hydro-Electric Commission 1979b).

PRESENTATION

Results obtained by me during the Lower Gordon River Scientific Survey have been published by the Hydro-Electric Commission, Hobart, Tasmania (King and HEC 1978, HEC, King and Coleman 1978) and this thesis contains the interpretation and discussion of these data, together with some unpublished data, particularly on the meromictic lakes. The data has been divided into two major sections, namely rivers and lakes, the latter being further separated according to whether meromixis exists in the lakes or not. The three major chapters of this thesis have also been published by the HEC (King and Tyler 1978 a, b and c).

The thesis format is as follows: Chapter 2 describes the geology, soils, vegetation, hydrology and climate of the Gordon River Basin, and follows with a discussion of seasonal variation and stratification of temperature in the river system. Factors affecting light penetration into the river are investigated, indicating the possible effects of Lake Gordon Power Station discharge on the light climate within the river. The major part of this chapter is devoted to a general description of water chemistry in the Gordon Basin and the causal effects of flow (and hence rainfall) and catchment geology on river chemistry are investigated. In particular, seasonal and longitudinal variation in ionic composition of the rivers are highlighted. The chapter concludes with a brief examination of the effect Lake Gordon has had on the chemistry of the river.

In Chapter 3 the general limnology of Perched Lake is discussed. This is a small dystrophic acid lake displaying some peculiar thermal and planktonic characteristics, which are intimately related to the south west region of Tasmania. Comparisons are drawn between Perched Lake and other waters in the region.

Chapter 4 describes three riverine levee meromictic lakes, one of which (Sulphide Pool) is believed to be the shallowest of its type in the world. In general terms this chapter is devoted to a limnological characterization of the lakes, pointing out their peculiarities and similarities, and where possible an explanation of events is attempted. Owing to the complex hydrology of these lakes and the intense and variable nature of their meromixis this thesis probably poses more questions than it attempts to answer.

Unfortunately long intervals between sampling trips are recognized as a major factor affecting the overall understanding of these lakes.

Like the Gordon RIver, the lakes are affected by the changed river flow pattern, and one of the lakes (Lake Morrison) is already displaying a breakdown in its salt gradient and evolving from a meromictic lake to a monomictic lake. The chapter concludes with an investigation of the light climate within the lakes, and various factors which attenuate it within the water body. This has definite biological importance as the chlorophyll-containing bacterial plates occur at depths below those of the traditionally defined photic zone limit. The biology and ecology of these plate organisms are poorly understood, but further studies by the Botany Department, University of Tasmania, will no doubt paint a clearer picture than presently exists.

Concluding remarks and suggestions for further research are contained in Chapter 5.

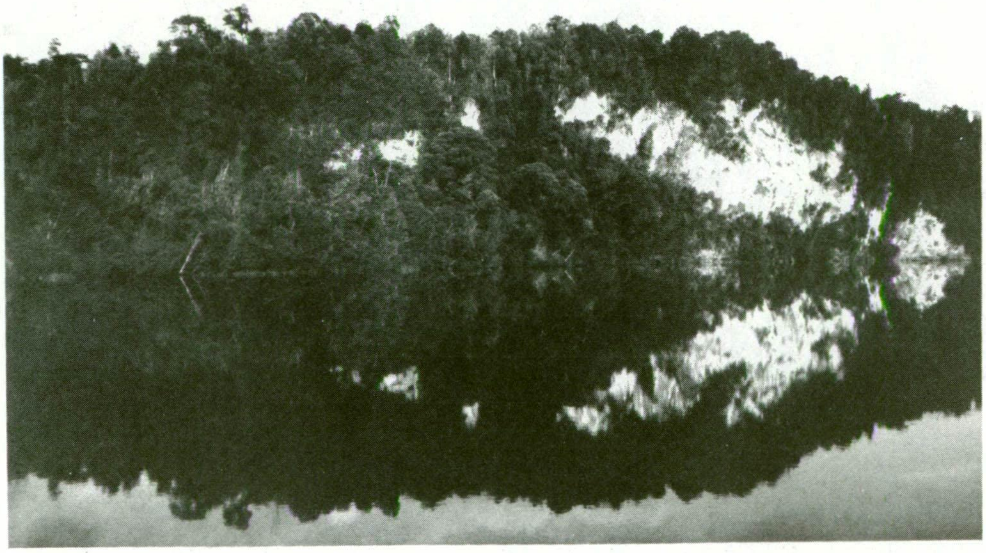
Lakes Gordon and Pedder have been thoroughly studied by Steane (1979) and the HEC have also collected information from these lakes. They were therefore not included in this study.

CHAPTER 2

Water chemistry of the Gordon River Basin

FRONTISPIECE

BUTLER ISLAND, LOOKING WEST (ABOVE), AND CHAMP CLIFFS, 3 km DOWNSTREAM OF BUTLER ISLAND, ARE COMPOSED OF GORDON LIMESTONE OF ORDOVICIAN AGE.



CONTENTS

CONTENTS (continued)

FRONTISPIECE

FIGURES

FIGURES (continued)

FIGURES (continued)

FIGURES (continued)

PLATES

PLATES (continued)

TABLES

1.0 INTRODUCTION

This report on the water chemistry of the Gordon River Basin forms part of the Lower Gordon River Scientific Survey initiated by the Hydro-Electric Commission (hereafter H.E.C.). The survey has been concentrated on that area of the Gordon River Basin likely to be affected by the proposed Stage 2 of the Gordon River Power Development. The overall survey was envisaged as a fact-finding study to allow description and interpretation of features, systems and processes in the area.

There is no published information on seasonal and spatial aspects of the chemistry of rivers in South West Tasmania. A few spot samples analyzed by Buckney and Tyler (1973 a & b) and Tyler (1974), mostly in the vicinity of the original Lake Pedder and in the Mt. Picton area, gave preliminary indication of the type of water chemistry to be expected.

The aims of this study were to investigate the chemical nature of as many rivers in the Gordon River Basin as possible, to attempt to relate this information to those factors which control chemical composition (such as climate and geology), and to assess what influence construction of the Gordon Dam has had on the chemistry of the river below the Dam.

Observations at various frequencies were made on rivers and creeks between October 1976 and April 1978. The intensity of observation depended on the accessibility of the river sites during the winter months when helicopters were not used.

2.0 THE STUDY AREA

The study area in South West Tasmania, as defined by the Lower Gordon River Scientific Survey, is shown in Figure 1. The area includes the catchment of the lower Gordon River which is likely to be impounded by Stage 2 of the Gordon River Power Development, and excludes the upper Franklin and upper Denison Rivers.

Because rivers cannot be isolated into sections and studied without reference to the system as a whole it was necessary in this study to sample rivers outside the survey area. For example, seasonal samples were collected from the upper Franklin River and the Collingwood River, and occasional samples from the Gordon River above Lake Gordon and below Butler Island were taken.

2.1 Geology

The regional geology of South West Tasmania has been discussed by Boulter (1978) and Volframs (1978) and the geology, geomorphology and land systems of the Gordon River Basin by Roberts and Naqvi (1978).

Because the geology of the area is diverse (Figure 2) each river catchment will be described separately, since composition and temporal variation of water chemistry will be related to catchment rocks.

2.1.1 The Gordon River

The source of the Gordon River, Lake Richmond, is in the King William Range, composed of undifferentiated Upper Carboniferous to Triassic sequences overlain by Jurassic dolerite.

The catchment of the upper Gordon River extends from the southern end of Lake King William, along the Vale of Rasselas to the Huntley Rivulet. The river valley is predominantly Holocene alluvium overlying Ordovician limestone. It is bounded to the east by lower Devonian - Silurian sequences of the Gordon Range, and to the west by Ordovician calcareous sandstones of Butler Island formation of the Denison Range.

From Huntley Rivulet until it meets Lake Gordon the river flows over calcareous sandstone belonging to Ordovician Butler Island Formation. The middle Gordon catchment extends from the Huntley to the Gordon Dam. This area is composed of Precambrian metamorphics and Cambrian turbidite sequences overlain by extensive Holocene alluvium. From the Gordon Dam the

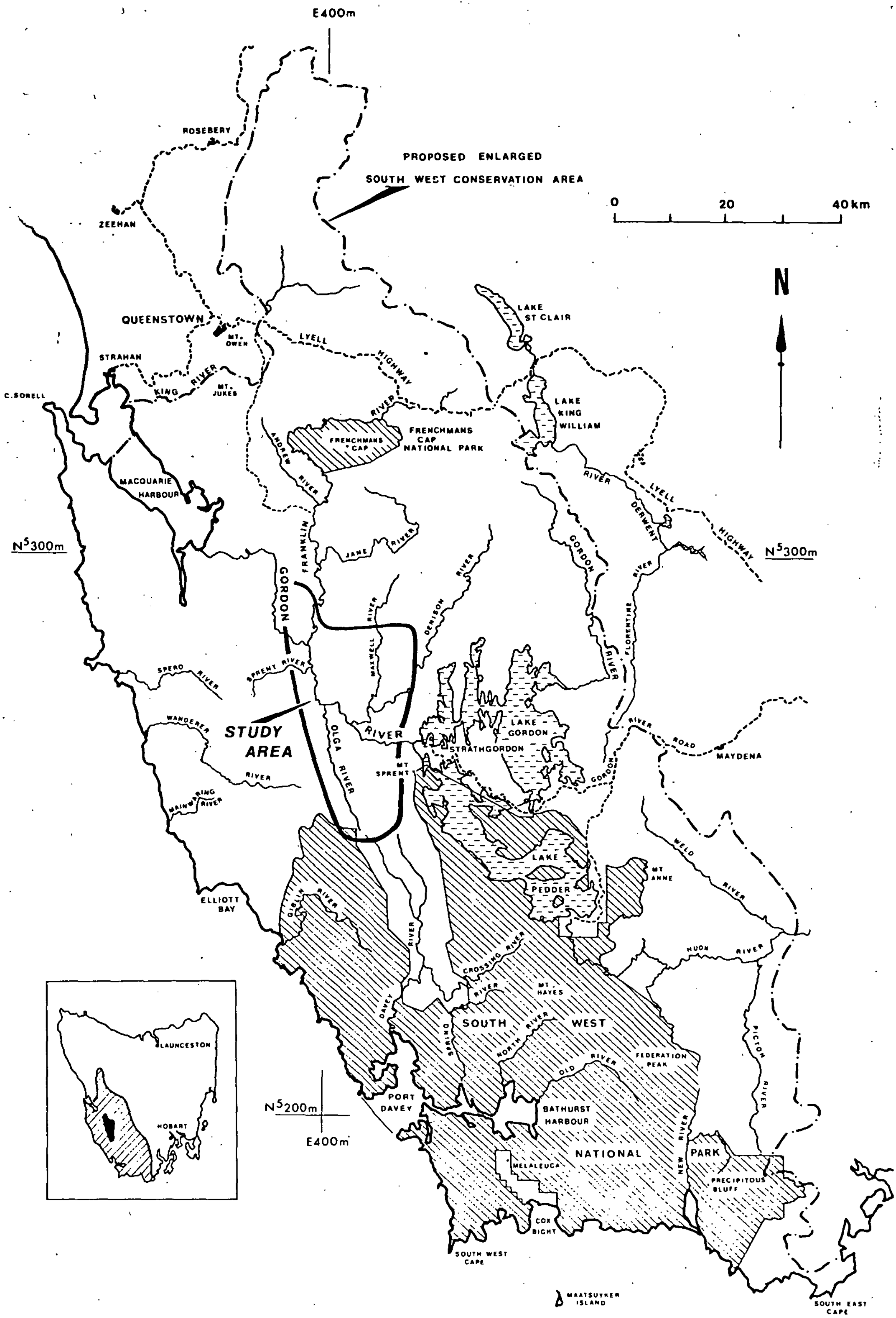


FIGURE 1

LOCATION OF THE STUDY AREA IN SOUTH WEST TASMANIA.

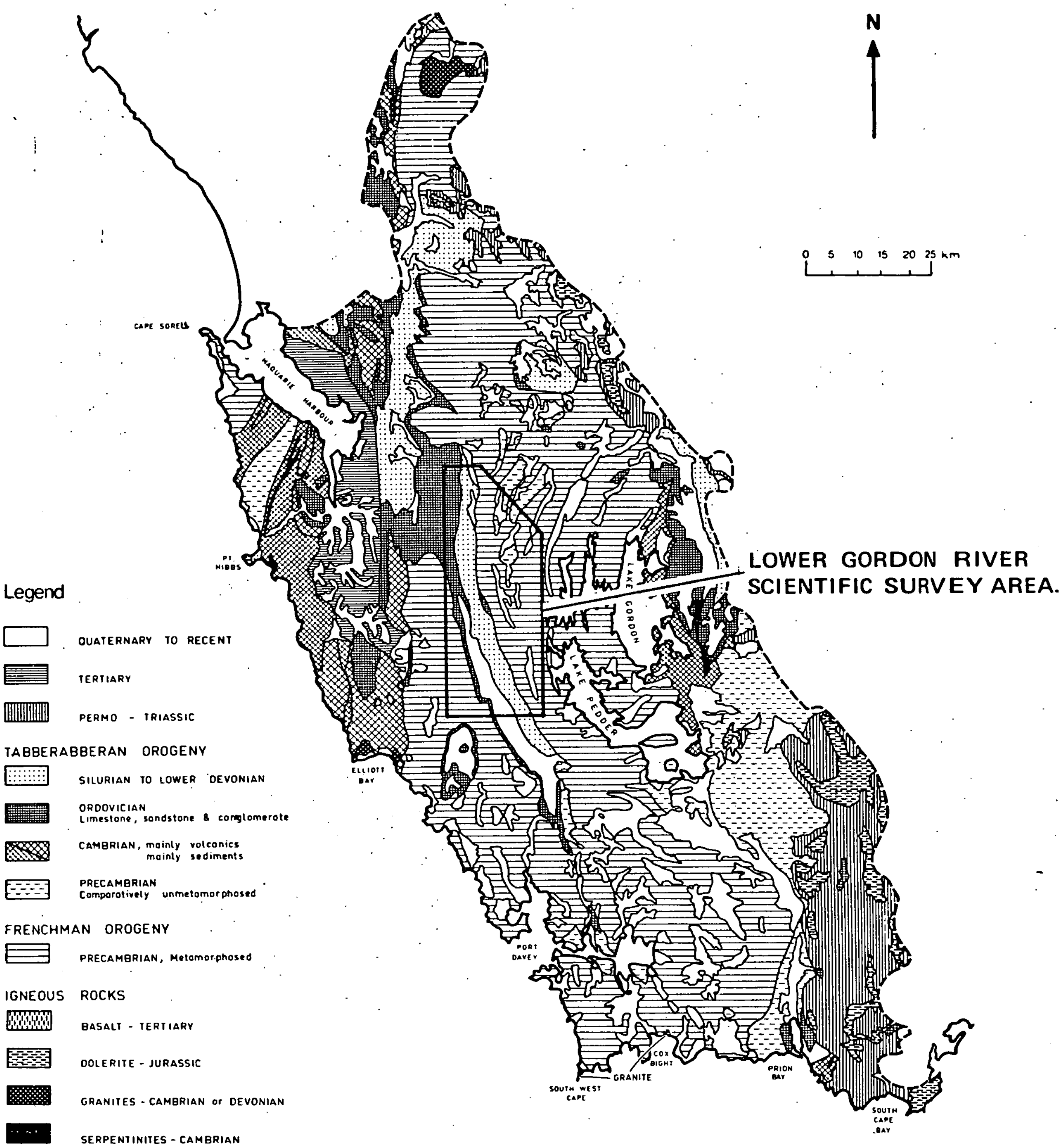


FIGURE 2

GEOLOGY OF SOUTH WEST TASMANIA.

river flows westerly over Precambrian metamorphic rocks to the junction with the Orange River, then north-westerly over Ordovician limestones until joined by the Olga River at the southern end of the Ordovician Gordon Limestone (Plate 1). From there it flows in a predominantly northerly direction through the Ordovician Gordon Limestone and calcareous sandstones of Butler Island Formation to the end of Lime Kiln Reach, then westerly over Lower Devonian - Silurian Limestone siltstone-shale sequences and Tertiary marine limestones before entering Macquarie Harbour. Holocene alluvial deposits occur in several areas along the banks of the river (Plate 2).

The major tributaries of the Gordon River are as follows:-

The Denison River rises on the western slopes of Mt. King William II and flows in a mainly south-westerly direction over Holocene alluvial deposits underlain by Precambrian metamorphic rocks to its junction with the Gordon River.

The Maxwell River rises to the east of the Norway Range and flows in a southerly direction across extensive plains of comparatively unmetamorphosed Precambrian dolomites and pelitic sequences overlain by Holocene alluvial deposits. The Maxwell River joins the Denison River about 6 km upstream from the Gordon River.

The Smith River flows between the Nicholls and Princess Ranges in a southerly direction across the Lower Devonian - Silurian siltstone-sandstone sequences.

The Orange River (= Albert Creek on some maps) flows in a northerly direction, parallel to the Olga River, along sequences contiguous with the Smith River valley.

The Albert River flows in a northerly direction to the east of the Orange River, primarily over Precambrian metamorphic rocks.

The Olga River flows in a predominantly northerly direction over Holocene alluvial deposits (Plates 3, 4 and 5). The creeks flowing in an easterly direction into the Olga River drain Precambrian metamorphic rocks. From about 4 km before the junction with the Gordon River, the Olga flows over Ordovician Gordon Limestone.

Plate 1
Gordon River at Sunshine Gorge looking east. Smith River and Harrison Creek are about 500 m further upstream.

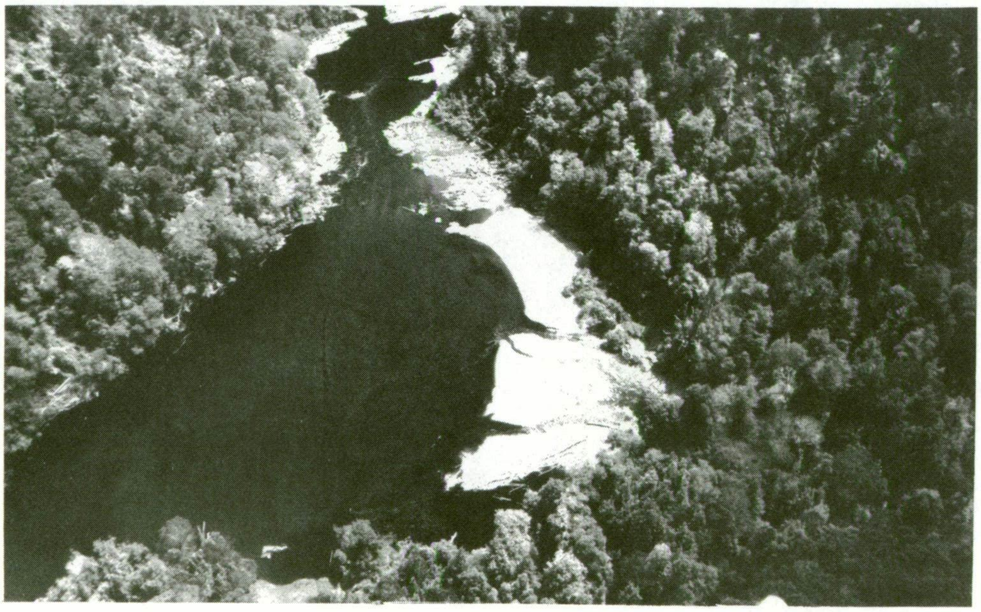


Plate 2
Exposed beaches on the Gordon River upstream from the Sprent River in January 1977, looking downstream.

Plate 3
Olga River 4 km upstream from the Gordon River.

Plate 4
Olga River downstream from the Olga/Hardwood saddle.

2.1.2 The Franklin River

The Franklin River is the major tributary of the Gordon River and from its source in the south-western corner of the Cradle Mountain - Lake St. Clair National Park it flows across Jurassic Dolerite and Precambrian metamorphics overlain by Holocene deposits along the river valleys, to the junction with the Collingwood River. The Collingwood River flows over similar deposits to the upper Franklin River. The Loddon River drains the Loddon Plains on the eastern boundary of the Franchmans Cap National Park, and flows over Precambrian metamorphic Devonian to Silurian siltstone-shale sequences overlain with Holocene deposits along the water courses. Some Ordovician Gordon Limestone lies to the west of the South Loddon River. From the Franklin - Collingwood River junction to about 7 km before the Jane River junction the Franklin River flows over predominatly Precambrian metamorphic rocks. Many of the creeks tributary to the Jane River flow over Holocene deposits or Precambrian dolomites and metamorphics (Plate 6). The confluence with the Franklin River is in the Ordovician Gordon Limestone. Alluvial material occurs intermittently along the entire course of the Franklin River (Plates 7 and 8).

The only major tributary of the Franklin River draining western slopes is the Andrew River which flows across Ordovician Gordon Limestone and sandstones of Butler Island Formation and Holocene alluvial deposits.

2.2 Soils

Soil types are variable in the Gordon River Basin. Soil-profile development is absent or minimal and there is a distinct absence of developed mineral soils. The soils of the study area have been broadly classified by Tarvydas (1979) into:-

(a) Alluvial deposits which occur on gently sloping valleys and river banks (Plates 2, 5 and 7).

(b) Fibrous peats in the valleys, overlying alluvial deposits, and, on moderate to very steep slopes, or overlying shallow to deep coarse siliceous sands containing various amounts of stones and gravel. Less commonly the sands incorporate silty clays, reflecting the nature of the underlying bedrock. These peats are between 20-50 cm thick with a pH of about 4.5, and are well drained both externally and internally.

Plate 5
Olga valley looking north, showing the complicated vegetation mosaic.

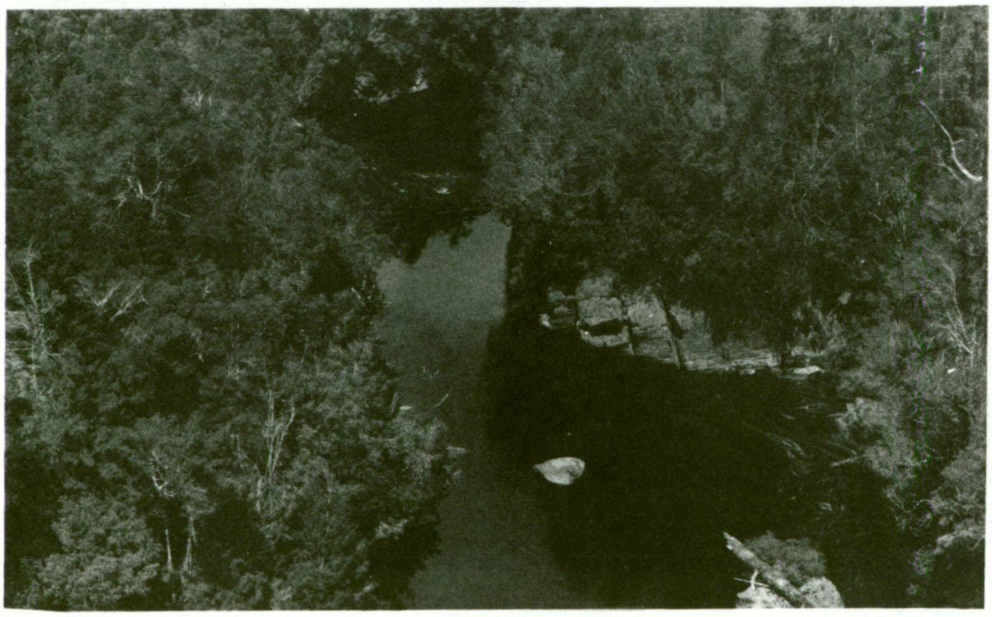


Plate 6

Jane River near Punt Hill.

Plate 7

Eroding alluvial river bank on the Franklin River just above the Franklin/Gordon junction.

Plate 8

Franklin River at Shingle Island (centre), 1 km upstream from the Franklin/Gordon junction, photographed in January 1977. Low summer river flows expose extensive shingle beds in the river, seen in the foreground.

(c) Muck peats, which are most evident in the Olga Valley, are black, muck to spongy or strongly organic clay loam of variable thickness (sometimes exceeding 100 cm), and overlie the alluvium on the valley floor. The soil profile is strongly acidic with pH about 4.5. Mineral matter increases with depth in the lower part of the peat. There is a general increase in peat thickness down the Olga Valley towards the Gordon River.

Soil erosion is almost absent in the Gordon River catchment, indicating that high hydraulic conductivity allows safe disposal of the high rainfall.

The peaty soils of the study area impart colour to the flowing waters thus delineating the south-west of Tasmania as a dark water province (Buckney and Tyler, 1973a).

2.3 Vegetation

The vegetation of the Gordon River Basin forms a complicated mosaic (Plate 5) which can be interpreted generally in terms of fire history (Jarman and Crowden, 1978; Kirkpatrick *et al.* 1978). The plant communities can be divided into four main types, namely, rainforest, sclerophyllous forest, scrub, and heathland/sedgeland. The latter is considered to be maintained by frequent burning, and as the average time interval between burning increases so the succession towards rainforest climax progresses (rainforest being distinct from the other vegetation types as it can be maintained by the total absence of fire). There is no apparent correlation between the four major vegetation types and edaphic and topographic features, and there is a well developed peat below the vegetation in each case. No vegetation type inhabits a particular habitat type, and all have a wide tolerance of environmental conditions (Jarman & Crowden 1978).

The rainforest communities are widespread in the Gordon River Basin. The major component species are:-

Nothofagus cunninghamii (Hook.) Aerst.
Atherosperma moschatum Labill.
Eucryphia lucida (Labill.) Baill.
Anodopetalum biglandulosum A. Cunn. ex Hook.f.
Acradenia frankliniae Milligan ex Kippist

Agastachys odorata R. Br.
Cenarrhenes nitida Labill.
Dacrydium franklinii Hook.f.
Acacia melanoxylon R.Br.

The sclerophyllous forests occur frequently within rainforests, scrub and button grass communities, and are dominated by:-

Eucalyptus nitida Hook.f.
E. ovata Labill.
Acacia mucronata Willd. ex H. Wendl.
Phebalium squameum (Labill.) Engler
Leptospermum glaucescens S. Schauer
L. lanigerum (Ait.) Sur.
Banksia marginata Cav.
Melaleuca squarrosa Donn. ex Sur.

Other conspicuous species are:-

Gahnia grandis Labill
Bauera rubioides Andr.
Calorophus elongatus Labill.
Gleichenia dicarpa R. Br.
Phyllocladus aspleniifolius (Labill.) Hook.

The scrub communities also occur throughout the Gordon River Basin, being most frequent in the wide, flat to undulating alluvial Olga and Maxwell Valleys, and merge into sclerophyllous forests or button grass heaths. Dominant taxa in scrub communities are:-

Bauera rubioides
Leptospermum glauscescens
L. nitidum Hoof.f.
L. lanigerum
Banksia marginata
Melaleuca squamea Labill.
M. squarrosa

Heathland/sedgeland occurs extensively in the Hardwood, upper Olga and Maxwell valleys with small stands occurring widely elsewhere throughout the study area. They are dominated by:-

Gymnoschoenus sphaerocephalus (R. Br.) Hook.f. (button grass).
Other major species in the heathland/sedgeland are:-

Leptospermum nitidum
L. glaucescens
L. scoparium J.R. & G. Forst.
L. lanigerum
Sprengelia incarnata Sm.
Restio monocephalus R. Br.
Lepidosperma filiforme Labill.
Lepidosperma longitudinale Labill.
Dillwynia glaberima Sm.
Boronia citriodora Gunn ex Hook.f.
Schoenus tenuissimus Benth.
Gleichenia dicarpa R. Br.
Leptocarpus tenax (Labill.) R. Br.
Lepyrodia tasmanica Hook.f.
Actinotus suffocata Rodw.
A. bellidioides (Hook.f.)
Melaleuca squamea
Melaleuca squarrosa
Hakea epilottis Labill.
Baumea juncea (R. Br.) Palla
Liparophyllum gunnii Hook.f. (Jarman & Crowden 1978)

At this stage it is not possible to relate water chemistry of rivers or creeks to vegetation type in the drainage basins because no one catchment contained a uniform vegetation. Some waters were collected from seepages in specific vegetation types e.g. button grass and *Nothofagus* rainforest, but these did not prove to be very different from seeps in other vegetation types.

2.4 Hydrology

The study of hydrological potential and variation within a large drainage basin like the Gordon River requires the delineation of the basin into sub-catchment areas. Watson (1978a) has subdivided the Gordon River catchment into twelve sub-catchments (Figure 3), two of which are intimately related to Stage 1 of the Gordon River Power Development and do not

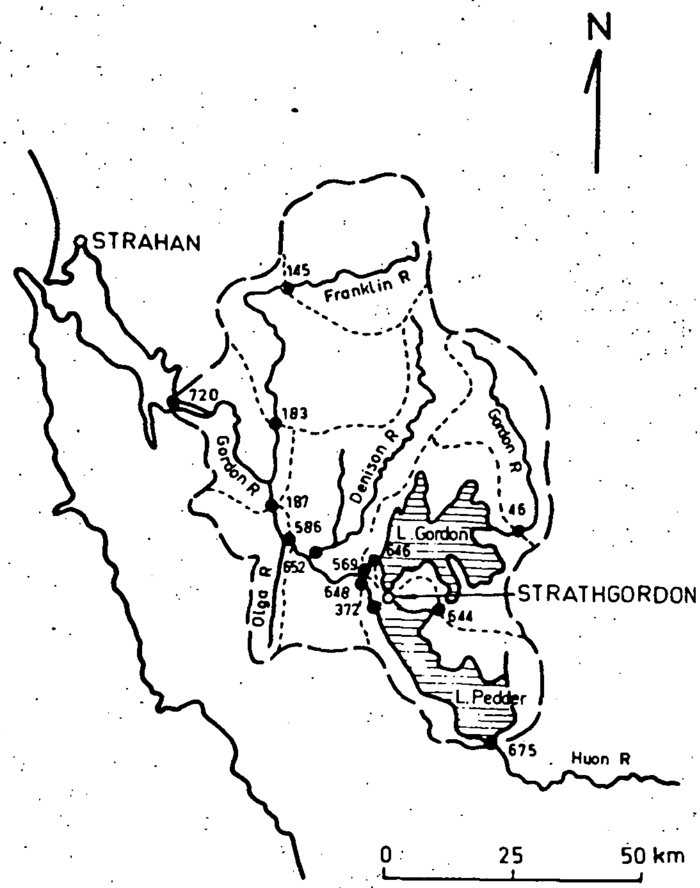


FIGURE 3

GORDON RIVER BASIN. THE BROKEN LINE (— —) INDICATES THE GORDON RIVER BASIN, AND THE DASHED LINE (- - -) THE HYDRO-ELECTRIC COMMISSION'S HYDROLOGICAL SUB-CATCHMENTS. GAUGING STATIONS ARE ALSO SHOWN (•187). (REDRAWN FROM WATSON 1978a.)

represent a true catchment as such. The mean hydrological features of these sub-catchments are presented in Table 1. The elevation of the Gordon River and its tributaries at given distances from Butler Island is illustrated in Figure 4 and Appendix 1. Alteration of the mean monthly flows as a result of the construction of the Gordon River Power Development Stage 1 is illustrated in Figure 5 and Appendix 2.

For river catchments of the West Coast region the major runoff-producing areas are the headwater sub-catchments (Watson, 1978a). This is a reflection of the predominatly north-south orientation of the prominent topographic features (Roberts and Naqvi 1978), and the prevailing westerly weather pattern. Annual rainfall increases progressively inland from about 1600 mm on the West Coast, and at the major mountain barrier increases rapidly to over 3000 mm (Watson, 1978b). The fluctuations in annual yields are small and the annual yield estimates for the period November 1931 to 1958 are very reliable.

Watson (1975) has shown that the magnitude of mean annual flood in the West Coast region varies with catchment area, mean annual runoff and centroidal lag. The tributaries of the Gordon River generally have a greater damping effect on their flood waves than does the main river. The natural basin of the Gordon River has been modified by two diversions:-

(a) Mt. Rufus and Mt. Arrowsmith diversion in 1968 resulted in 9.9 km^2 of the upper Franklin River catchment being diverted into the upper Derwent River system.

(b) Diversion of the upper Huon River at Scotts Peak in June 1972 resulted in the addition of 261 km^2 of the Huon catchment to the Gordon River Basin.

Recently the flow of the Gordon River below The Knob and the Serpentine River has been substantially altered by Stage 1 of the Gordon River Power Development. Ten per cent of the original catchment area has been inundated by the formation of Lakes Gordon and Pedder, which have provided sufficient storage to regulate the river downstream of these lakes. The lower Gordon River flow is therefore composed of discharge from the Gordon Power Station plus the uncontrolled pickup from the sub-catchments below the dam. The flow in the Franklin River is at present unaltered except for the minor diversion in its upper catchment.

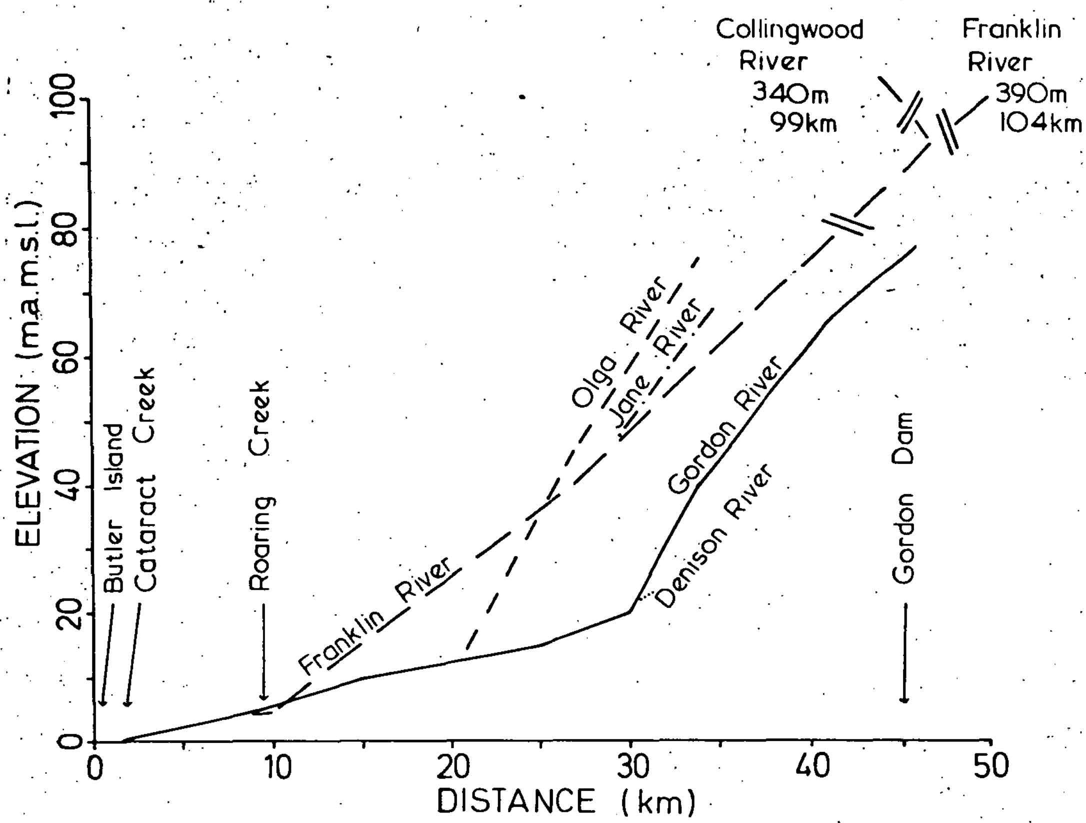


FIGURE 4

RIVER ELEVATIONS ALONG THE RIVERS UPSTREAM FROM BUTLER ISLAND.

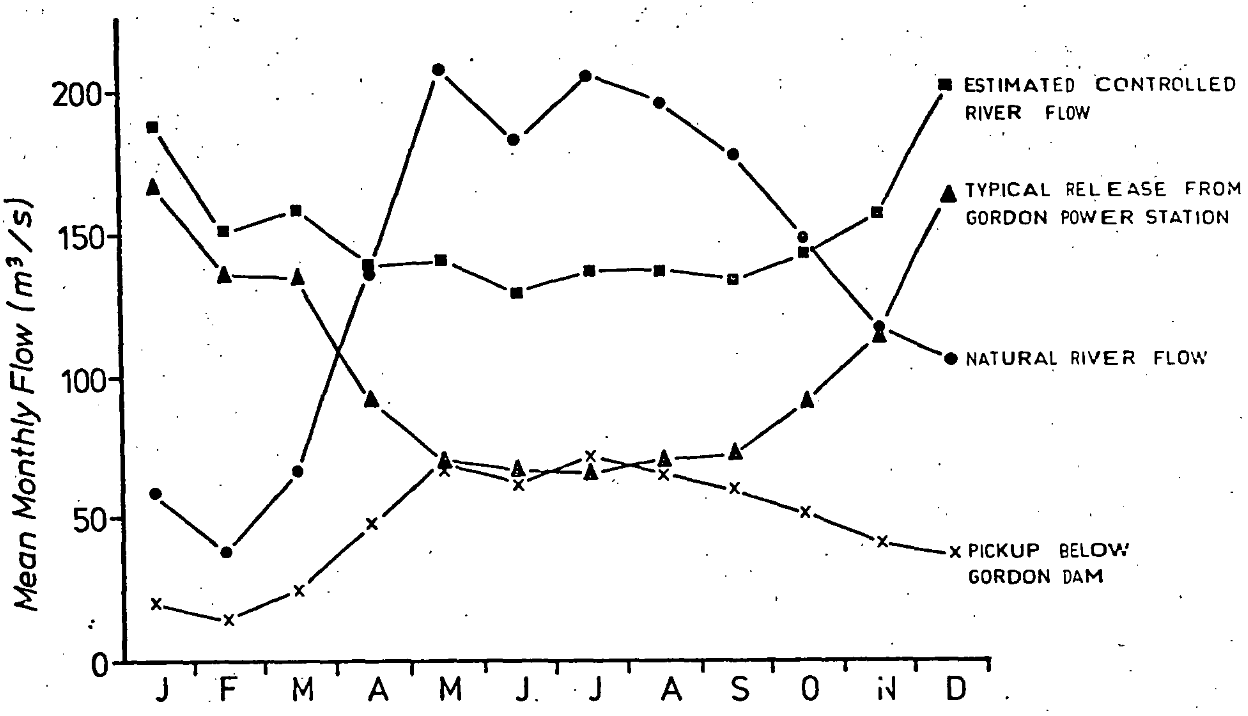


FIGURE 5

MEAN MONTHLY RIVER FLOWS BEFORE AND AFTER COMMISSIONING OF THE GORDON POWER STATION. (DATA FROM WATSON 1978a.)

TABLE 1

Hydrological Information for the Gordon River Basin Sub-catchments

(Extracted from Watson 1978a)

	Period of Record	Mean Annual Runoff (3111-5811) (mm)	Mean Annual Flood (m^3/s)	Centroidal Lag (hrs)	Physical Characteristics		
					Area (km^2)	Length (km)	Slope (m/km)
Gordon River Basin							
Gordon River below Huntley	1952-	1588	246	33	458	61	2.9
Gordon River above Knob	1964-1974	1505	414	31	1280	106	4.4
Gordon River above Olga (P.U.)	1968-	1788	-	20	909	90	3.79
Gordon River above Franklin (P.U.)	1958-	1769	-	22	1228	99	4.5
Huon River at Scotts Peak	1963-1972	1590	109	30	258	31	2.2
Serpentine River above Gordon	1961-1971	1930	121	63	457	55.2	0.6
Denison River above Gordon	1972-1975	1753	-	16	664	84	5.24
Franklin River at Fincham	1953-	2018	659	12	757	54.5	9.1
Franklin River below Jane	1957-	1988	1094	17	1590	102	5.7
Jane River at Punt Hill	1970-1974	1748	-	20	415	60	7.5

P.U. - Pick Up

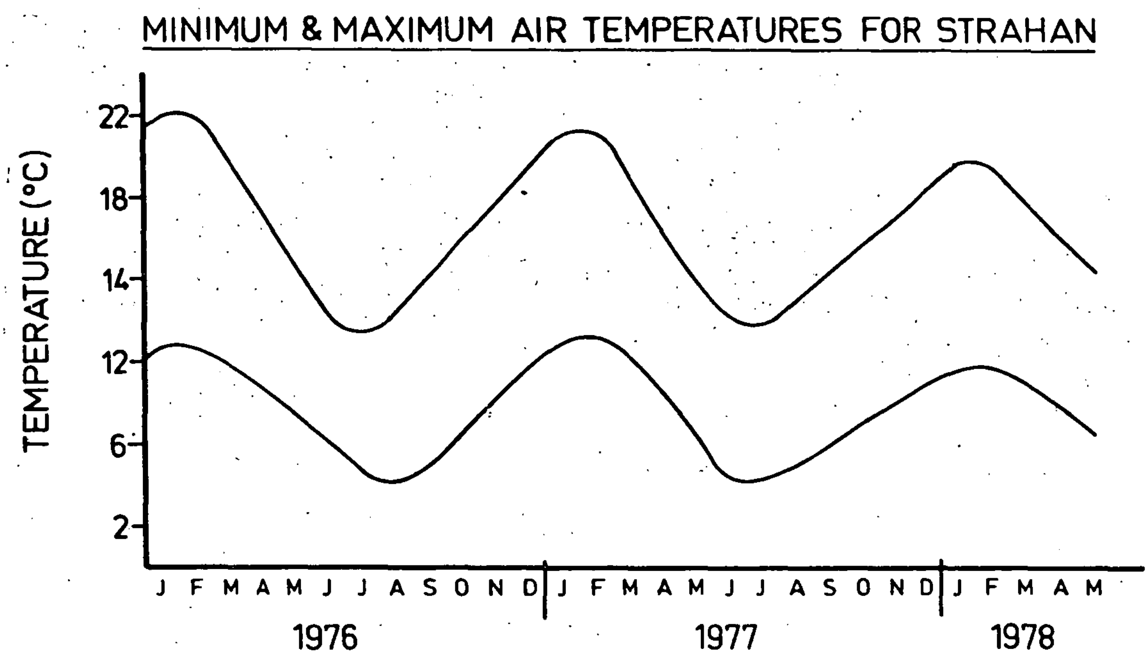
The projected operation of the power station will cause a reversal in the seasonal flow pattern in the Gordon River below the dam (Figure 5). The estimated mean monthly flows are changed from high mean winter flows to high mean summer flows. Already the mean monthly summer flows are only slightly lower than the natural mean monthly winter high flows. Generally to date, there has been a smoothing out of variations in average monthly flows, but this pattern will possibly vary as the system changes with future policy and requirements from the power station.

2.5 Climate

The climate of South West Tasmania has been reviewed by Bosworth (1978), Nunez (1978) and Faircloth (1978), and Watson (1978b) has described the climate of the Lower Gordon Scientific Survey study area. Graphs of various climatic parameters for Strahan and Strathgordon are illustrated in Figures 6A and B. The climate of the study area, classified as temperate maritime (Bureau of Meteorology, 1977), is influenced greatly by heat absorption and storage by the seas. This produces mild winters and cool summers. The West Coast area falls within the belt of the prevailing westerly winds.

The description of the climate which follows is for the general long term pattern which should not be confused with the specific data presented in Figures 6A and B.

During the winter (June - August) cold fronts cross Tasmania from the west, producing heavy rainfall and gale force winds. Rainfall is highest during the winter and increases eastwards as the westerly airstream experiences orographic lifting over the mountain ranges which lie at right angles to prevailing winds. The mean annual rainfall at Strahan is 1734 mm and for Strathgordon is 2628 mm. As spring (September - November) approaches there is a southward shift in the cyclonicity of the weather, causing the winds to blow more consistently from the south-west. The weather at this time is similar to winter conditions. Towards the end of spring there is a further southward progression in the paths of the cyclones and anti-cyclones, and summer (December - February) is characterised by a minimum in precipitation and cloud. Consequently the air temperature and number of sunshine hours increases, and the westerly winds weaken and become more variable, tending northerly. During autumn (March - May) the



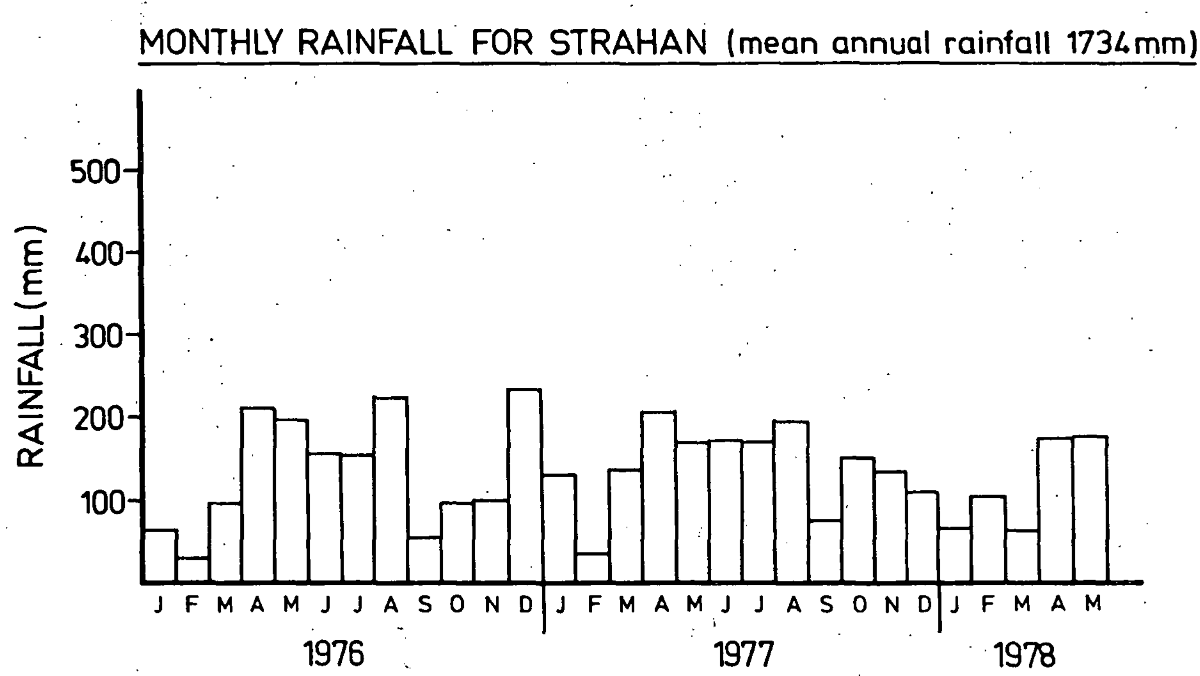


FIGURE 6A

CLIMATIC DATA FOR STRAHAN (BUREAU OF METEOROLOGY).

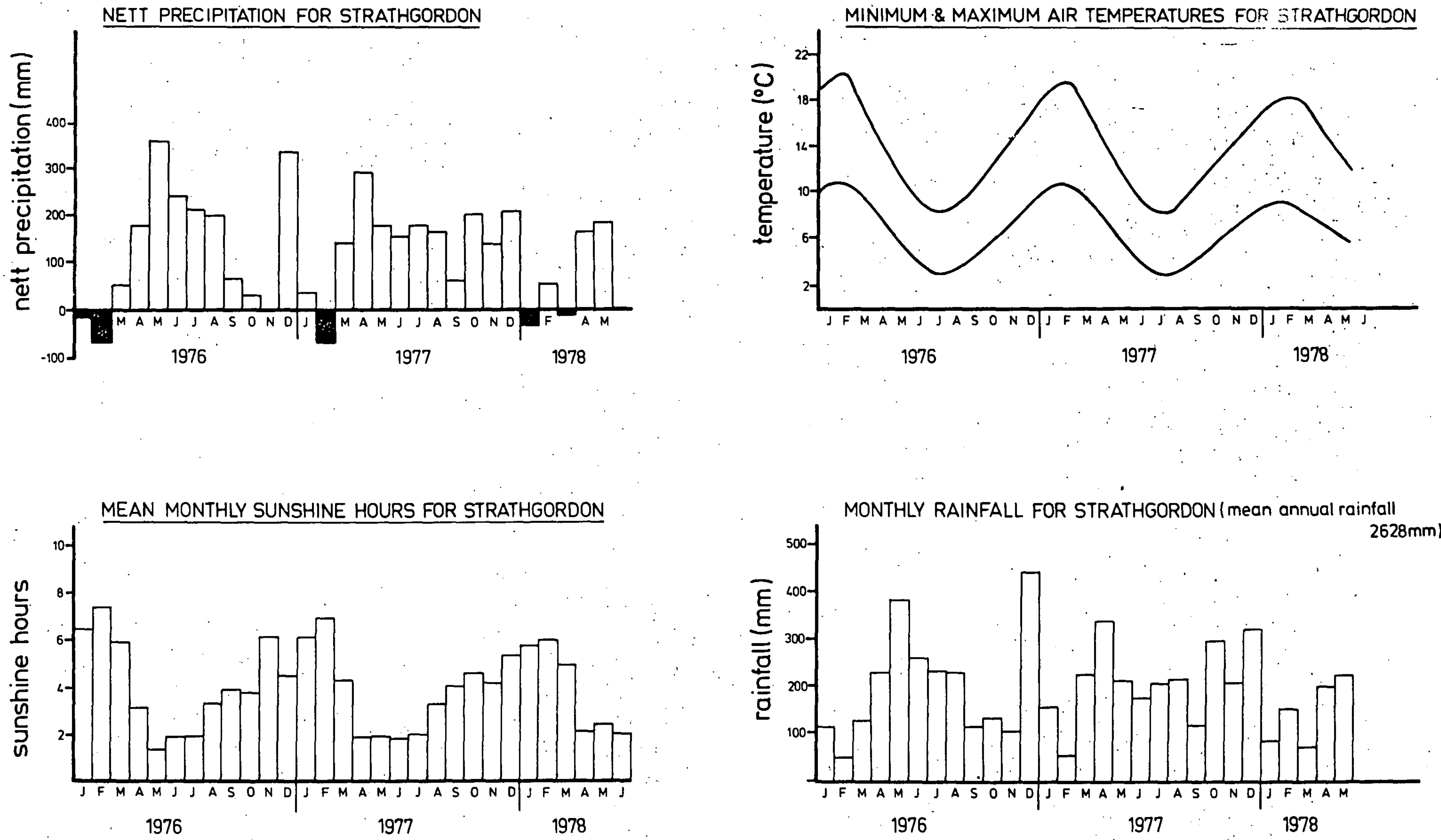


FIGURE 6B

CLIMATIC DATA FOR STRATHGORDON (BUREAU OF METEOROLOGY).

anticyclones tend to become stationary in the Tasman Sea, moist tropical air is adverted over the State and fair weather is experienced.

3.0 METHODS

Water sampling stations were selected to provide a representative picture of the variations in water quality throughout the drainage basin, and on the basis of accessibility. The stations were numbered according to the Australian Water Resources Council - Tasmanian Drainage System. Sampling sites were specified by grid co-ordinates in metres on the 1:100 000 map series prepared by the Lands Department, Tasmania.

Details of the river stations sampled and all water chemistry information in the Gordon River Basin are presented in King and H.E.C. 1978. Figure 7 shows the sites where stream flow was recorded (Hydro-Electric Commission gauging stations; Watson, 1978a), as well as recording stations for water temperature and chemical sampling sites.

3.1 Field Measurements

River flow and water temperatures were continuously recorded by the Hydro-Electric Commission using Stevens A35 water level recorders with thermograph attachment. The installation accuracy and reliability of this equipment is discussed in Watson (1978a). Only the locations of stations which produced reliable data have been illustrated in Figure 7. All available water temperature data, collected during the Lower Gordon Scientific Survey, are presented in H.E.C. et al. (1978), and King and H.E.C. (1978).

Flow has been estimated for all river stations by the Hydro-Electric Commission, Hydrology Section, as average daily flow on day of sampling. For sampling sites adjacent to established hydrological stations the flow estimates can be considered reliable. For other stations flow has been estimated pro rata from a measured catchment flow in the region of the catchment area basin. For small creeks and seeps the flow has been described as a "trickle". Water temperatures were recorded in the area from the Franklin River junction to Butler Island using standard mercury-filled maximum/minimum thermometers, installed on the 1st May 1976 at various sites (Figure 7). The thermometers were attached to timber staves and inserted into open-ended plastic pipes with additional holes to allow water to circulate freely. The plastic pipes were mounted in an inclined position on the river bank so that the thermometers would be below

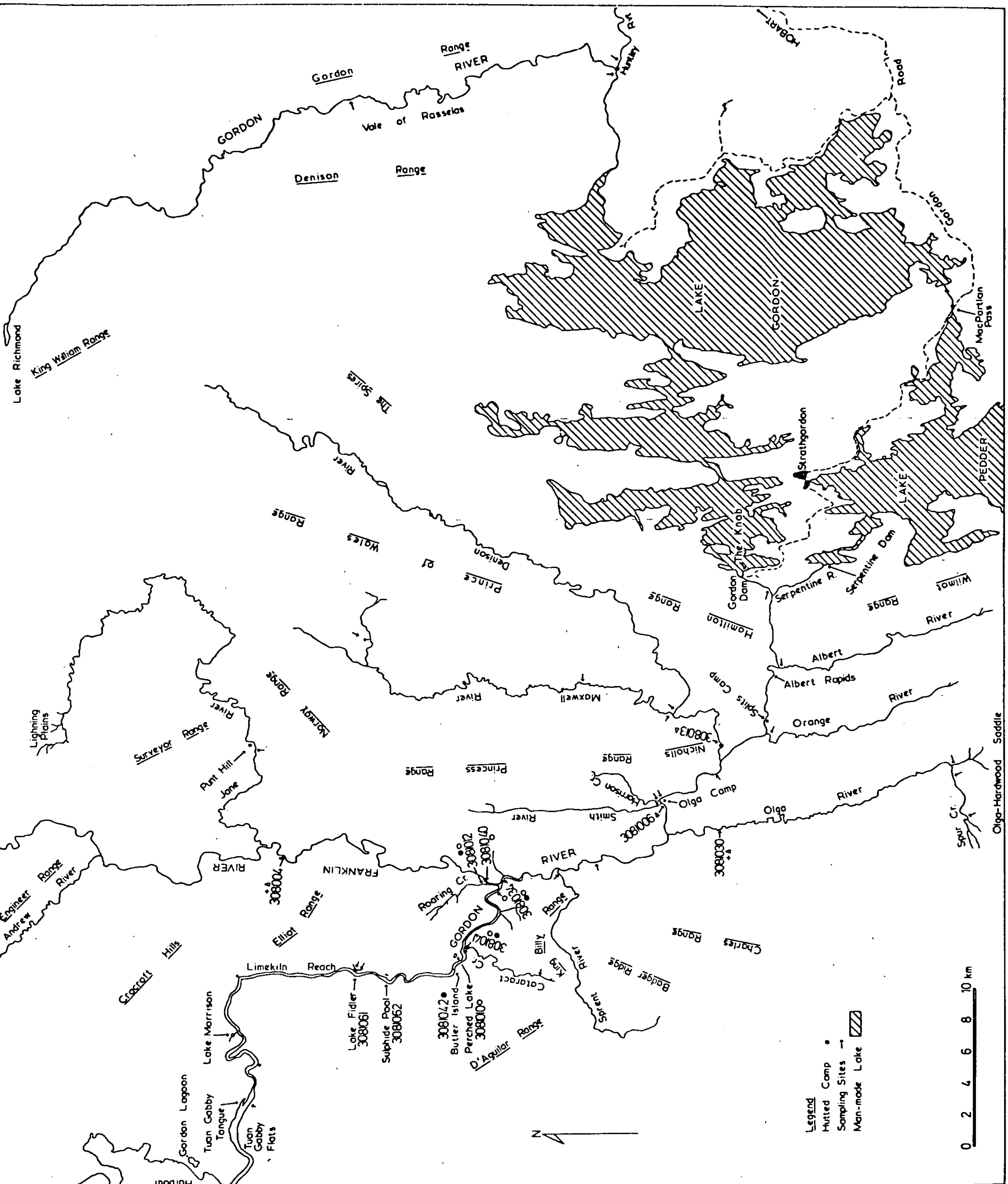


FIGURE 7

LOCATION OF SAMPLING SITES. INFORMATION COLLECTED AT EACH SITE IS AS FOLLOWS: WATER CHEMISTRY (●), MAXIMUM-MINIMUM WATER TEMPERATURES (○), WATER TEMPERATURE RECORDERS (+) AND RIVER FLOW (△). SAMPLING SITES INDICATED BY RESPECTIVE AUSTRALIAN WATER RESOURCES COUNCIL NUMBERS. (Details of sampling stations are in King and Hydro-Electric Commission [1978].)

expected minimum river level (H.E.C. et al. 1978). These thermometers measured littoral river temperatures, which are more extreme than main stream river temperatures.

Spot field water temperatures were measured at a large number of sites throughout the Gordon River Basin using standard $-0.5^{o}C$ to $+45^{o}C$ mercury thermometers.

Field pH was measured electrometrically with a portable Pye Unicam pH meter. The intensity of downwelling photosynthetically-active radiation (PAR) in the 400-700 nm waveband was determined using a Li Cor Li-185 quanta-meter combined with an underwater Li-192S quantum sensor. Underwater values were expressed as a % of incident values at the surface. The use of this instrument has been discussed by Kirk (1977).

3.2 Sampling

Water samples were collected by the Botany Department of the University of Tasmania and the Hydrology Section of the Hydro-Electric Commission. At some sites both collecting agencies obtained samples. All sample details and resultant analyses are arranged in chronological order for each station in King and H.E.C., 1978, and H.E.C. et al., 1978.

Samples for chemical analysis, obtained by immersing detergent or acid-washed bottles 10 cm under the surface of the water and filling them completely to avoid an air space above the sample, were kept as cool as possible before being delivered to the laboratory, where they were stored at $5^{o}C$ prior to analysis. There was a delay of a few days before delivering samples to the laboratory.

The frequency of sampling for the various stations fell into three categories:-

(a) Seasonal samples were collected at regular intervals between October 1976 and April 1978 at five river sites in the vicinity of the Franklin River Junction and Butler Island (Figure 7). Less frequent seasonal samples were collected from the upper Franklin and Collingwood Rivers on the Lyell Highway (Figure 8).

(b) A series of summer samples was collected at various sites along

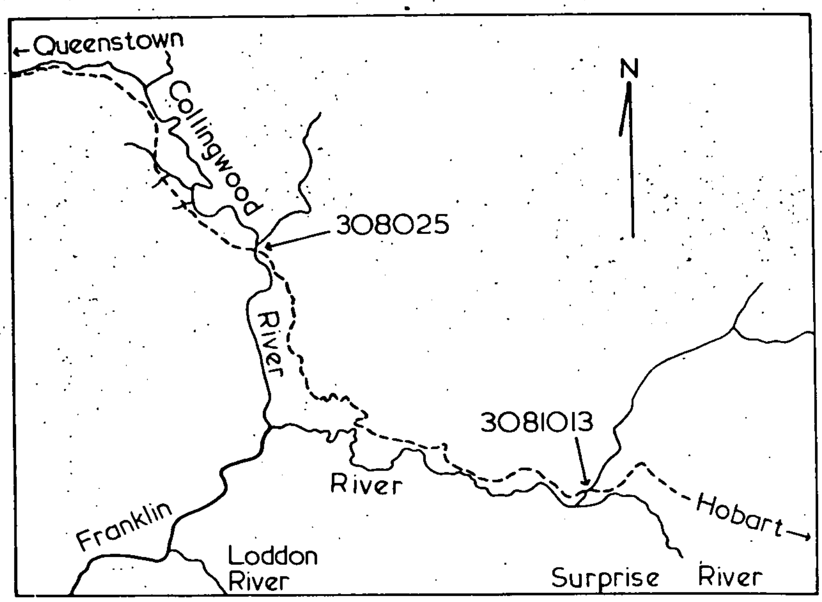


FIGURE 8

SAMPLING SITES ON THE UPPER FRANKLIN (3081013) AND COLLINGWOOD (308025) RIVERS.

the Gordon and Franklin rivers. These longitudinal profiles were normally collected over a two day period. Apart from the sampling sites mentioned in (a) above, access was by helicopter only. Occasionally weather conditions prohibited collection at some sites. From the 10th October 1977 the Hydro-Electric Commission began discharging water from the Gordon Dam power station, which resulted in much higher summer river levels and consequently the flooding of some helicopter landing sites.

(c) Occasional samples were collected at various sites through the Gordon River Basin. These sites were visited on a few occasions, or once only during the Lower Gordon River Scientific Survey.

3.3 Analysis

On their return to the laboratory, samples were immediately analysed for pH and alkalinity. For the latter, an end point of pH = 4.5 was used with 0.01N HCl on filtered samples (Golterman, 1967). Turbidity was measured with a Hach 2100 turbidimeter, which measures the amount of light scattered at right angles to an incident beam. Samples were filtered through 0.45 µm pore size discs. Conductivity was measured electrometrically at 18^{o}C and chloride by conductimetric titration with silver nitrate (Golterman, 1967). Sulphate was determined turbidimetrically by precipitation with barium chloride. This method may not be very accurate for low concentrations of sulphate, particularly in the presence of organic matter (colour) (American Public Health Association, 1971). Other methods for sulphate are also difficult in coloured waters (Cronan, 1979). Though sulphate values reported here may be underestimates it is unlikely that they are vastly greater than the concentrations quoted, and unlikely to affect consideration of ionic proportions. Calcium concentrations were measured colorimetrically using Glyoxal bis (2-hydroxyanil) (Kerr, 1960), magnesium, sodium and potassium by atomic absorption spectroscopy, and silica as "molybdate reactive silica" using the molybdate yellow method (American Public Health Association, 1971).

The colour of the river waters was measured on filtered samples in Hazen Units (Pt units) with a Lovibond colour comparator. The absorbance of river water (= dissolved organic matter) or gilvin - see King and Tyler, 1978a) was determined in 40 mm cuvettes, and calculated for a 1 m path length (Kirk, 1976). Salinity was calculated as the sum of the major ion concentrations in mg/l. Total concentration, as defined by Buckney (1976b), was calculated by summing the cations in equivalent units.

4.0 TEMPERATURE

Continuous seasonal recordings of air temperature for Strahan and Strathgordon, and water temperatures for the Franklin River below Jane River (308004) and for the Olga River 4 km from the mouth (3081030) are presented in Figure 9. Maximum/minimum temperatures for four river sites and for Perched Lake are presented in Figure 10. Figure 11 illustrates the difference in temperature (maximum - minimum) for these river stations.

Seasonal temperatures recorded from the upper Franklin River and Collingwood River at crossovers on the Lyell Highway are illustrated in Figure 12, and summer spot temperatures from the Gordon River catchment in Table 2. Temperature stratification in relation to the under-cutting saline water is illustrated in Figure 13 for the Gordon River downstream from Butler Island, and at Tuan Gabby Tongue in Figure 14. Temperature variation along the Gordon River from the Gordon Dam to Butler Island measured on four occasions is shown in Figure 15.

4.1 Seasonal Variation

4.1.1 Uncontrolled Rivers

Temperature variations of the Franklin and Olga Rivers showed a direct relationship with mean air temperatures at Strahan and Strathgordon (Figure 9). Air temperature was obviously a major factor affecting temperature of uncontrolled rivers. The mean monthly maximum temperature for Strahan is higher than that for Strathgordon, due to the elevation and cooling effect of the orographic uplifting of the westerly airstream at the latter (altitude = 366 m). At both river stations maximum temperatures were recorded between December - February (13.3°C to 18.3°C) and minimum temperatures in July - August (5.0°C to 8.9°C).

The difference between maximum and minimum river temperatures was greater in summer months than in winter months (Figure 9). Maximum and minimum temperatures of Cataract Creek (Sir John Falls), Roaring Creek and, for comparison, the littoral zone of Perched Lake (Station M220, see King and Tyler 1978a) are shown in Figure 10. The seasonal variation is similar in pattern to that of the Franklin and Olga Rivers.

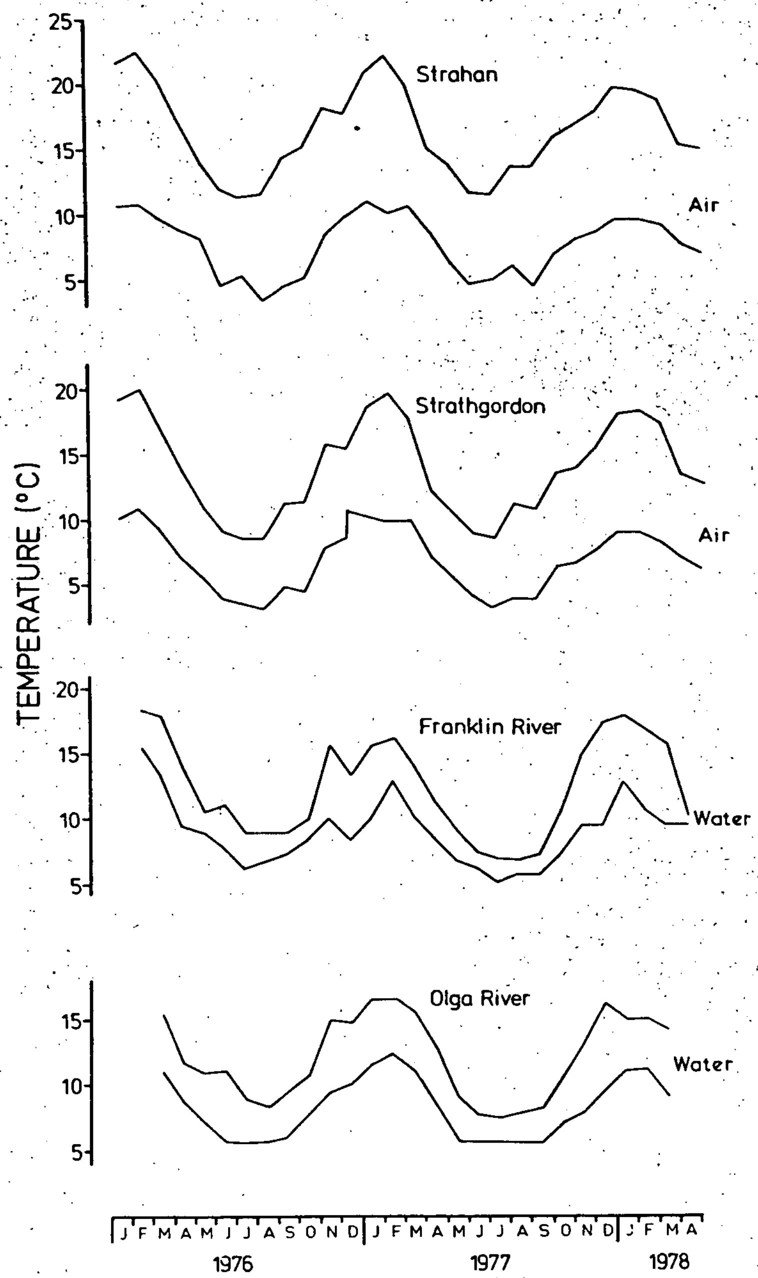


FIGURE 9

SEASONAL VARIATION OF MONTHLY MEANS OF DAILY MAXIMUM AND MINIMUM AIR TEMPERATURES FOR STRAHAN AND STRATHGORDON, AND OF EXTREMES OF MAXIMUM AND MINIMUM WATER TEMPERATURE RECORDED EACH MONTH IN THE FRANKLIN RIVER BELOW THE JANE RIVER (308004) AND IN THE OLGA RIVER 4 KM FROM ITS MOUTH (3081030). (AIR TEMPERATURE RECORDS FROM BUREAU OF METEOROLOGY.) (WATER TEMPERATURES FROM HEC ET AL 1978)

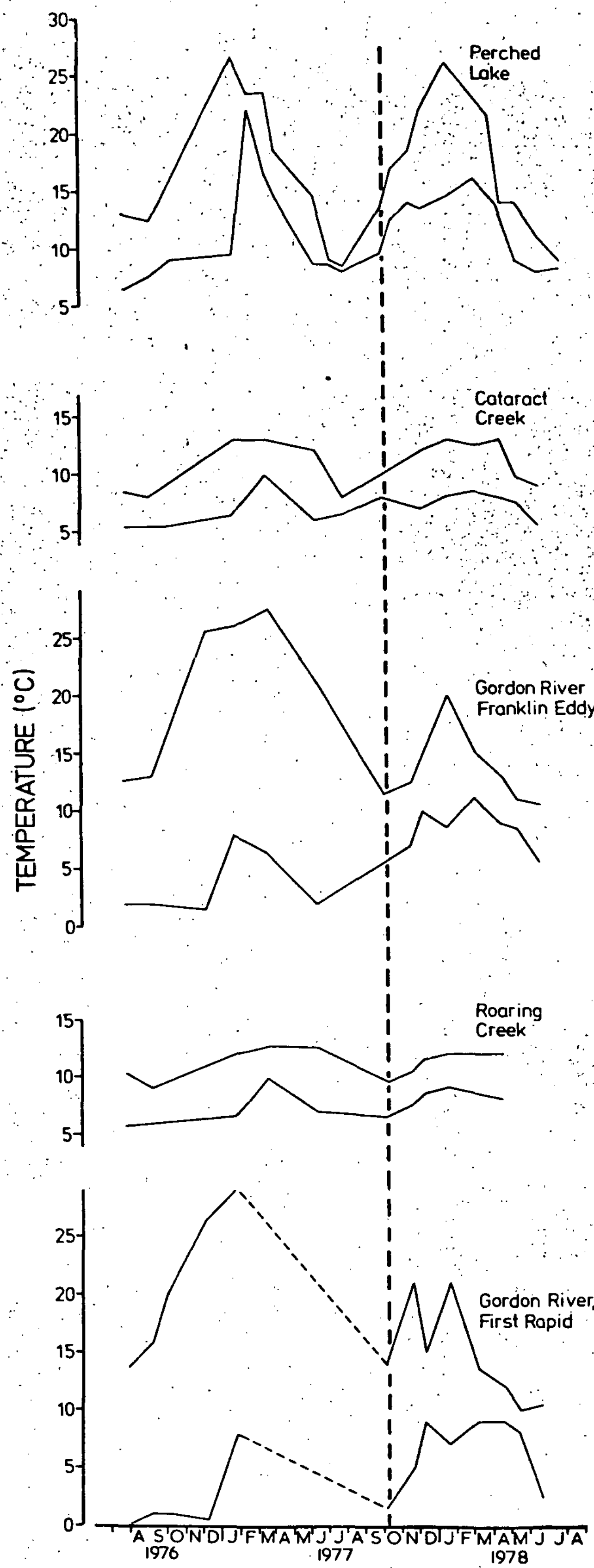


FIGURE 10

MAXIMUM AND MINIMUM RIVER TEMPERATURES. PERCHED LAKE IS INCLUDED FOR COMPARISON. VERTICAL BROKEN LINE (¦) INDICATES WHEN POWER STATION FIRST COMMENCED DISCHARGE.

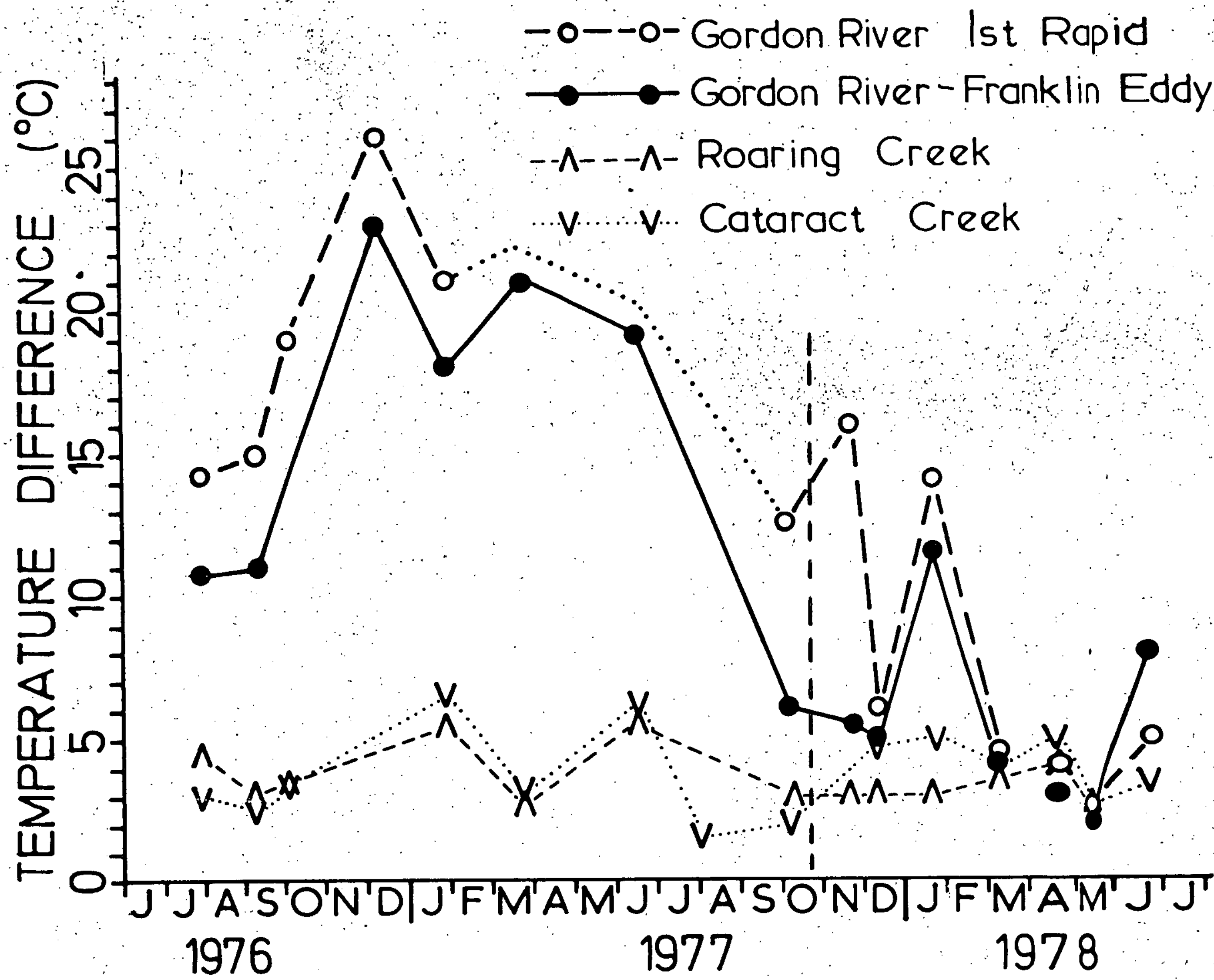


FIGURE 11

RANGE OF DIFFERENCE (°C) BETWEEN MAXIMUM AND MINIMUM TEMPERATURES IN THE LOWER GORDON RIVER AREA. VERTICAL BROKEN LINE MARKS THE DATE WHEN WATER WAS FIRST DISCHARGED FROM LAKE GORDON. (DATA FROM HYDRO-ELECTRIC COMMISSION, KING AND COLEMAN 1979.)

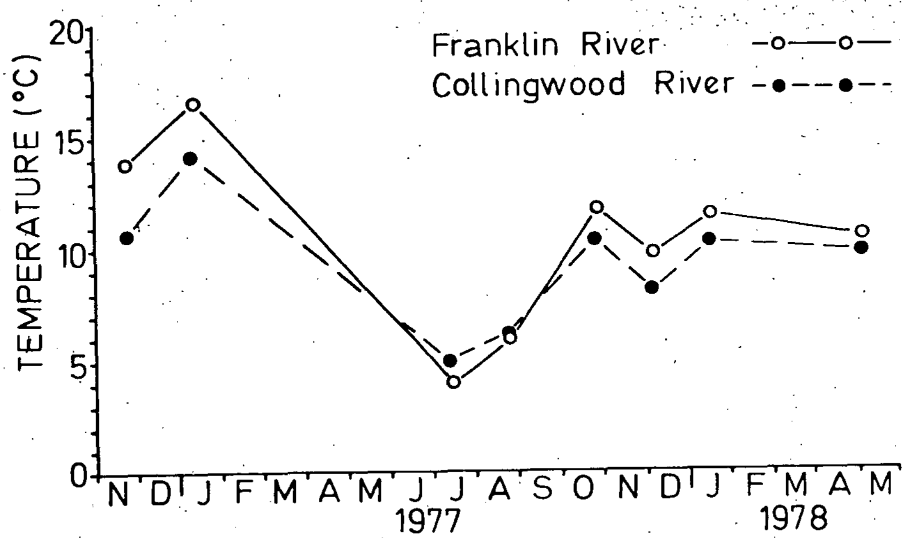


FIGURE 12

TEMPERATURES IN THE UPPER FRANKLIN RIVER (3081013) AND COLLINGWOOD RIVER (308025).

TABLE 2

Summer River Temperatures for the Gordon River Basin
Spot Measurements were made from Late Spring to Early Autumn

	Distance from Butler Island	TIME						
		23-24.11.76	12.1.77	22-23.11.77	15.12.77	15.2.78	13.3.78	3.4.78
Franklin River								
Jane River	27 km	12.7	-	10.3	-	-	-	-
Shingle Island	10	11.7	16.0	10.1	14.8	13.6	16.5	10.2
Roaring Creek	10	10.8	12.0	8.5	10.9	11.0	12.1	9.1
Jane River								
Punt Hill	35	11.6	-	-	-	-	-	-
Olga River								
Upstream Gordon	27	11.7	-	11.1	-	-	15.0	-
Hardwood Saddle	34	14.3	16.5	16.4	-	-	16.5	-
Denison River								
Denison Camp	31	12.2	15.5	10.2	-	-	15.5	-
Gordon River								
Albert Rapids	41	11.0	14.6	8.7	-	-	10.1	-
Splits Camp	34	13.9	16.0	9.0	-	-	10.7	-
Smith River	25	12.8	18.0	9.9	-	-	-	-
Sprent River	15	13.7	-	9.2	-	-	11.4	-
Franklin River	9	11.9	16.0	9.6	11.8	10.9	11.5	10.0
Butler Island	1	11.8	15.3	9.9	13.0	11.5	11.7	10.0
Cataract Creek	2	10.8	-	9.8	11.1	11.4	12.6	-
	Mean	12.2	15.5	10.2	12.3	11.7	13.1	9.8

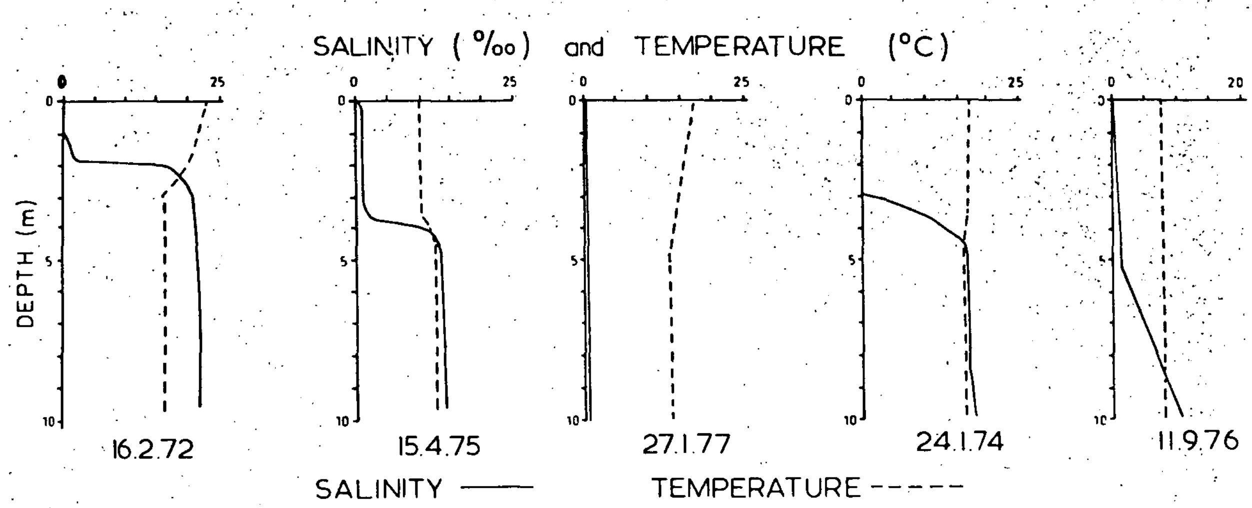


FIGURE 13

TEMPERATURE AND SALINITY PROFILES IN THE GORDON RIVER MEASURED IMMEDIATELY DOWNSTREAM FROM BUTLER ISLAND. (Redrawn from Kearsley 1978.)

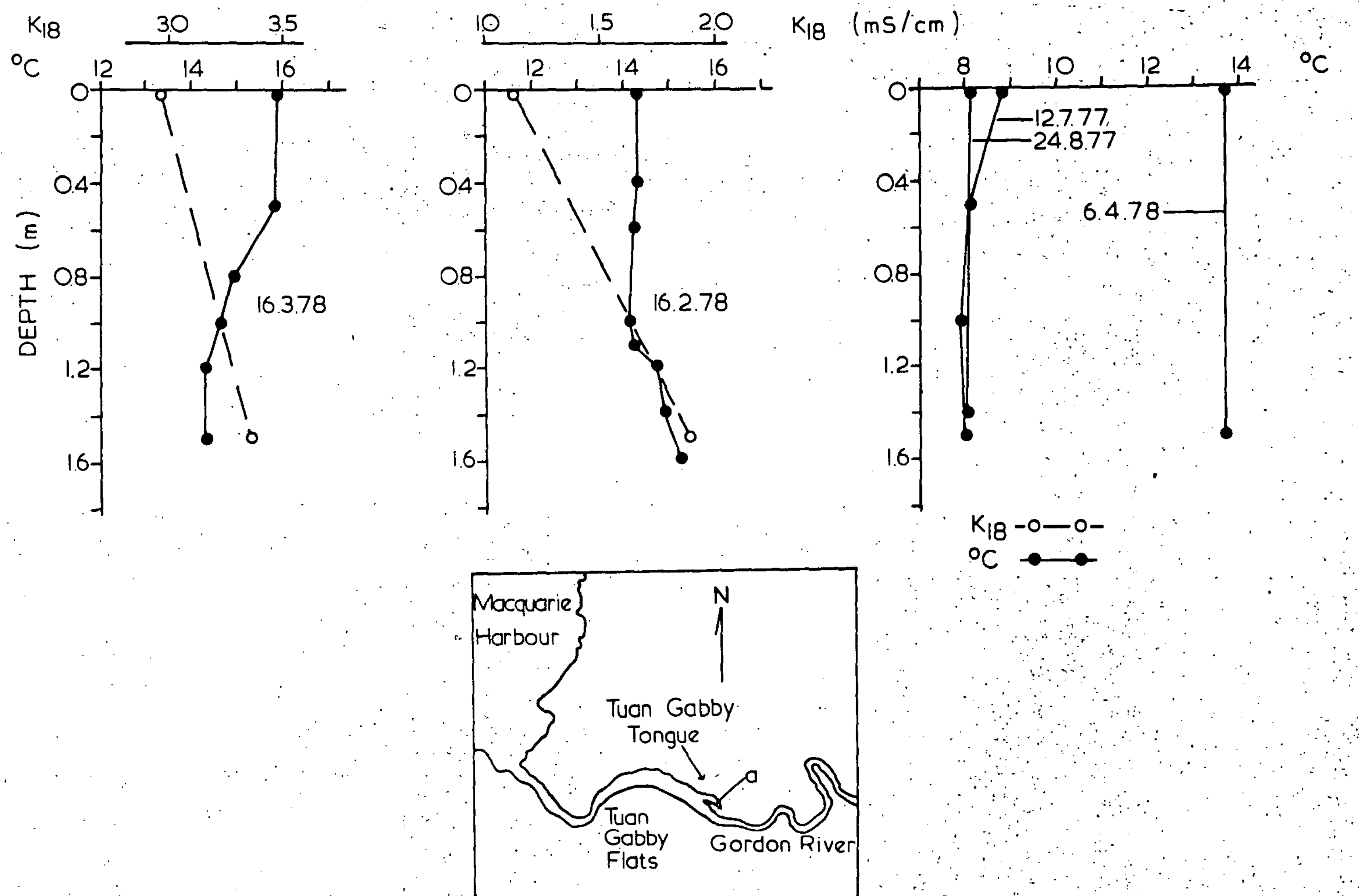


FIGURE 14

TEMPERATURE AND CONDUCTIVITY PROFILES IN TUAN GABBY TONGUE (a).

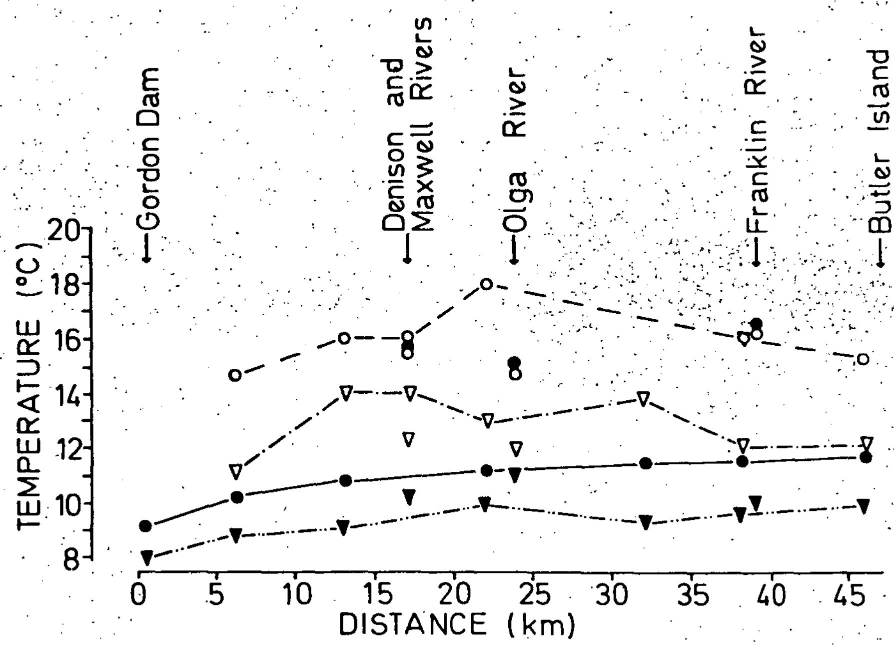


FIGURE 15

TEMPERATURES ALONG THE GORDON RIVER FROM THE GORDON DAM TO BUTLER ISLAND, MEASURED ON 24.11.76 (○- - ○), 23.11.77 (▽—·—▽) AND ON THE 12.1.77 (▼—··—▼) AND 13.3.78 (●——●). TEMPERATURES OF SOME TRIBUTARY RIVERS ARE SHOWN FOR COMPARISON. (DATA FOR LAKE GORDON FROM STEANE AND TYLER [1978].)

4.1.2 Effects of the Gordon Dam on River Temperatures

The spot water temperatures for the Gordon River presented in H.E.C. et. al. (1978) (see also Table 2) are considered insufficient to assess the effect on river temperatures of the release of water from Lake Gordon (see Section 6.2).

Unfortunately, data from the maximum/minimum thermometers (Figure 11) are not un-equivocal. While apparently showing a reduction in water temperature variations after the power station commenced operating, the values of the difference between maximum and minimum temperatures before October 1977 are extraordinarily high. For December 1976 temperature differences of 26°C and 24°C were recorded for two stations in the Gordon River (Figure 11). The corresponding maxima and minima for that month were 26.5°C and 0.5°C, and 25.5°C and 1.5°C, respectively. While snow melt from headwater mountains is possible at mid-summer it is most unlikely that the effect would be felt below the Gordon Dam (see Steane and Tyler, 1978), and we must suspect the low minima at that time. From comparisons of the maxima with those for Cataract Creek, Roaring Creek, the littoral of Perched Lake (Figure 10), and the upper reaches of the Franklin (Figure 12), it seems unlikely that the data of Figure 11 before October 1977 are those of a large, flowing body of water.

The results of this survey do not clearly demonstrate the effects of the Gordon Dam on downstream river temperatures. However, the likely effect of continuous operation of the power station would be to produce the conditions of March - July 1978 (Figure 11), with river temperatures at a relatively invariable, low level similar to that of the discharge stratum of Lake Gordon (Steane and Tyler, 1978; see also Walker et al, 1978). Conversely, intermittent operation of the power station would allow capricious and wide fluctuations of temperature downstream, and, to some extent, this is illustrated by the data from November 1977 onwards (Figure 11).

4.1.3 The Upper Franklin River

Water temperatures for the headwaters of the Franklin River are shown in Figure 12. Maximum and minimum recorded temperatures were 14.2°C and 5.0°C for the Collingwood River, and 16.6°C and 4.0°C for the Franklin. These temperatures were spot measurements and may not indicate the true seasonal extremes. The variability of the South West's climate is apparent from a comparison of summer maxima for 1976/77 and 1977/78 respectively.

During the winter, snowmelt water enters the Franklin River rendering it colder than the Collingwood. The latter may be fed with a small amount of snow melt water but, because of its lower altitude and the insulating effect of the catchment vegetation, remained about 1.8^{o}C warmer than the Franklin.

4.2 Stratification

4.2.1 Salt Wedge

Temperature stratification is not a common phenomenon in rivers because of their turbulent flow (Hynes, 1970). Shadin (quoted in Hynes 1972) states that in rivers deeper than 15 m there should be some slight difference between top and bottom temperatures. The lower Gordon River exhibited well stratified temperature profiles, which were coincident with a layer of dense salt water (salinity about 20-25^{o}/oo) which intrudes up the river from Macquarie Harbour during high tides and moderate to low river flows. This transient "wedge" can extend up as far as the Franklin Rocks, about 48 km from the river mouth (Kearsley, 1978).

When there is a sharp increase in salinity with depth in the river, there is often associated with it a temperature change at the interface between fresh and salt water.

Figure 13 illustrates some of the temperature and salinity profiles measured by Kearsley (1978). When the salt "wedge" is present, there may be a negative (16/2/72) or positive (15/4/75) temperature discontinuity at the interface between salt and fresh water. On other occasions a slight temperature gradient may exist in the absence of a pronounced salinity gradient, (27/1/77) or the temperature gradient may be negligible despite a pronounced salinity gradient (24/1/74 and 11/9/76). The nature of the profiles obviously depends on the temperatures of the overflowing and intruding waters, respectively, at the time of measurement. Floods in the river flush out the salt "wedge" and it has not been recorded during high flow periods of winter. The constant high flows since operation of the Gordon Power Station have prevented intrusion of the saline water since October 1977 (Watson, 1978a).

4.2.2 Tuan Gabby Tongue

Tuan Gabby Tongue, situated opposite Tuan Gabby Flats about 6 km upstream from the mouth of the Gordon River (Figure 14) is a sheltered inlet bordered by a levee bank of silt deposited by the Gordon River. A shallow sand bar across the mouth is sparsely colonised by Eleocharis sphacelata R.Br. and Triglochin procera R. Br. in water less than 1 m deep at low tide (Plates 9 and 10). Continuing siltation and increased colonisation by the macrophytes at the mouth of Taun Gabby Tongue would result in the formation of a levee lake. Lake Morrison, Lake Fidler and Sulphide Pool, 14 km, 25 km and 27.5 km respectively from the mouth of the Gordon River, are levee lakes probably formed in this way. All three are meromictic and show pronounced physico-chemical stratification (King and Tyler 1978b).

Temperature profiles and conductivity of surface and 1.5 m water were measured in the upstream section of Tuan Gabby Tongue (Figure 14). The overall temperature of this water body varied with the seasons, with coldest temperatures recorded in midwinter (c.8.0^{o}C), and maxima in mid-summer (c.16.0^{o}C). The thermal pattern was very dependent upon weather. Several calm, hot days during the summer heated surface waters and stratification persisted because of the increase in salinity with depth (Figure 14, 16/3/78). However, during poor weather the surface waters cooled and the profile became isothermal (Figure 14, 6/4/78). Isothermy, however, does not preclude the existence of a salinity gradient. When poor weather continued, surface waters continued cooling to produce inverse stratification (Figure 14, 16/2/78).

This is possible because bottom waters are more saline and more dense, and inhibit vertical mixing. During the colder periods of the year the water profile was isothermal, but slight surface diurnal heating and cooling occurred (Figure 14, 1977).

Thermal stratification is a transient feature in Tuan Gabby Tongue but chemical stratification would probably be evident most of the year because of the tidal effect. Estuarine water could repeatedly intrude, to be overlain by seepage and rainwater, so producing a density layering.

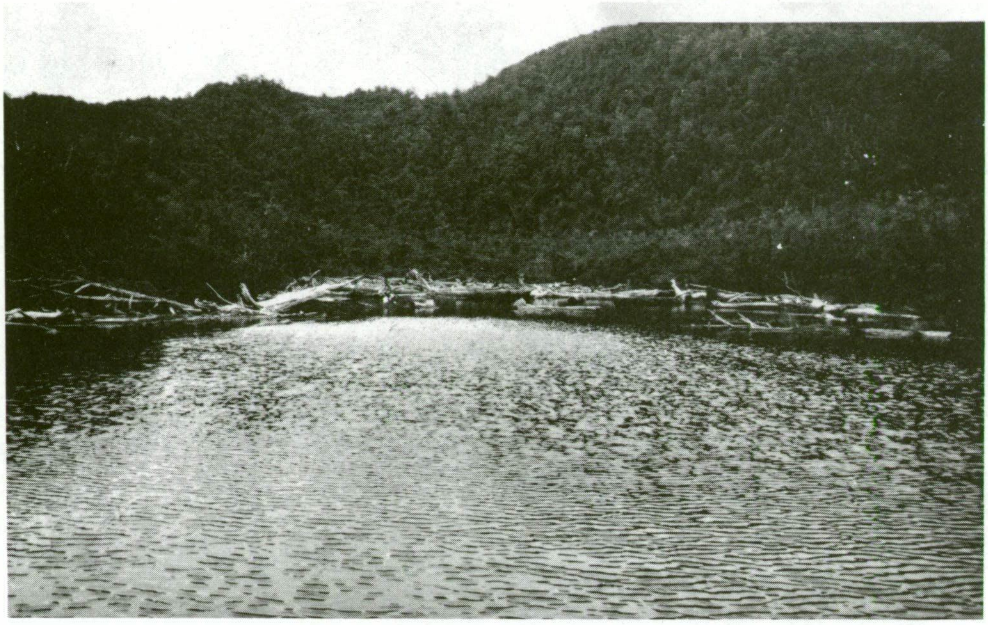


Plate 9
Tuan Gabby Tongue, upstream site.

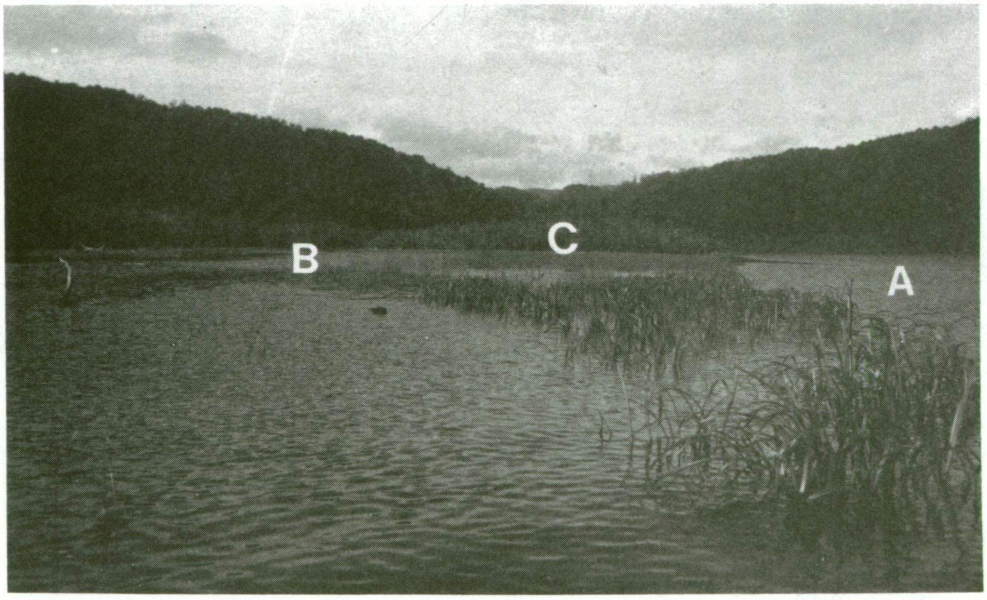


Plate 10
Gordon River at Tuan Gabby Flats (A). Tuan Gabby Tongue (B) is partially separated from the Gordon River by the levee bank (C), and the shallow zone is colonized by *Triglochin procera* (foreground) and *Baumea rubiginosa.*

However, because of its shallowness and the severity of westerly winds, vertical mixing could also occur, weakening this chemical stratification. The relatively high conductivity values (Figure 14) of surface water, compared with upstream reaches (Figure 23) indicates some mixing with underlying saline waters (see also Section 6.2). The intensity of the salinity gradient at any given time would depend on river flow, seepage and rainfall, and the height of the tides. It is likely that in the winter, when rainfall (and hence river flow) are high (Watson, 1978a), salinity gradients would be low. In summer when rainfall and river flow are low, they would be high.

4.3 Longitudinal Variation

Water temperature varies along the lengths of river valleys. For European streams, Eckel (1953) and Schmitz (1961) claim that summer temperatures increase downstream such that the rise is more or less proportional to the logarithm of the distance from the source. The temperature along the Gordon River undergoes some changes caused by contact with the air and rocks and mixing with the tributaries, but more recently it has been significantly altered by the altered flow regime consequent upon the release of water from the Gordon Power Station (Figure 5 and 11). Lack of access to the sampling stations between the Franklin junction and the Gordon Dam prevented temperature measurements being made during the winter but Figure 15 presents four horizontal profiles of temperature during the summer.

The effect of the construction of the Gordon Dam and subsequent power station release on the flow of the Gordon River is illustrated in Figure 5.

The mean monthly flows for May recorded at Olga have been reduced from 208 $m^3\ s^{-1}$ (uncontrolled flow) to 141 $m^3\ s^{-1}$ after construction of the Gordon Dam, with two turbines in operation at the power station (Watson, 1978a). The monthly mean summer flows have been increased from 38 $m^3\ s^{-1}$ to 151 $m^3\ s^{-1}$(for February). This means that the flow patterns have been reversed, from low summer and high winter flows to high summer and moderate winter flows.

The Gordon Power Station began releasing Lake Gordon water on

October 10th, 1977 and its effects on temperatures in the Gordon River are shown by comparing measurements from similar seasons in different years, i.e. compare data for 23nd November 1976 with 22nd November 1977, and compare 12th January 1977 with 13th March 1978 (Figure 15).

Before release of dam water, summer temperatures rose above 16^{o}C, and varied by about 4^{o}C along the 46 km length of the river from the dam to Butler Island (Figure 15). Most probably similar temperature variations occurred from mainstream to littoral, in accordance with the nature of the bed, weather, degree of shading, and tributary temperatures.

In November 1976, when the temperature of the Denison/Maxwell Rivers entering the Gordon was close to that of the Gordon itself, the temperature of the Gordon rose in the reach between the Denison and Olga Junctions. Entry of the Olga at a significantly lower temperature apparently caused a drop in temperature (Figure 15). In January 1977 entry of colder Denison/Maxwell water apparently caused the drop in main river temperature observed before the Olga. The subsequent temperature rise, despite the influx of colder Olga water, and then the drop after the 32 km station (Figure 15) cannot be explained from available data. What is apparent is that before release of dam water the temperature at points along the river varied significantly, influenced by the temperature of inflowing tributaries and, apparently, also by conditions in the intervening reaches.

This is in marked contrast to conditions after release of Lake Gordon water commenced. First, summer temperatures were then considerably lower (Figure 15), and varied less (by about 2.5^{o}C) along the length. The temperature of inflows had little effect on main river temperature. In November 1977 and March 1978 the overall trend was a gradual rise from the low temperatures of the release stratum (Steane and Tyler 1978) of Lake Gordon, the considerably higher temperatures of the Denison/ Maxwell, Olga and Franklin inflows in March 1978 (Figure 15) not producing marked changes. It is apparent that the temperature of Lake Gordon water was then the major factor controlling the river temperature.

5.0 FACTORS AFFECTING LIGHT PENETRATION INTO THE GORDON RIVER

5.1 General

Light is almost always a factor limiting primary production in rivers. The irradience incident upon the water surface is significantly affected by the solar altitude; Steane (1979) has calculated that the vertical attenuation coefficient, in a non-scattering medium, can increase by 27% when the solar altitude decreases from 70^{o} to 30^{o}.

Of the radiation incident upon the river, some is lost by reflection from the water surface itself, and to a lesser extent by back-scattering from suspended particles in the water and bubbles on the surface (Jerlov, 1976, and Strickland, 1958). Depending upon weather conditions, solar altitude and wave length, surface losses can vary from a few percent to over 30% (Jerlov, 1976, Strickland, 1958, and Talling, 1957).

Mountainous terrain and river gorges restrict radiation striking the water surface (Plate 1), particularly when the solar altitude is low. Mists and valley fogs which lie in these deep valleys can further reduce available light (Plate 11). River bank vegetation also significantly reduces light in the littoral zones of rivers (Mann _et al_ 1972, cited in Westlake 1975) and smaller rivers and creeks under thicker tree cover or completely roofed over (Plates 3 and 12) will have incident radiation further reduced (Westlake 1966, Westlake and Dawson 1975).

The principle causes of attenuation of light in rivers are water itself, dissolved organic material, and suspended particles. Rivers generally contain a sparse phytoplankton, so that light absorption by algae is insignificant. Strickland (1958) suggests that absorption of light by pure water is small, particularly in the shortwave region of photosynthetically active radiation (PAR spectrum) (Hulbert 1945), but increases towards the long wave region (Sullivan 1963). Absorption increases very rapidly above 700 nm. In the Gordon River, the absorption of light by the water itself is insignificant compared with the overriding effect of high concentrations of dissolved organic material. This significantly absorbs the downward quantum irradiance, over very shallow depths, throughout the PAR spectrum, but mainly in the short wavelength region (King and Tyler, 1978a).

Plate 11
Morning mist in the Gordon River valley restricting light falling on to the surface of the river.

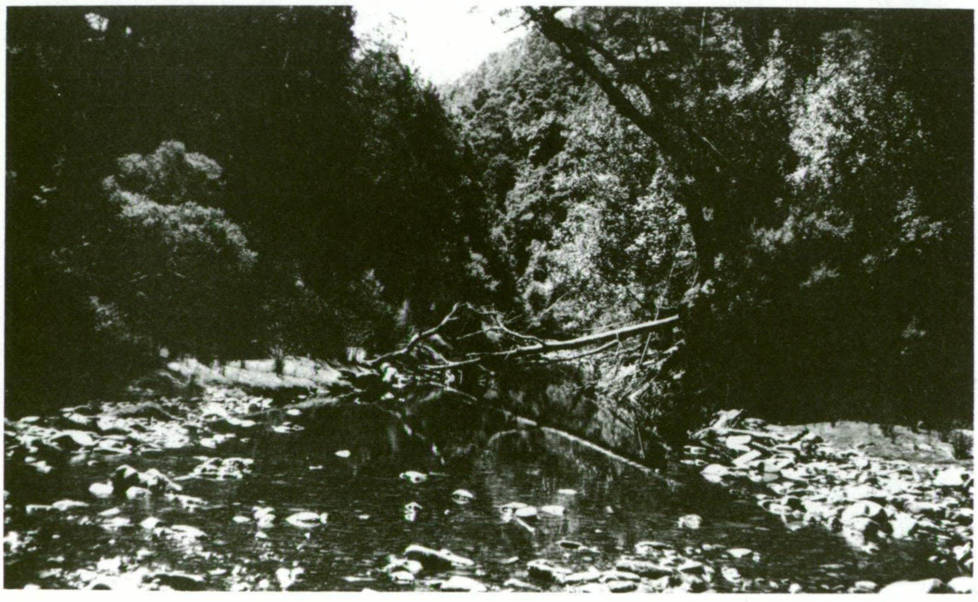


Plate 12
Harrison Creek, 2.5 km upstream from the Olga River junction in January 1977.

The major factors, therefore, which are likely to influence the light climate in the rivers of the Gordon River Basin are shading by riparian vegetation and cliffs, suspended particles and dissolved organic material.

5.2 Riparian Vegetation

The riparian vegetation of the Gordon River, unlike that of many rivers in the world, is almost unaltered by man. It is an evergreen, temperate rainforest dominated by *Nothofagus cunninghamii* (Jarman and Crowden, 1978), and, in contrast to the deciduous vegetation of northern hemisphere rivers, shades the river banks heavily throughout the year (Plates 3,4,6 and 8). River shading by deciduous vegetation reduces incident radiation by 35 - 95% (Owens and Edwards 1961; Westlake and Dawson 1975), depending on the leaf development of the trees. This is one reason for low submerged macrophyte productivity in rivers (Westlake 1966).

Large rivers are shaded mostly along their banks, but small rivers and creeks may be completely roofed over (Plates 4 and 12). Figure 16 shows how riparian vegetation shades the Olga River 4 km upstream from the Gordon (Plate 3). Quantum irradiance was greatest in midstream where the canopy was open and decreased markedly towards the banks where dense forest reduced light to very low levels. This shading of river banks has a significant effect on large, deep rivers because plankton was scarce or absent and primary production was restricted to the narrow littoral zone along the banks, or to shallow riffle zones. The steep sides of river gorges along much of the Gordon's length, by shading the banks, also reduce light availability and therefore the annual budget of photosynthesis.

5.3 Turbidity

Running waters are generally more turbid than standing waters and high turbidity is usual for rivers (Hynes, 1970), particularly during floods. Walker and Hillman (1977) recorded greatly increased turbidity in the Murray River in the aftermath of heavy rains. Generally, in contrast to mainland Australia, Tasmanian rivers carry only small particulate loads. Buckney (1974) reported turbidity values for the Derwent River ranging between 0.52 and 12.0 F.T.U. This river has several man-made lakes along its course and intense agricultural activity in the lower catchment, but still has low turbidity. However, rivers with mining activities in their catchments are more turbid. Turbidity in the South Esk River, which is fed by mine effluents, ranges between 1.2 and 410.0 F.T.U., with high turbidities occurring when rainfall is high (Tyler and Buckney, 1973).

Turbidity in the Gordon River system is low, ranging from 0.35 to 4.8 F.T.U. (Figure 17). If construction of the Gordon Dam caused localised turbidity, it is no longer evident. Logging causes some soil erosion around Lake Gordon during periods of high rainfall (personal observation), but the suspended material does not reach the offtake of Gordon Dam (Steane, pers. comm.), and therefore does not effect the lower Gordon River.

Turbidity values for the Gordon River show no correlation with flow (Figure 17). This is true for measurements both on the F.T.U. scale, and on the silica scale used by the H.E.C. (King and H.E.C., 1978). The two sets of data are not intercomparable because of the complex nature of turbidity itself and differences in instrumentation.

The low turbidity values for the Gordon River indicated that there would be little or no attenuation of light by scattering and, compared with gilvin, the effect of turbidity on light penetration would be negligible.

5.4 Colour

Waters of the Gordon River Basin are all coloured by organic material leached by percolating rainwater from podzolic peats derived from the four vegetation types delineated by Jarman and Crowden (1978). From available data it is not possible to relate colour of the water to any one of these four different vegetation types. However, waters of the upper Franklin and Collingwood Rivers are generally lighter in colour than waters from the remainder of the Gordon River Basin. This is perhaps because of the inert rocks and the poorly developed soils and peats in these lightly forested sub-catchments.

The intensity of colour in waters of the lower Gordon River are not correlated with river flow. However, in the Franklin River, Cataract

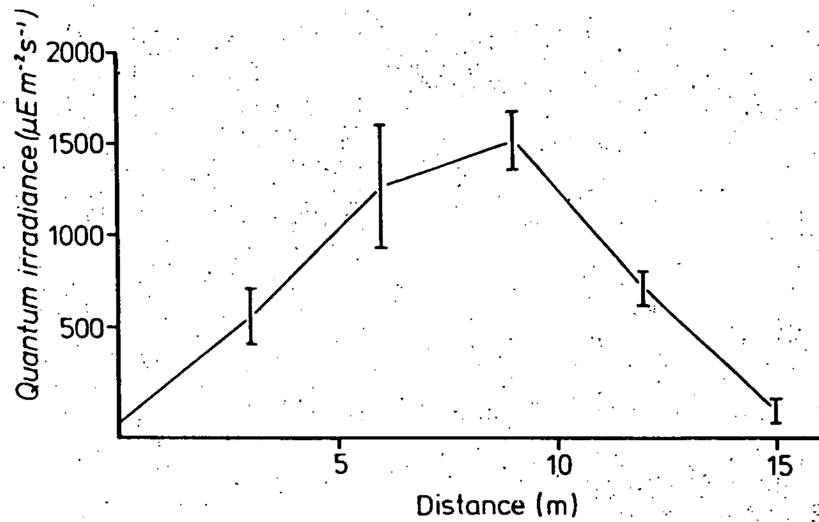


FIGURE 16

RIPARIAN RAINFOREST SHADING THE BED OF THE OLGA RIVER 4 km UPSTREAM FROM THE GORDON RIVER IN SUMMER. QUANTUM IRRADIANCE MEASURED WHEN SUN WAS VERTICALLY OVERHEAD. MEANS AND STANDARD DEVIATIONS OF 4 TRANSECTS PLOTTED.

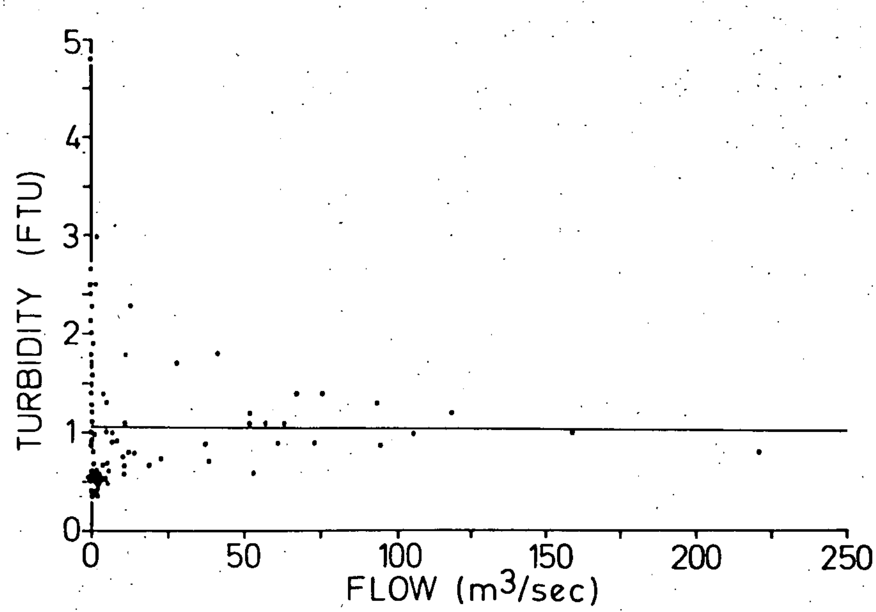


FIGURE 17

RIVER FLOW AND TURBIDITY IN THE GORDON RIVER BASIN. EQUATION TO THE REGRESSION LINE FITTED IS PRESENTED IN APPENDIX 4.

Creek and Roaring Creek catchments, all with similar vegetation types to the lower Gordon, stream flow appears to determine the amount of dissolved organic material in the water. No explanation for this difference is possible with present information. The dissolved organic material, called "gilvin" by Kirk (1976) is vicariously measured with a spectrophotometer as optical absorbance at 440 nm (G440). This is more precise than measuring colour with a comparator (in Hazen units) where operator errors can be considerable. The relationship between gilvin and Hazen colour for Gordon River Basin waters is presented in Figure 18.

Light is greatly attenuated by colour in the water (Kirk 1976, Steane 1979). Figure 19 shows that waters of the Gordon River area, including the river itself, have high absorption coefficients, such that incident radiation is attenuated to 1% of surface values by a shallow layer of water (2 m for Gordon River). The effect of this is that only in very shallow water is there sufficient light for photosynthesis. Other implications of colour in water are discussed by King and Tyler (1978a).

Before Stage 1 of the Gordon River Power Development was commissioned, the hydrological pattern in the Gordon River was for high winter, and low summer flows (Figure 5 and Section 2.4). During the latter, large areas of the river bed became exposed (Plates 2 and 8) and pebbly beaches or shallow riffles appeared in midstream. Stones in these shallow areas, where light penetration was adequate, were coated with a rich growth of diatoms and other algae, contributing greatly to the overall biomass of the river. (Plate 13.)

Since October 1977 operation of the Gordon Power Station has produced a new flow regime in the Gordon River such that summer river levels near the Olga junction (Figure 20) are now more than 1 m higher, and winter levels about 0.4 m lower, than for natural flow (see also Appendix 2). This means that riffle zones, shallows and pebble banks are no longer exposed. From Figure 19 it can be calculated that an increase in water level of 1 m will reduce quantum irradiance at the original depth by about 90%. This must reduce the productivity of the system appreciably. The reduced fluctuation of river level (Figure 20) under the new regime may allow development of a more permanent littoral flora along the banks, but as these are heavily shaded it is unlikely to compensate for loss of summer shallows.

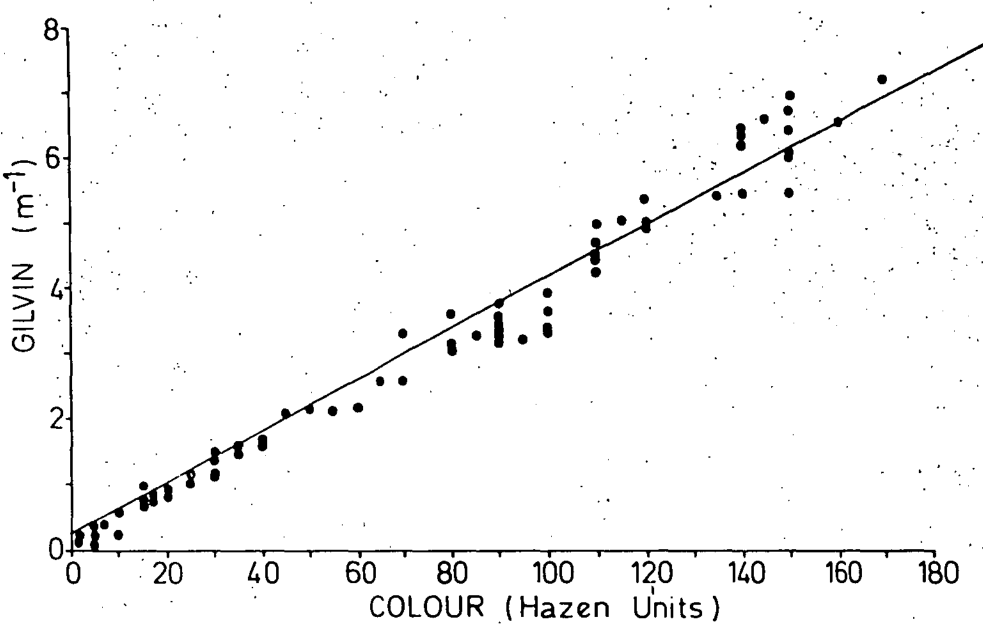


FIGURE 18

GILVIN (G_{440}) AND COLOUR (HAZEN UNITS) FOR GORDON RIVER BASIN WATERS. HAZEN UNITS 22 x G_{440}. REGRESSION EQUATION OF THE LINE FITTED IS IN APPENDIX 4.

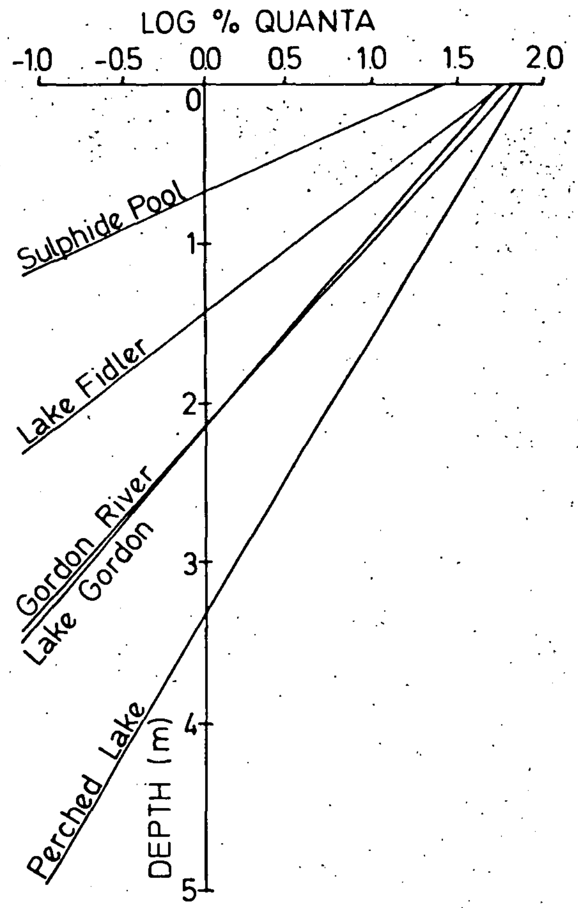


FIGURE 19

SUMMER ATTENUATION OF PHOTOSYNTHETICALLY ACTIVE RADIATION ($\mu E\ m^2\ sec^{-1}$, 400 TO 700 nm WAVEBAND) IN THE GORDON RIVER AT OLGA AND SOME DYSTROPHIC SOUTH WEST LAKES. LOCATION OF LAKES IN FIGURE 4. (DATA FOR LAKE GORDON FROM STEANE [1979].)

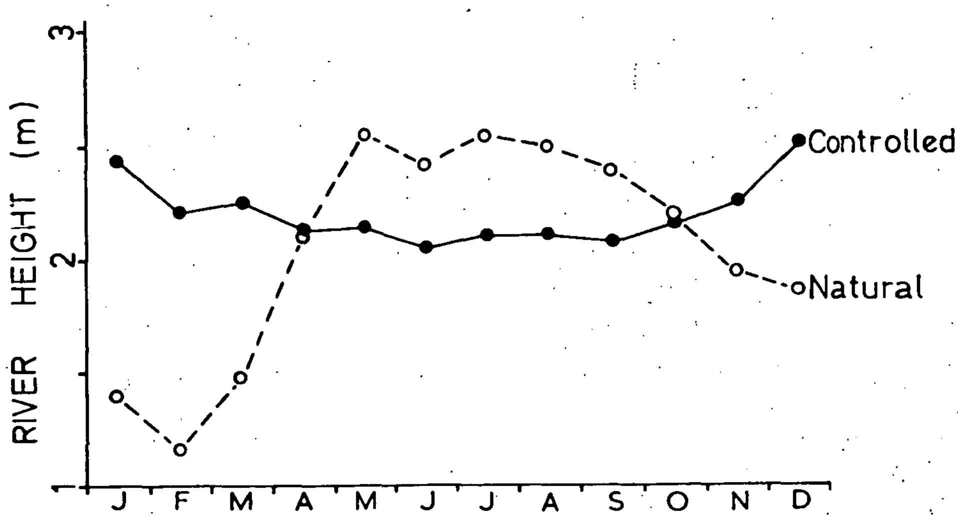


FIGURE 20

ESTIMATED ALTERATION TO MEAN MONTHLY HEIGHT OF THE GORDON RIVER AT OLGA (3081006) BY DISCHARGE FROM LAKE GORDON. (RE-DRAWN FROM WATSON 1978a, APPENDIX 2.)

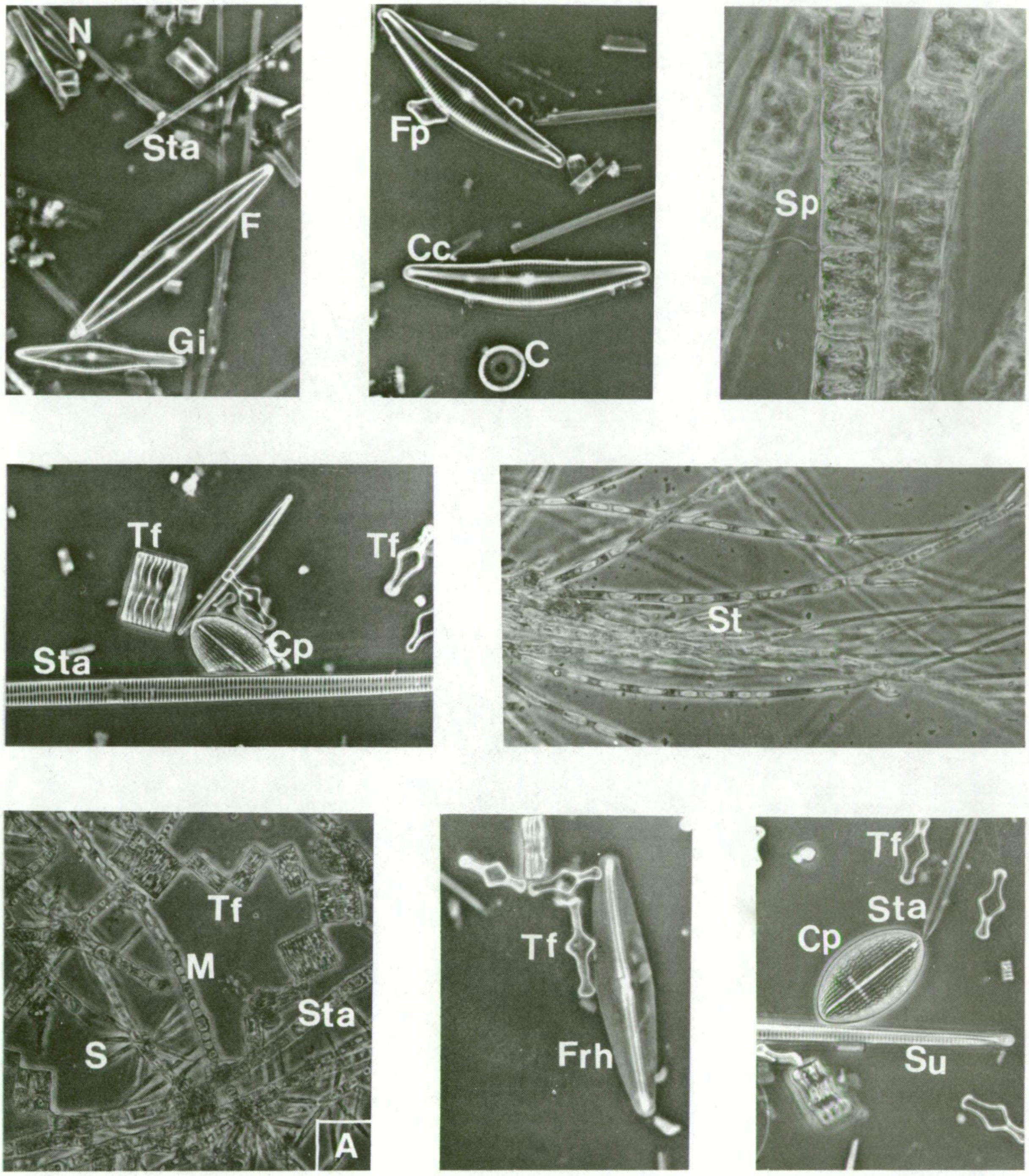


PLATE 13

COMMONLY OCCURRING ALGAE OF THE GORDON RIVER. ALL FIGURES x 600 UNLESS OTHERWISE STATED. Cp - *COCCONEIS PLACENTULA*; C - *CYCLOTELLA* sp. cf. *C. PSEUDO-STILLIGERA* HUSTEDT; Cy - *CYMBELLA CISTULA* var. *MACULATA* (KÜTZING) VAN HEURCK; Fp - *FRAGILARIA PINNATA* EHRENBERG; F - *FRAGILARIA* sp.; Frh - *FRUSTULIA RHOMBOIDES* (EHRENBERG) DE TONI; G - *GOMPHONEMA INTRICATUM* KÜTZING; N - *NAVICULA* sp. cf. *N. AVENACEA* (BRIBBISSON) CLEVE; Sta - *SYNEDRA TABULATA* (C. AGARDH) KÜTZING; Su - *SYNEDRA ULVA* (NITZSCH) EHRENBERG; S - *SYNEDRA* spp.; Tf - *TABELLARIA FLOCCULOSA* (ROTH) KÜTZING; Sp - *SPIROGYRA* sp x 240; St - *STIGEOCLONIUM* sp.; M - *MOUGEOTIA* sp. x 240. FIGURE A ILLUSTRATES ATTACHED DIATOMS ON FILAMENTIOUS ALGAE.

6.0 WATER CHEMISTRY

6.1 Introduction

According to Golterman (1975) the relationship between the concentration of dissolved solids and time in rivers can be one of two types. First, the concentration of dissolved salts may vary inversely with river flows (Casey and Newton, 1972, 1973). This presumes a constant rate of input of salts homogeneously dissolved and mixed with the river water. Alternatively, the concentration of salts remains constant, implying that salt input varies with flow.

The variation of any chemical parameter in relation to rainfall and/or flow will be greatly influenced by the immediate history of the catchment. The state of the peats and soils will determine the watershed capacity for water retention, ion exchange, organic acids release, and so on.

Without extensive, systematic, and close-interval data collection on the scale of the Hubbard Brook investigations (Likens et al. 1977), it is impossible to explain some of the capricious fluctuations in concentrations of various substances observed during this study. It is emphasised that the interval between sampling was often unfortunately long and during that interval fluctuations in flow and in the concentrations of various chemical species may have been greater than the differences between the values for the two successive samples in question. Much closer sampling intervals would be necessary to detect true seasonal trends, and to differentiate them from changes caused by sporadic climatic events. However, with those limitations in mind, certain trends and relationships which may be reasonably expected can be detected in the data. Events between two successive samplings may also be affected by intermittent operation of the Gordon Power Station.

Watson and Wylie (1972) found a close correlation (r = 0.92) between mean monthly rainfall at Olga Camp (Adjacent 308008) and that at Queenstown, 70 km to the north. The close correlation between these 2 stations enabled Watson (1978a) to produce a map relating rainfall around the State to that at McPartlan Pass (Figure 21). Much of South West Tasmania, and certainly the study area, lies within a zone bounded by the 0.9 correlation coefficient isopleth, so that rainfall at a station

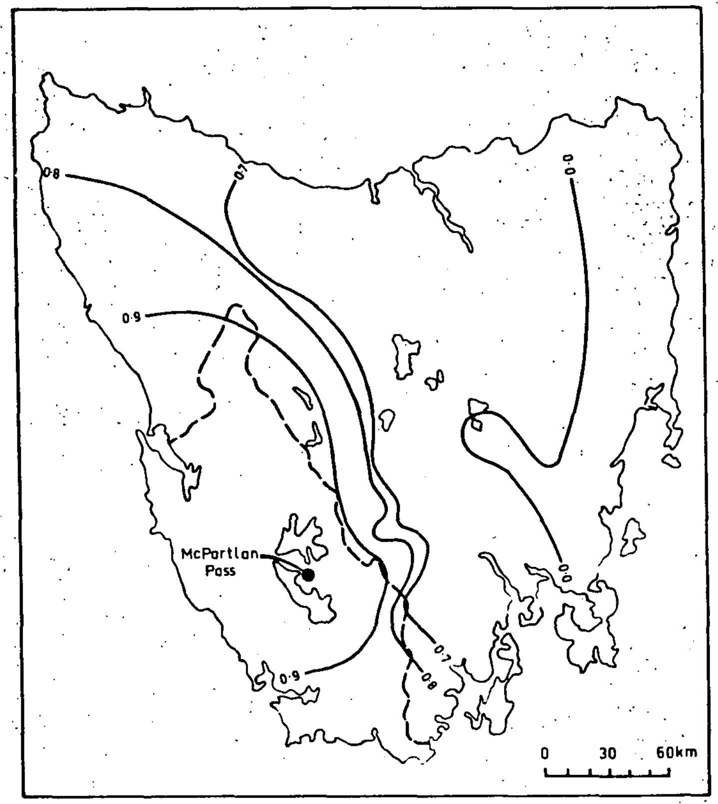


FIGURE 21

CORRELATION COEFFICIENTS FOR MONTHLY RAINFALL AT McPARTLAN PASS WITH OTHER STATIONS IN TASMANIA. BROKEN LINE INDICATES THE SOUTH WEST AREA AS ADOPTED BY THE CARTLAND COMMITTEE AND THE SOUTH WEST TASMANIA RESOURCES SURVEY. (REPRODUCED FROM WATSON 1978b.)

without a gauge can be predicted confidently. In the same area, rainfall and river flow are also closely correlated (Watson, 1978a). Therefore, flow data can be extrapolated for stations without flow gauges or rain gauges provided catchment and river channel characteristics are known. Because accurate flow gaugings were made at a number of stations (Figure 3), correlation of chemical behaviour is sought with flow rather than rainfall.

A striking feature of the Gordon River Basin is its considerable storage of groundwater which is released to the rivers throughout the year, even after long dry periods. Watson (1978a) recognizes three artesian water sources - firstly, water flowing from forest peats; secondly, shallow water storages from weathered bedrock immediately below the peats, and thirdly, deep storage water emanating from rock fissures. The first two types are most likely to vary seasonally with rainfall, while the deep storage supply is likely to be fairly constant, except if rainfree periods persist. These storages, together with the nature of the rock types in the various catchments, influence river water chemistry significantly. Artesian water is altered by contact with rocks, and as rains recharge the aquifers flow through them increases, so that contact time between water and rock decreases progressively. Groundwater is then less influenced by rock contact than during slow releases in summer.

All the rivers of the Gordon River Basin display, to a greater or lesser extent, geochemical influence and modification of their waters. The limestone sequences of the Gordon River Basin expectedly produce water rich in alkaline earth bicarbonate ions, but, surprisingly, also with abnormally high proportions of sodium and chloride, a fact attributed to the marine origin of these limestones (Watson pers comm.). When flows are very low the Gordon River water originates largely from ground storage, and chloride contributes about 40% of total anions, while principal cations occur in about equal proportions. There is a tendency for the chemical composition to be alkaline earth bicarbonate-dominated when rainfall and river flows are low during the summer, and sodium and chloride dominated when flows are high during the winter. The river water is then similar in composition to sea water. This general pattern is true for rivers from catchments with abundant calcareous rocks, but elsewhere the chemical composition of the water is similar to that of sea water irrespective of flow. These waters are mostly creeks and small seepages.

Raw data on chemistry of river water collected during the Lower Gordon River Scientific Survey are presented in detail in King and H.E.C. (1978) together with spot flow figures for the rivers on the sampling dates.

6.1.1 Rainwater Quality

Water is supplied to the Gordon River system primarily by rainfall and groundwater discharge (derived from rainfall). No rainwater samples were collected during the Lower Gordon River Scientific Survey, but limited chemical information is available from the Department of Science, Australian Government (1978) and Donovan (1977). The sampling sites are not within the study area, but the data presented provide some indication of the quality of the rainwater of the prevailing westerly weather.

Maximum, minimum and mean rainwater chemistry data for the Tasmanian West Coast and for Macquarie Island are presented in Table 3, and the ionic proportions of these samples plotted in Figure 22. The sampling apparatus and analytical reliability of the Tasmanian data is discussed by Donovan (1977).

The ionic composition of the rainfall resulting from the maritime westerly weather is that of sea water, dominated by sodium and chloride. The concentration of salts of maritime origin is dependent upon the distance of the recording station from the nearest coast in the path of prevailing weather (Bayly, 1964; Gorham, 1958; Hutton and Leslie, 1958). Cape Grim and Maatsuyker Island stations are adjacent to the coast, probably receive sea spray, and thus contain higher concentrations of dissolved salts than the more inland stations like Mount Bobs and Adamsons Peak. Samples from these two station probably describe more accurately the rainwater chemistry of the Gordon River Basin than do the coastal stations.

Tasmanian West Coast lagoons immediately behind the beach dunes contain higher concentrations of dissolved salts than do lagoons further inland, even though the major ionic composition is similar in all cases.

Tyler (1972) found no correlation between salt concentrations of Macquarie Island lakes and the distance from the nearest coast, but found direct relationship between concentration and distance from the West Coast, from where the winds come.

TABLE 3

Maxima, minima, and means of Chemical Parameters of Rainfall from Tasmania and Macquarie Island.

	Date	Number of Samples	pH	Conductivity µS/cm	µ eq/l HCO$_3$	Cl	SO$_4$	Ca	Mg	K	Na	Salinity mg/l
					TASMANIA**							
Cape Grim												
Max/Minimum	11/76 to	15	7.2-5.9	305-24	143-16	2907-14	119-2	185-15	559-19	67-10	2453-44	181-4
Mean	9/77		6.3	139	51	1111	48	85	222	36	1014	74
Maatsuyker Island	-	1	5.9	75	339	725	23	30	156	20	622	65.1
Mt. Bobs												
Max/Minimum	5/75 to	3	5.5-5.2	25-10	-	166-87	<5	10-<2	25-16	4-1	165-65	10.5-5.1
Mean	9/75		5.4	16	-	116		-	21	2	100	7.1
Adamsons Peak												
Max/Minimum	5/75 to	4	5.5-5.0	102-25	-	206-90	6-<5	10-<5	33-16	5-1	204-57	13.0-5.6
Mean	10/75		5.3	18	-	127	-	-	24	2	109	7.8
					MACQUARIE ISLAND***							
Isthmus (Rain)	25/11/71	1	6.9	62	81*	356	44	41	83	13	344	
Prion Lake (Snow)	26/11/71	1	5.9	-	-	-	-	5	8	5	43	-

* Calculated by difference.
** Department of Science - Australian Government.
*** Tyler (1972)

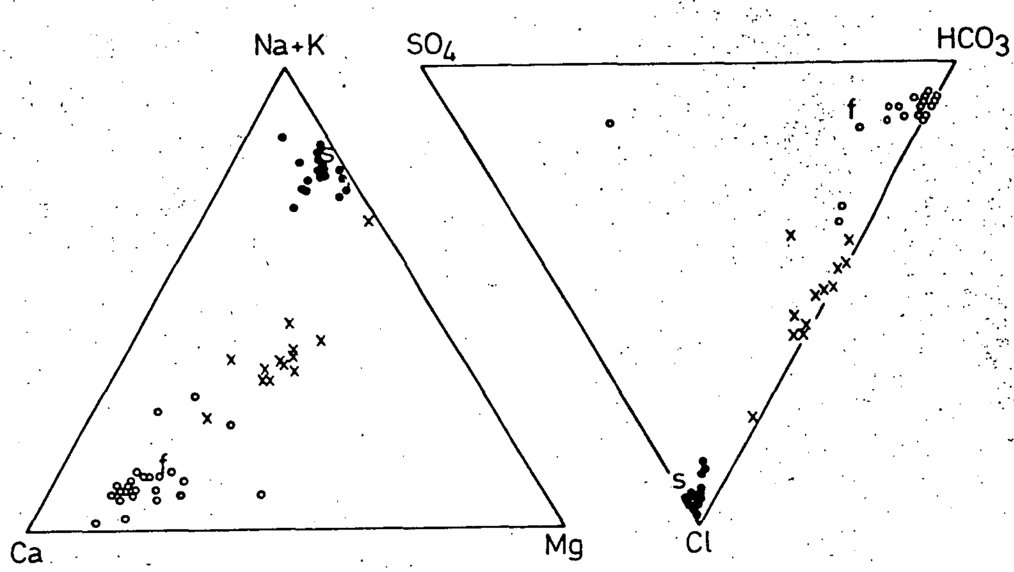


FIGURE 22

IONIC PROPORTIONS OF RAINWATER (•), ARTESIAN WATER (○) AND FOR THE GORDON RIVER AT BUTLER ISLAND (x). WORLD AVERAGE FRESHWATER (f) AND SEAWATER (s) ARE INCLUDED FOR COMPARISON. (DATA FROM KING AND HEC 1978.)

It is clear from Table 3 and Figure 22 that for the entire south west the chemistry of rainfall is that of sea water of various dilutions.

6.1.2 Artesian Water

Ordovician limestones are widely distributed throughout the Gordon River Basin (Figure 2) and can be expected to exert a profound effect on artesian water and hence on river chemistry. The type and quantity of ionic species dissolved in artesian water depends on the composition and solubility of catchment rocks. Chemical composition of limestones and dolomites is dependant upon the original mineralogy and chemical characteristics of the dolomitizing brine solutions (Benson, 1974). Cyrstallization of dolomites is largely controlled by Mg/Ca ratio (Folk and Land, 1975), and can occur under various salinities ranging from hypersaline to relatively fresh water (Folk and Land, 1975: Folk and Siedlecke, 1974 cited in Rao and Naqvi, 1977), or by admixture of low salinity fresh water with sea water (Badiozamani, 1973 cited in Rao and Naqvi, 1977).

The mean molar ratio of Mg/Ca in Gordon River limestones is 0.09, and in dolomites 1.03 (Rao and Naqvi, 1977) so that artesian waters from catchments composed predominantly of limestones should have Ca > Mg whereas in predominantly dolomite catchments Ca and Mg should be approximately equal.

According to Rao and Naqvi (1977) strontium and sodium, and their molar ratios with calcium, are important in determining limestone deposition. Variation of the Na/Ca molar ratio reflects salinity variation of the depositional solutions, and in the Gordon River limestones below the Franklin Junction sodium varies considerably (Rao and Naqvi 1977) in relation to calcium.

It is likely, therefore, that the Na/Ca molar ratio would be extremely variable throughout the limestones and dolomites of the Gordon River Basin, and that these rocks would impart not only alkaline earth bicarbonates to the artesian waters, but also sodium and chloride in varying amounts.

Artesian water was collected by the H.E.C. from several drill holes between Franklin Junction and Butler Island. Data and the location map of these drill holes are presented in King and H.E.C. (1978). The geology of the area was Lower Ordovician quartzitic sandstones with two interbedded sequences of limestones, folded into a gently dipping anticline (Rao and Naqvi 1977, Tarvydas, pers. comm). Drill holes were mostly in the river bed or on the banks, with some on the river valley slopes. Samples were collected from the drill casing after excessive turbidity had abated.

The ionic proportions of artesian waters are shown in Figure 22. Salinity ranged from 135 - 363 mg/l except for one sample (< 50 mg/l).

Most were calcium bicarbonate dominated (Table 4, Figure 22), with a cationic dominance order similar to world average freshwater (Livingstone, 1963).

TABLE 4

Mean Ionic Proportions (milliequivalents percent) of Various Water Types

Maximum/minimum values in brackets.

	Ca	Mg	Na	K	HCO_3	Cl	SO_4
Artesian water	72 (86-50)	18 (40-12)	10 (28-2)	< 1 (4-0)	86 (92-28)	12 (34-7)	2 (59-0)
Rain*	6	16	72	3	4	92	4
Gordon River at Butler Island	33	29	30	3	46	52	2
World average freshwater (Livingstone 1963)	64	17	16	3	74	10	16

* Data for Cape Grim - Table 3.

One sample was dominated by calcium and sulphate, with magnesium ≥ sodium, and < 30% bicarbonate, while two others, though dominated by calcium and bicarbonate, contained between 25-35% of sodium and of chloride, and had a salinity of < 50 mg/l. Unfortunately only spot samples were collected so no seasonal variation in artesian water chemistry can be ascertained.

6.2 Seasonal Variation

6.2.1 Lower Gordon and Franklin Rivers

The lower Gordon and Franklin Rivers were sampled from October 1976 to April 1978 at three accessible sites near the Gordon-Franklin Junction (Figures 3 and 4). The Gordon River immediately above the Franklin confluence (3081034), gave an integration of upstream tributaries until November 1977 when water release from Lake Gordon began. Then the flow pattern was altered, and stored water entered the Gordon River. The Franklin was sampled at Shingle Island (3081040), about 1 km upstream of its junction with the Gordon. Its flow pattern has, so far, remained unaltered. Samples at Butler Island camp (3081042) of the combined flow of the Gordon and Franklin characterised the Gordon River surface waters from Butler Island for many kilometres downstream until the marine influence of Macquarie Harbour became evident. Some mixing of surface fresh waters and underlying saline waters was apparent at Tuan Gabby Tongue (Figure 14) and may extend further upstream. Analytical data are given in detail in King and H.E.C., 1978).

The flow regimes of the Gordon and Franklin Rivers have been discussed in Section 2.4 and illustrated in Figure 5. The natural pattern is intimately controlled by rainfall from prevailing westerly winds (see Section 2.4 and 2.5). Generally flows are lowest during summer, increase in autumn, and reach a maximum in winter. However, anomalies do occur:-

(a) Occasionally heavy rains occur in summer, as at Strathgordon during December 1976 (Figure 6B). This event was not apparent from the spot flow figure for the Gordon River (Figure 23).

(b) In most years river flows are reduced in June (see Figure 5). According to Watson (1978a) this is a peculiarity of the weather of this south west region of Tasmania.

(c) Flows in the Gordon River have been changed significantly since October 1977. For a period of several weeks after this date the flow pattern was erratic depending on the pattern of turbine operation, and spot flow figures probably do not illustrate the true flow pattern (Figure 23). Thereafter Lake Gordon discharge remained fairly constant approximating the estimated flows presented in Figure 5.

The reservations concerning the undersirably long sampling intervals (Section 6.1) apply to the following discussion of the chemistry of the lower Gordon and Franklin Rivers.

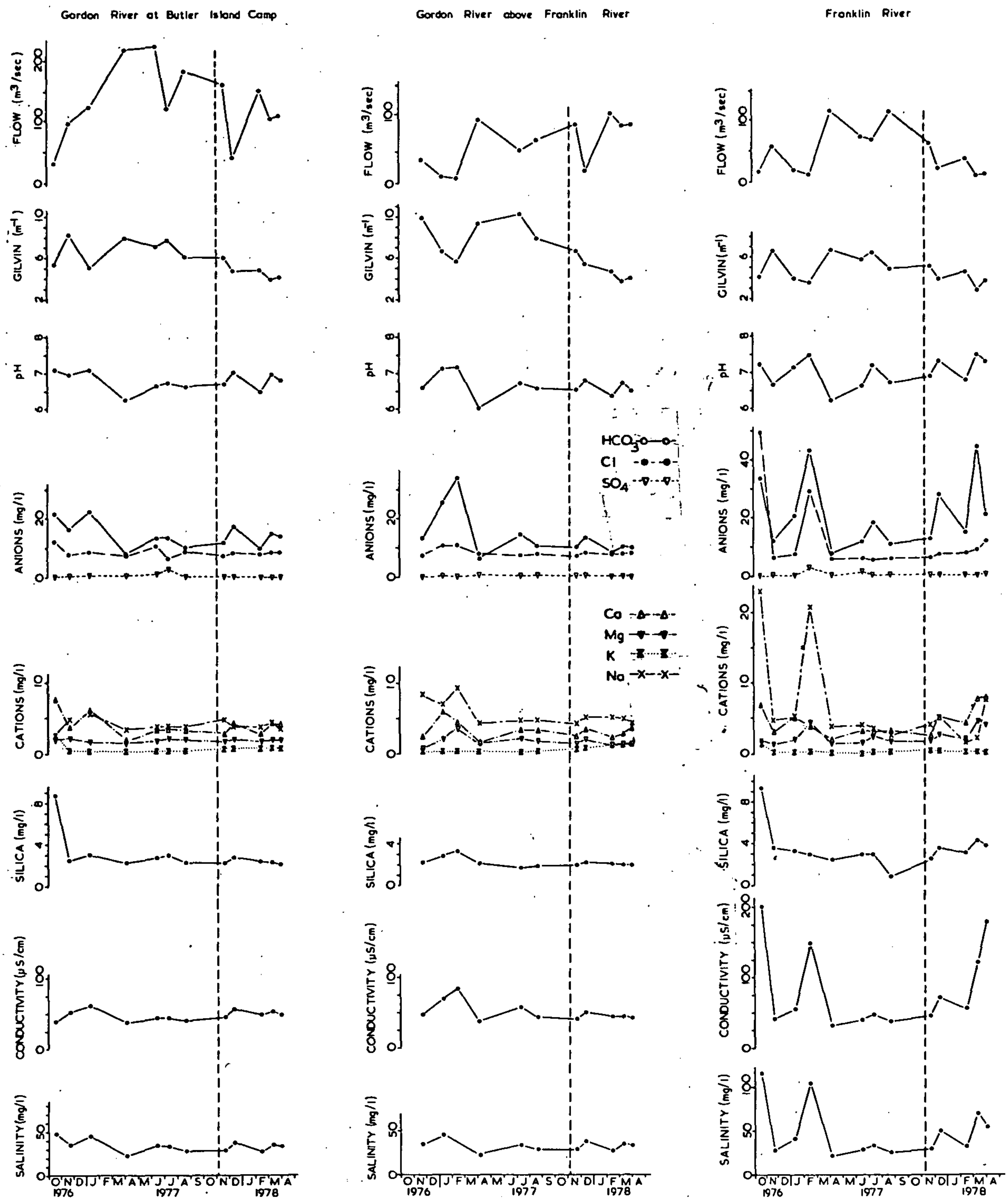


FIGURE 23

SEASONAL VARIATION OF VARIOUS CHEMICAL PARAMETERS IN THE GORDON AND FRANKLIN RIVERS. THE VALUES FOR FLOW ARE AVERAGE DAILY FLOW VALUES FOR THE DAY OF SAMPLING. THE VERTICAL, BROKEN LINE INDICATES WHEN THE GORDON POWER STATION BEGAN DISCHARGING.

6.2.1.1 Dissolved Organic Material

The colour of the Gordon River (measured as an absorbance at 440 nm, and called gilvin by Kirk (1976) (see King and Tyler 1978a, page 24) attributable to dissolved organic material, varied greatly (Figure 23) in the first summer of the study (G440 from 5.08 m^{-1} to 9.98 m^{-1}). It decreased dramatically in the reach above the Franklin Junction from July 1977 until the termination of the study in April 1978. After October, the decline in gilvin values is attributable at least in part to release of Lake Gordon water. The Franklin River showed a more gentle decline over the same period.

Before October 1977, the Gordon River was least coloured when river flows were low (early in 1977), and increased when rainfall and flow increased. However, in June 1977 colour increased slightly despite a reduction in flow, probably because rainfall continued percolating slowly through the peats. After Lake Gordon discharge commenced the water colour decreased beyond the values of the previous summer, but not to the low values (c. 3-4 m^{-1}) of water in the off-take stratum of Lake Gordon (50 m depth - Steane and Tyler, 1978). The reason for declining colour values from November 1977 onwards is not clear, but the large volume of Lake Gordon water released must have had an effect. However, the Franklin River also showed a general decline in colour over the same period so that natural events also played a likely role. The Franklin River had lower colour than the Gordon and values fluctuated dramatically.

6.2.1.2 pH

During the survey the pH varied between 6.07 and 7.11 in the Gordon River (Figure 23), with no well-defined seasonal pattern. The lowest values in 1977 coincided with autumn rains, leaching vegetable acids from the peats. Between January and April 1977, a rise in river flow was accompanied by an increase in colour and decrease in pH. Throughout the winter months of high rainfall the pH varied little, probably because waters percolating to creeks and rivers were in equilibrium with the peats.

The pH of the river was slightly alkaline during low flows of the first summer, but became acid in January 1977 when flow increased, and remained acid during winter, ranging between 6.6 and 6.8. After October 1977 the pH appeared to fluctuate harmoniously throughout the catchment. This is surprising since the pH of the Gordon River would presumably be dominated by the nature of the release water.

In the Franklin, as in the Gordon, the pH (Figure 23) was apparently controlled by the rate of rainwater percolation through the peats. With rising river levels or high winter flow waters were acidic, but with falling levels and at low flows, the pH tended to neutral or slightly alkaline. The pH of the river during the study varied between 6.26 and 7.50.

The pH of the Franklin River at Flat Island, below the Jane River, was significantly affected by dissolution of bicarbonate from the upper Jane catchment, particularly during low summer flows. The Jane River itself became acidic only at high autumn flows (pH = 6.4 at flow of 121.8 m^3/sec.); at low summer flows (3.4 m^3/sec.) the pH was 8.0 (see Section 6.3.13).

6.2.1.3 Major Ions

The seven "major ions", Na^+, K^+, Ca^{++}, Mg^{++}; HCO_3^-, Cl^-, SO_4^{--}, together constitute a high percentage of the total dissolved solids in most natural, unpolluted waters. Their relative molecular abundance, expressed as percentages of the sums of the milliequivalents of cations and anions respectively, affords a means of comparing the chemical characters of different waters and is thought to influence the distribution of freshwater flora and fauna. Two convenient reference points are the ionic proportions of sea water and of World Average Freshwater (Rodhe, 1949).

Three major factors may control the chemical composition of rivers (Gibbs, 1970). First there is the contribution of rainwater, with a fairly constant composition akin to sea water (Na > Mg > Ca > K: Cl > SO_4 > HCO_3). Unfortunately we have scant knowledge of the magnitude of the variation in salt concentration, but available chemical information suggests that salts are contributed to the rivers and lakes by direct sea spray for about one kilometre inland, and beyond by rain of low concentration.

Secondly, the rocks in the various sub-catchments may alter the chemical composition of the rainwater to one closer to world average fresh water (Ca > Mg > Na > K: HCO_3 > SO_4 > Cl). However, because the Gordon limestone sequences are of marine origin, both sodium and chloride are fairly well represented in the chemical composition of the rivers, even after fairly long rain-free periods when river water originates principally from subterranean aquifers. Most of the rivers in the Gordon Basin contain carbonate rocks to a greater or lesser extent in their catchments and therefore have waters with geochemically influenced chemistry (Figure 24). However, creeks and seepages not draining calcareous rocks have water chemistry akin to seawater at all times (Figure 36).

A third mechanism, preferential salting out of monovalent cations under high evaporative concentration, does not apply to the Gordon River Basin.

The seasonal variation in concentrations of major ions is shown in Figure 23. Sulphate and potassium are present in very low concentrations and can be neglected from further consideration. (The high sulphate value for Butler Island in June 1977 and the high potassium in October 1976 are both considered to be analytical errors.)

In all three river stations the directions of changes in concentrations of the various ions were generally the same. Chloride concentrations remained relatively constant in the Gordon but fluctuated more widely in the Franklin. At all three stations, bicarbonate concentrations fluctuated more widely than chloride concentrations. The unusually high values for chloride in the Franklin in October 1976 and February 1977 are real events, as they are matched by corresponding peaks of sodium. Fluctuations in bicarbonate concentrations are matched by fluctuations in calcium and magnesium.

Without closer interval sampling it is impossible to explain confidently the observed variation in major ion concentrations though the reasons obviously lie in the complex relationship between rainfall, groundwater and rock contact. Some of the obvious trends are better seen when ionic proportions are examined (Figures 25,26) rather than concentrations.

In the Franklin River anionic dominance oscillated between chloride and bicarbonate (Figure 25). Bicarbonate usually dominated during low flow periods. Among the cations, as expected, sodium exchanged dominance with the two alkaline earth elements (calcium and magnesium) as chloride exchanged dominance with bicarbonate.

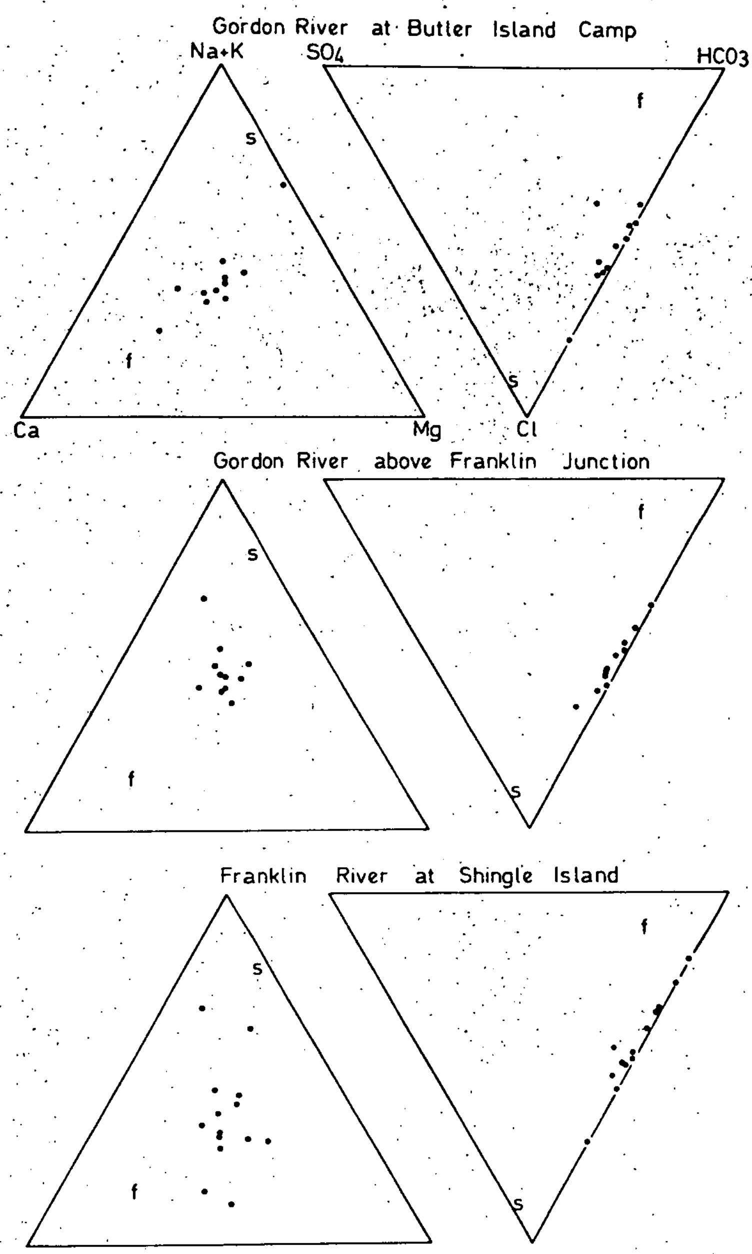


FIGURE 24

IONIC PROPORTIONS OF GORDON RIVER AND FRANKLIN RIVER SAMPLES. WORLD AVERAGE FRESHWATER (F) AND SEAWATER (S) PROPORTIONS ARE INCLUDED FOR COMPARISON.

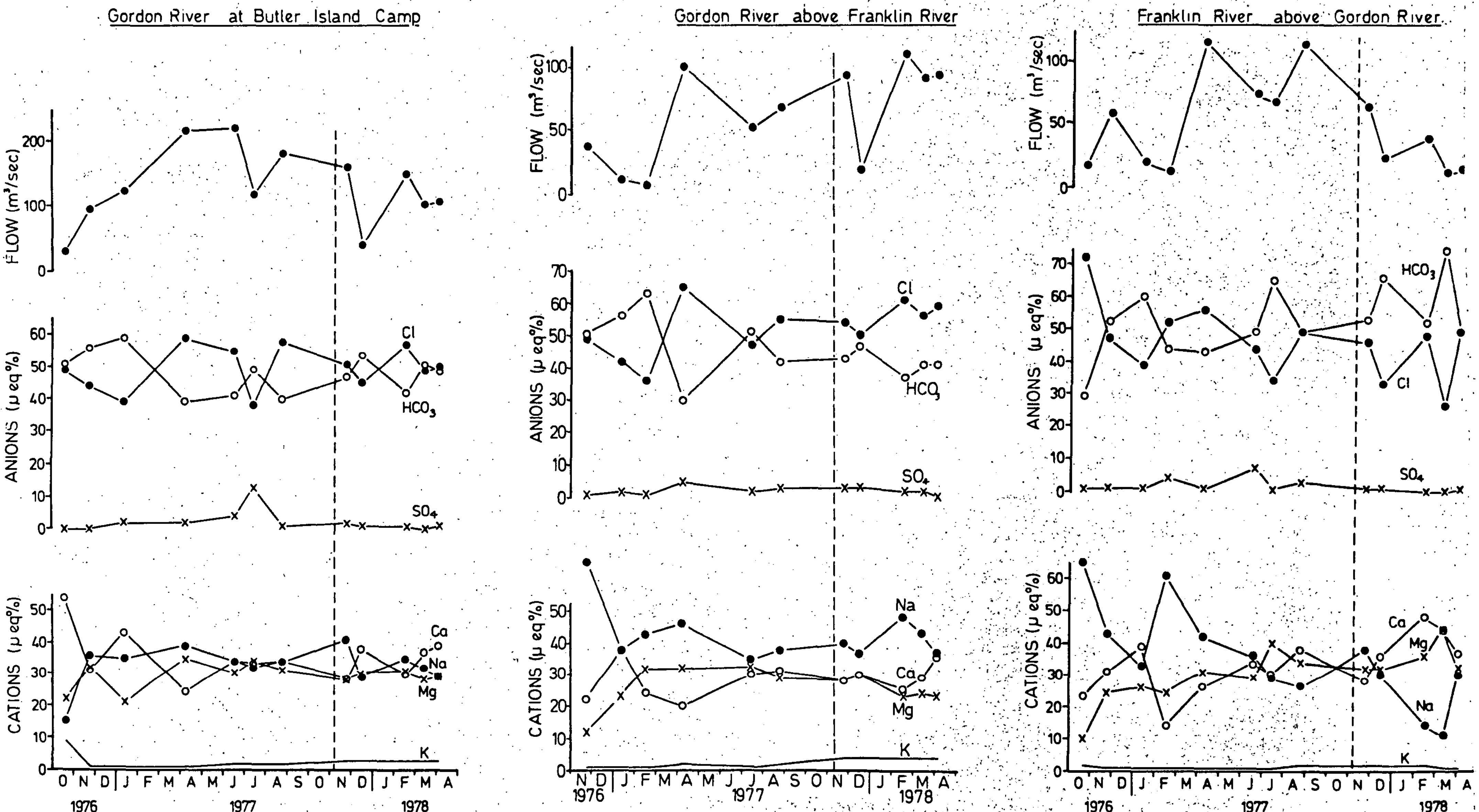


FIGURE 25

SEASONAL VARIATION IN PROPORTIONS OF MAJOR IONS IN RELATION TO AVERAGE DAILY FLOW ON THE DAY OF SAMPLING, FOR THE GORDON AND FRANKLIN RIVERS.

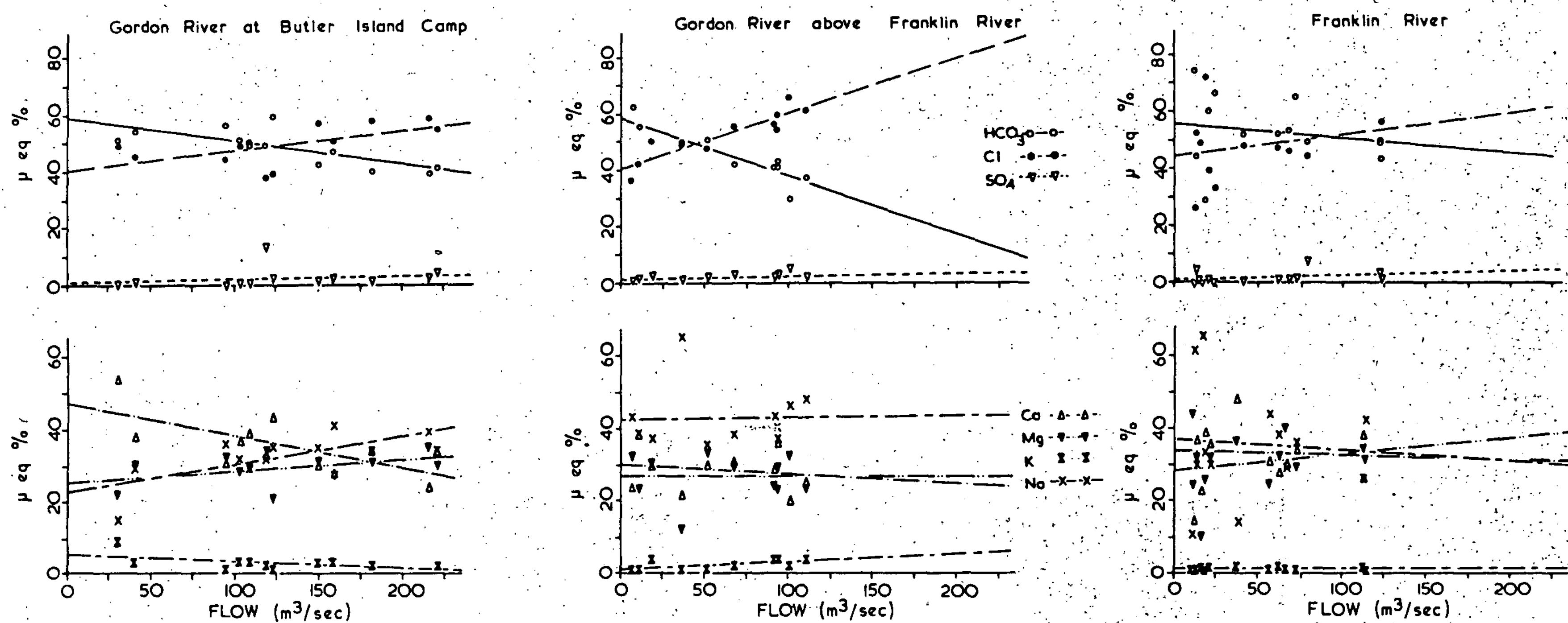


FIGURE 26

RIVER FLOW AND COMPOSITION OF MAJOR IONS. REGRESSION EQUATIONS OF THE LINES FITTED ARE IN APPENDIX 4.

The relationship between low flow and bicarbonate dominance, and high flow and chloride dominance (Figures 25 and 26) appears to be a general one throughout the catchment where calcareous rocks occur (see subsequent sections). In the Gordon River above the Franklin Junction, as for the Franklin River, chloride and bicarbonate exchanged the positions of dominance in response to fluctuations in flow. At low flows bicarbonate was the dominant, at high flows it was chloride.

The effects of release of Lake Gordon water are apparent from a comparison of ionic proportions for the Franklin River and for the Gordon above its junction with the Franklin (Figure 25). After November 1977, for a period of several months, flows in the Franklin were low and bicarbonate was the dominant anion. Prior to that date, low flows were accompanied by bicarbonate dominance in the Gordon River also. However, after discharge commenced the Gordon was dominated by chloride at a time when the presumed natural state would be for bicarbonate dominance, as in the Franklin (Figure 25).

This is attributed to release of chloride-dominated water from the power station. Since the lower strata at discharge depth are dominated by chloride all through the year (Steane & Tyler, 1978), it seems likely that the lake will continue to suppress the natural chemical fluctuations in the river.

Variations in ionic dominance in the Gordon River at Butler Island naturally are influenced by the Franklin River. Before power station releases began chloride and bicarbonate alternated as dominants, as in the Gordon above the junction. After releases began the bicarbonate contributed by the Franklin was sufficient for the ion to assume dominance in the Gordon during the low flow in December 1977 and again, just, in March 1978 (Figure 25).

6.2.1.4 Silica

Silica in freshwater is usually monomeric and below pH-9 is present as dissolved silicic acid ($Si(OH)_4$) (Stumm and Morgan, 1970). Solubility increases with increasing temperature (Krauskopf, 1956). Silica may also occur in freshwaters in particulate form. Diatoms and some other organisms use large quantities of dissolved silica for the formation of their frustules, and may thus affect silica concentrations in lakes and rivers.

The variation of natural silica concentrations is small compared with other inorganic constituents, with little variation between continents. In rivers and lakes 2 to 25mg/l (Cole 1975) or silica are usually present with groundwater being higher than surface drainage (Davis 1964). The groundwaters of the lower Gordon River area generally contained less dissolved silica than the world average value of 13 mg/l (Table 5).

TABLE 5

Mean and Range of Dissolved Silica (mg/l) in Artesian and Surface Waters in the Lower Gordon River Area

	Mean and Range
Artesian waters	8.1 (12.0-4.0)
Gordon River at Butler Island	3.0 (8.7-2.1)
Franklin River at Shingle Island	3.9 (9.4-0.9)
Roaring Creek	2.7 (7.8-1.5)
Cataract Creek	1.9 (5.0-0.9)

A major factor influencing silica concentration in the Gordon River Basin is contact between water and rock. Artesian waters discharging from deep storage aquifers within the Gordon limestone sequences contain silica concentrations approaching the world average (Table 5). Peat seepages, shallow artesian waters, and particularly Lake Gordon water, on the other hand, contain very low silica concentrations.

Figure 23 shows that silica concentrations in the lower Gordon River were low and relatively constant. They showed greater variation in the Franklin. The declining concentrations of dissolved organic material (gilvin) after power station operation commenced did not effect silica concentrations in the way expected (Wetzel, 1975).

6.2.1.5 Conductivity and Salinity

For many natural waters, the total dissolved solids are accounted for almost entirely by the seven major ions. Further, Rodhe (1949) has shown that the electrical conductivity of natural waters is dictated by the concentrations of these same ions. Various empirical relationships, allowing calculation of salinity or total dissolved solids from a conductivity measurement have been published (Buckney and Tyler, 1973a, 1976; Tyler, 1972). For the major rivers of the lower Gordon River area salinity and conductivity were closely correlated (Figure 23) and the relationship

$$K_{18} = 1.37 \text{ Salinity (mg/l)}$$

can be used with reasonable justification (Figure 27).

A major factor affecting salinity and conductivity is the unusually high artesian discharge to rivers. During long rain-free periods (Watson, 1978a; see also Section 6.1.2) the supply of dissolved salts from deep aquifers, relative to that from surface runoff, will increase, especially in catchments composed of calcareous rocks. Accordingly, the most concentrated waters encountered in this survey (except for samples from Tuan Gabby) occurred in the Franklin below the Jane River Junction (Figure 28), and in the Gordon below the dam while the lake was filling. (Figures 13 and 14; see Sections 2.1 and 4.2.2). Salinity below the dam decreased significantly after power station discharge commenced, and many of the points clustering around 20-40 mg/l salinity (Figure 27) are of discharge water. The mean value of salinity for the discharge stratum of Lake Gordon reported by Steane and Tyler (1978) was 21 mg/l, the range 20 to 24 mg/l. This is likely to be the salinity of the Gordon River in future, while the power station is discharging. During this survey the range of salinities before discharge commenced was 23 to 111 mg/l (Figure 28), and afterwards 18 to 38 mg/l.

During periods of high rainfall, and hence high flows, dilution of artesian discharges by surface runoff would occur, and hence, negative correlation between flow and salinity would be expected. In general, this was true for the Franklin and Gordon Rivers (Figure 28). The overwhelming influence of Lake Gordon is seen in the relative independence of salinity on flow after discharge commenced (Figure 28).

6.2.2 Gordon River at Tuan Gabby Flats (3081047)

The chemical characteristics of the Gordon River at Tuan Gabby Flats (Figure 14; Plates 9 and 10) were determined on 5 occasions between August 1977 and April 1978 and compared with those for the river at Butler Island camp sampled on the same day or, at most, a few days apart (Table 6). The ionic composition of the river at the two sites is shown in Figure 29.

Table 6 shows that surface waters of the river at Tuan Gabby Flats were considerably more saline than at Butler Island (up to 57 times greater) and Figure 29 shows that the ionic composition at Tuan Gabby was close to that

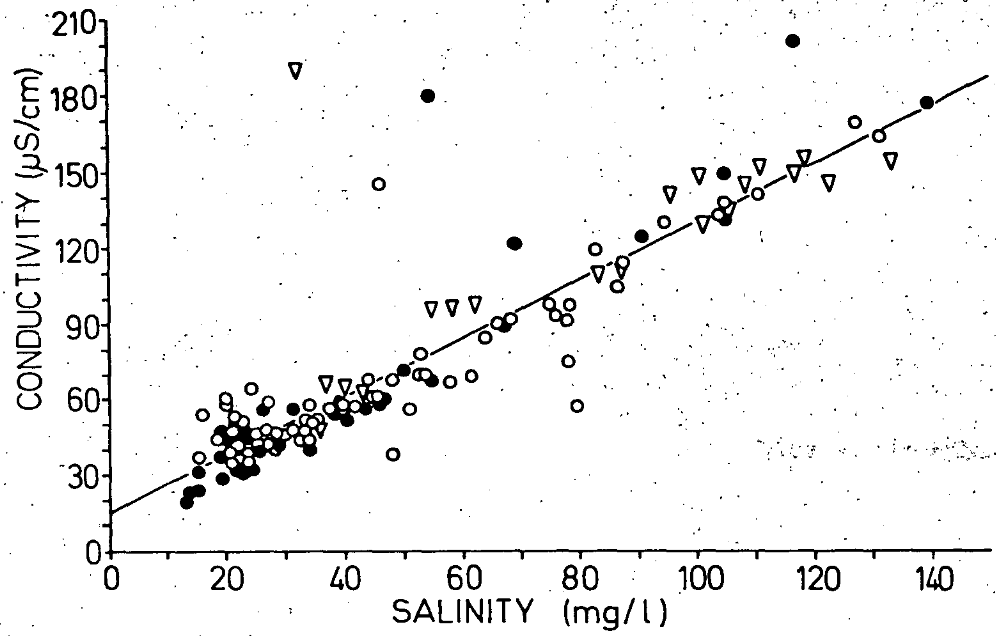


FIGURE 27

CONDUCTIVITY AT 18°C AND SALINITY IN THE GORDON RIVER (o), FRANKLIN RIVER (●) AND OLGA, DENISON AND MAXWELL RIVERS (▼). THE FACTOR RELATING CONDUCTIVITY AND SALINITY IS: K_{18} = 1.37 SALINITY.

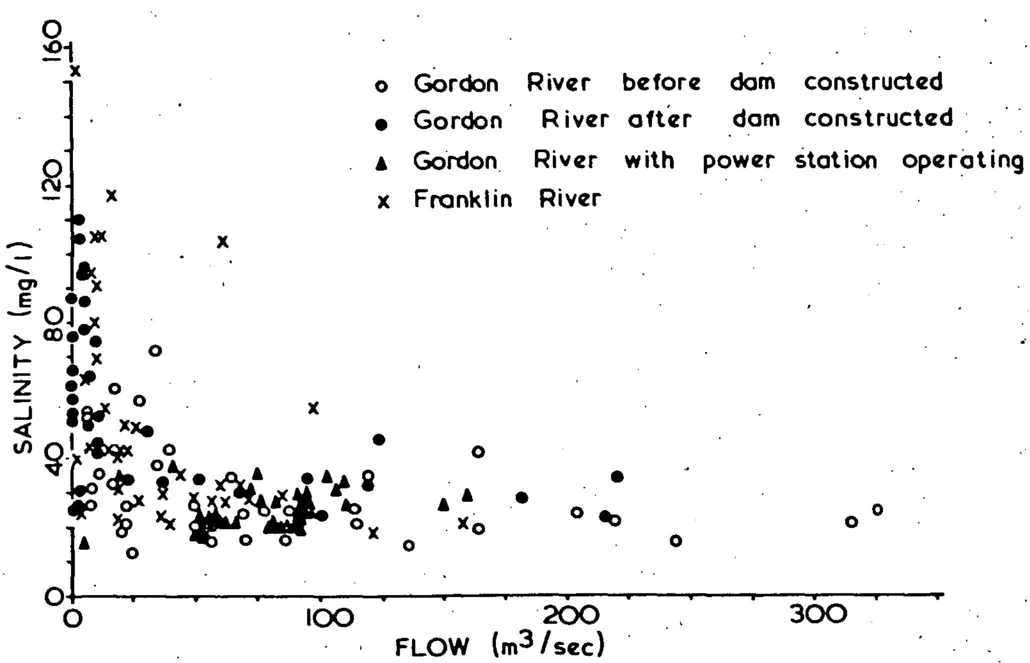


FIGURE 28

SALINITY AND FLOW IN THE GORDON AND FRANKLIN RIVERS.

TABLE 6

Comparison of Water Chemistry from the Gordon River at Butler Island (A) and the Gordon River at Tuan Gabby Flats (B). Site A is 32 km and Site B 8 km from the Mouth of the Gordon River. The Major Ions are in mg/l with ueq/l Units in Brackets. Vertical Line Indicates Before (left) and After Discharge from Lake Gordon Commenced.

	12-13.7.77		24.8.77		15-16.2.78		13-16.3.78		3-6.4.78	
	A	B	A	B	A	B	A	B	A	B
Flow	119		182		150		103		109	
Lab. pH	6.75	7.18	6.64	6.45	6.50	6.57	7.00	7.23	6.83	7.10
Alkalinity (HCO_3)	13.95	22.15	10.35	12.35	9.95	9.80	15.20	21.35	14.25	20.00
	(229)	(363)	(170)	(202)	(163)	(161)	(249)	(350)	(233)	(328)
Chloride (Cl)	6.40	989.70	8.70	53.20	7.80	496.45	8.51	1063.80	8.51	992.90
	(180)	(27910)	(245)	(1500)	(220)	(14000)	(240)	(30000)	(240)	(28000)
Sulphate (SO_4)	2.90	180.00	0.30	1.00	0.20	7.60	0.00	14.70	0.20	82.40
	(60)	(3748)	(6)	(21)	(4)	(158)	(0)	(206)	(4)	(1716)
Calcium (Ca)	3.50	24.40	3.26	2.96	2.80	18.00	4.40	22.00	4.20	34.00
	(174)	(1217)	(163)	(148)	(140)	(898)	(220)	(1098)	(210)	(1697)
Magnesium (Mg)	2.20	75.00	1.80	3.50	1.75	33.50	2.00	75.00	1.94	71.70
	(181)	(6168)	(148)	(288)	(144)	(2755)	(104)	(6168)	(160)	(5897)
Potassium (K)	0.30	24.00	0.34	0.71	0.63	9.90	0.73	20.60	0.70	20.20
	(8)	(614)	(9)	(18)	(16)	(253)	(19)	(527)	(18)	(517)
Sodium (Na)	3.90	580.00	3.80	23.80	3.80	276.00	4.30	580.00	3.60	560.00
	(170)	(25236)	(165)	(1035)	(165)	(12006)	(187)	(25230)	(157)	(24360)
Silica (SiO_2) (mg/l)	3.00	2.60	2.30	1.90	2.40	2.00	2.30	2.20	2.10	2.20
Conductivity at 18 degrees Celsius (micro siemens cm^{-1})	44.70	2740.00	40.00	76.00	48.20	1135.00	53.00	2840.0	48.50	2660.00
Salinity mg/l	33.15	1895.30	28.55	97.50	26.93	851.10	35.15	1797.50	33.40	1781.20

of sea water while at Butler Island it was closer to that of World Average Freshwater, as for most samples from that site (Figure 24). This indicates a significant marine influence on the river at Tuan Gabby. However, there is considerable variation in salinity at Tuan Gabby (Table 6) and Figure 30 shows that this is related to flow.

The source of this marine influence at Tuan Gabby, must have been the intrusion of a salt water underflow ("wedge") from Macquarie Harbour (Kearsley, 1978). Eddy effects at the salt-freshwater interface would have caused a certain amount of underlying salt water to be mixed with the freshwater above. The amount of mixing, and hence the salinity of surface waters, will depend on such factors as flow, and strength and direction of winds. Under conditions of low flow, particularly while Lake Gordon was filling, the underflow (usually at a salinity of 20-25 $^{o}/oo$) extended as much as 48 km upstream. However during the high flow of winter, and during the operation of the Gordon Power Station, saltwater was unable to penetrate up the river (Kearsley, 1978).

Under these circumstances, when the power station was operating, the Gordon River was likely to have had a practically homogeneous water chemistry, akin to that of the discharge stratum of Lake Gordon, as modified by influent tributaries (see Section 6.4). Marine influence is likely to be limited to a short distance near the mouth, perhaps as far as Tuan Gabby Flats, as the salinity of surface waters at that site (Table 6) appear to demonstrate.

The data from the Tuan Gabby samples suggest that the effects of Lake Gordon on Gordon River chemistry are felt as far downstream as Tuan Gabby Flats. Table 7 presents measurements of the colour of river water and of the discharge stratum of Lake Gordon. Before discharge, gilvin values at Butler Island ranged from 5.08 to 8.25 (mean 6.74), and at Tuan Gabby Flats from 6.68 to 6.83. After discharge, both at Butler Island and at Tuan Gabby the values were usually considerably lower, and bore close resemblance to those of the discharge stratum of Lake Gordon (Table 7).

Values of 6.08 on 23rd November 1977 and 6.28 on 16th February 1978 cannot be explained. It is unlikely that they were connected with any shutdown of the power station.

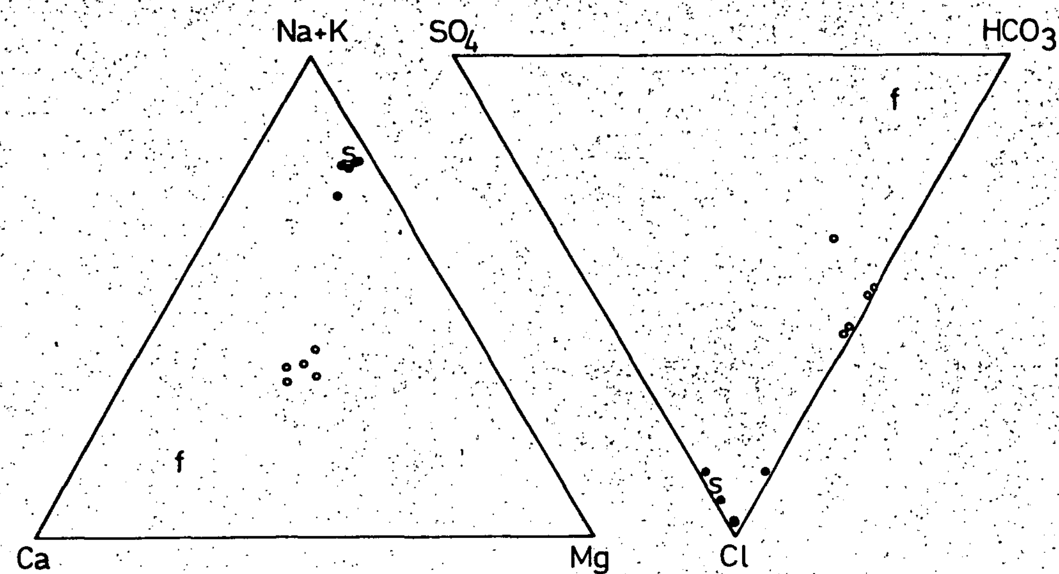


FIGURE 29

PROPORTIONS OF MAJOR IONS IN THE GORDON RIVER AT BUTLER ISLAND CAMP (○) AND AT TUAN GABBY FLATS (●). WORLD AVERAGE FRESHWATER (f) AND SEAWATER (s) ARE INCLUDED FOR COMPARISON. SEE ALSO FIGURES 24 AND 25.

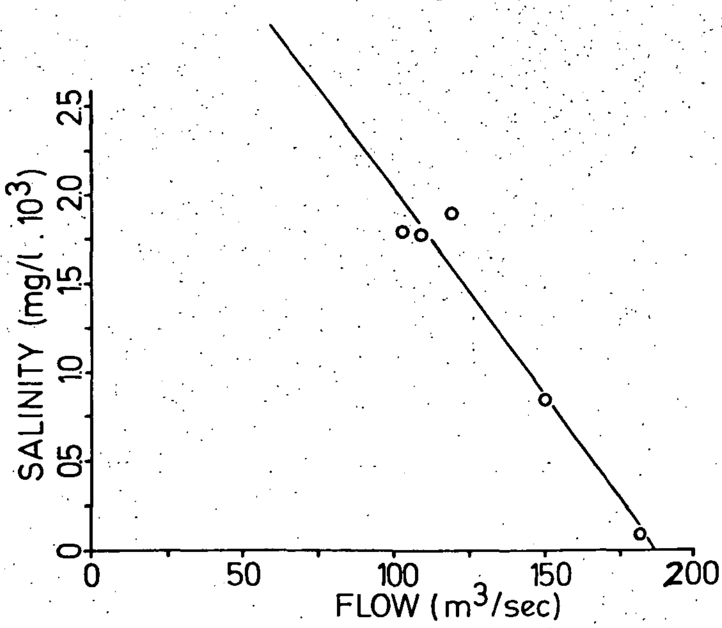


FIGURE 30

ESTIMATED RIVER FLOW AT BUTLER ISLAND CAMP AND SURFACE SALINITY IN THE GORDON RIVER AT TUAN GABBY FLATS. REGRESSION EQUATION TO THE LINE FITTED IS IN APPENDIX 4.

TABLE 7

Colour (gilvin), Measured as an Optical Absorbance (m^{-1}), of the Gordon River at Butler Island Camp and at Tuan Gabby Flats, Before and After Discharge Commenced from Lake Gordon, and of the Discharge Stratum of Lake Gordon (Lake Gordon data from Steane and Tyler, 1978). Broken line indicates before (above) and after Discharge.

Gordon River, Tuan Gabby		Gordon River, Butler Island		Lake Gordon, 55 m	
Date	Colour	Date	Colour	Date	Colour
		27.5.76	6.30		
		19.10.76	5.35		
		23.11.76	8.25		
		12.1.77	5.08		
		7.4.77	7.95		
		16.6.77	7.08		
12.7.77	6.83	13.7.77	7.75		
24.8.77	6.68	24.8.77	6.15		
- - - -	- - - -	- - - -	- - - -	- - - -	- - - -
		23.11.77	6.08		
		15.12.77	4.80	6.1.78	3.94
16.2.78	6.28	15.2.78	4.83	9.3.78	4.10
16.3.78	3.68	13.3.78	3.93		
6.4.78	3.95	3.4.78	4.18		
				19.5.78	4.10
				23.5.78	4.18
				2.6.78	3.92
				12.6.78	3.72
				30.6.78	3.45
				27.7.78	3.40
				21.8.78	3.70
				28.8.78	3.63
				11.9.78	3.55
				20.10.78	3.40
				3.11.78	3.31
				6.12.78	3.28
				5.1.79	3.08

Admixture of relatively small volumes of saltwater, while elevating salinity values of surface waters appreciably (Table 6), would produce little or no effect on gilvin values.

6.2.3 Franklin River Headwaters

The headwaters of the Franklin River were sampled where the Lyell Highway crosses over the upper Franklin and Collingwood Rivers (Figure 8, 3081013 and 308025 respectively). River flow and chemical characteristics are presented in Figure 31. The seasonal fluctuation of percentages of major ions is shown in Figure 32 and ionic proportions in relation to flow is shown in Figure 33. A ternary plot of ionic proportions is shown in Figure 34.

For both rivers there was good correlation between variations in flow and variations in a number of chemical parameters (Figure 31).

High flows were accompanied by high colour (gilvin), presumably because the rains flushed the catchment peats. The negative correlation between colour and pH is explained partly by the contribution of hydrogen ions by the humic materials and partly by coincidental changes in concentrations of alkaline earth bicarbonates.

The seasonal variation of pH, from 6.15 to 7.34 for the upper Franklin River and 6.50 to 7.50 for the Collingwood River, was within the pH range of other rivers of the Gordon River Basin.

Chemical composition appeared to be considerably influenced by flow (Figure 33). During low flows, with rivers fed mostly by groundwater seepage (Watson 1978c) considerable geochemical influence by catchment rocks resulting in bicarbonate domination of the anions was evident (Figures 31 and 32). Conversely at high flows chloride dominated bicarbonate, more as a result of a decrease in bicarbonate than an increase in chloride (Figures 31 and 32). The increases in bicarbonate also contributed to the inverse relationship between flow and pH. In both rivers the chloride proportions only exceeded bicarbonate proportions at flows above about 15-20 $m^3 s^{-1}$.

The variation in cationic proportions was less clear. Calcium, magnesium and sodium were all present in roughly similar ionic proportions and varied approximately in harmony with flow (Figure 32). The rather

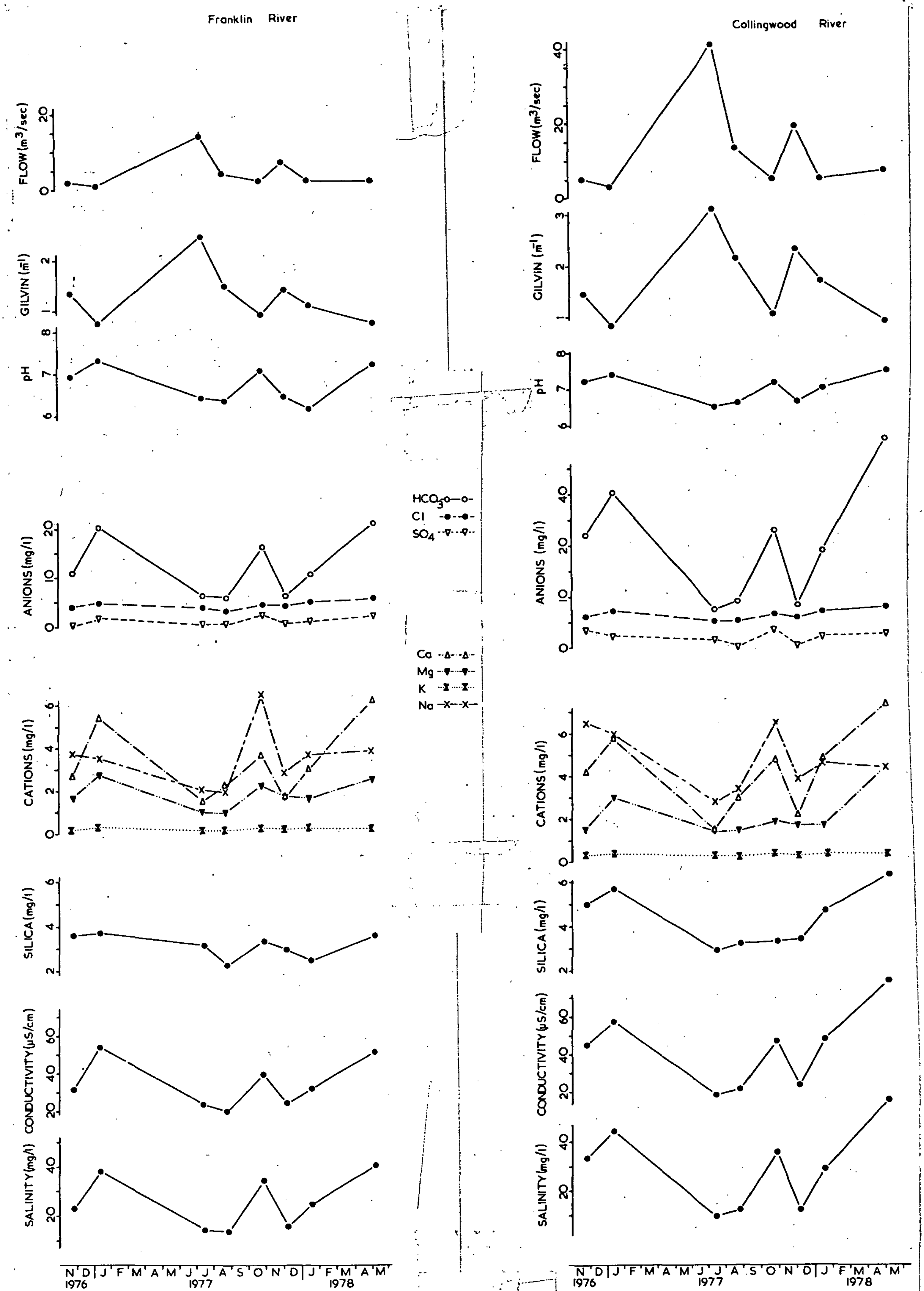


FIGURE 31

SEASONAL VARIATION IN THE RIVER FLOW, DISSOLVED ORGANIC MATERIAL AND WATER CHEMISTRY, FOR THE FRANKLIN AND COLLINGWOOD RIVERS, LYELL HIGHWAY.

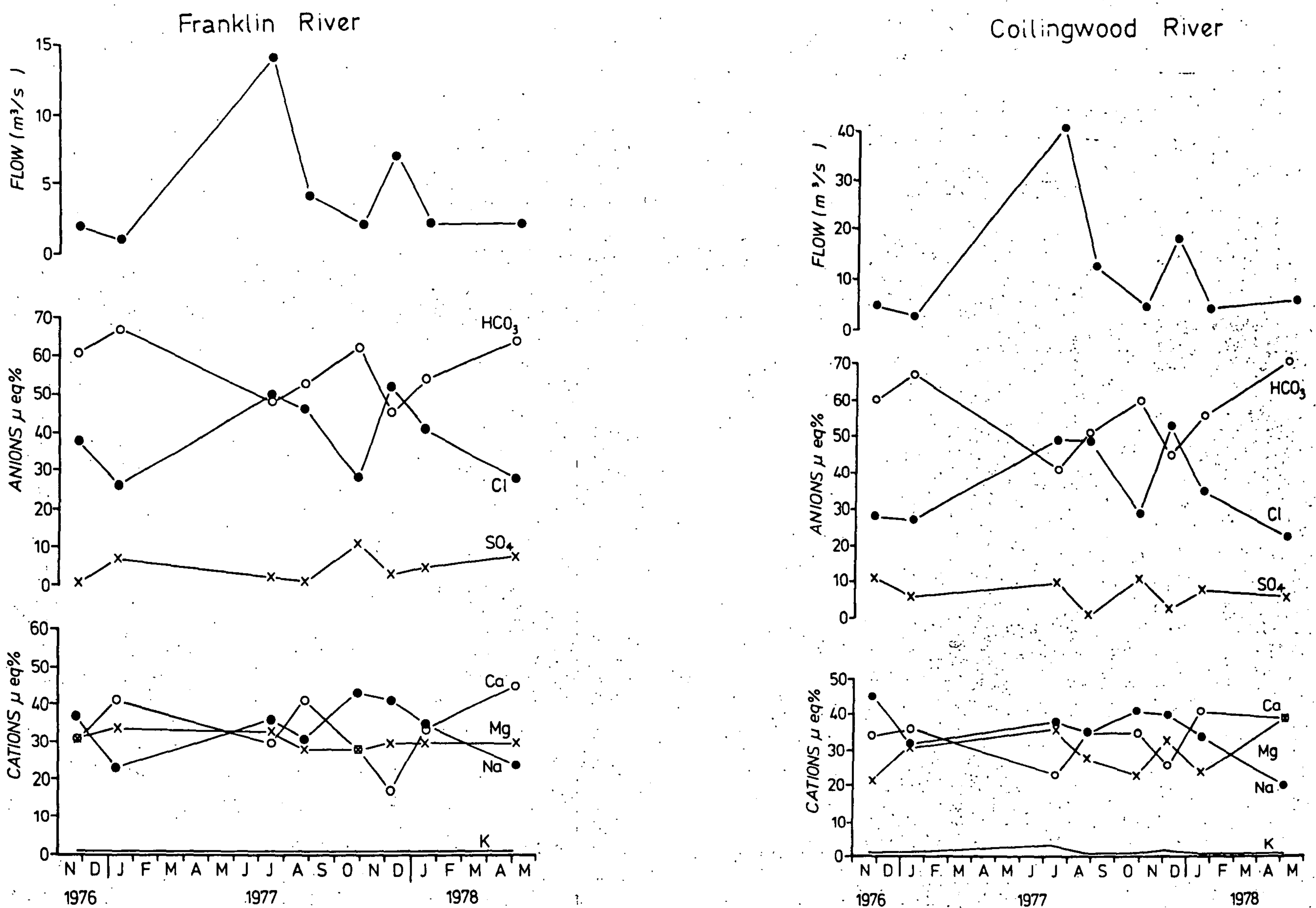


FIGURE 32

SEASONAL VARIATION IN RIVER FLOW AND PROPORTIONS OF MAJOR IONS.

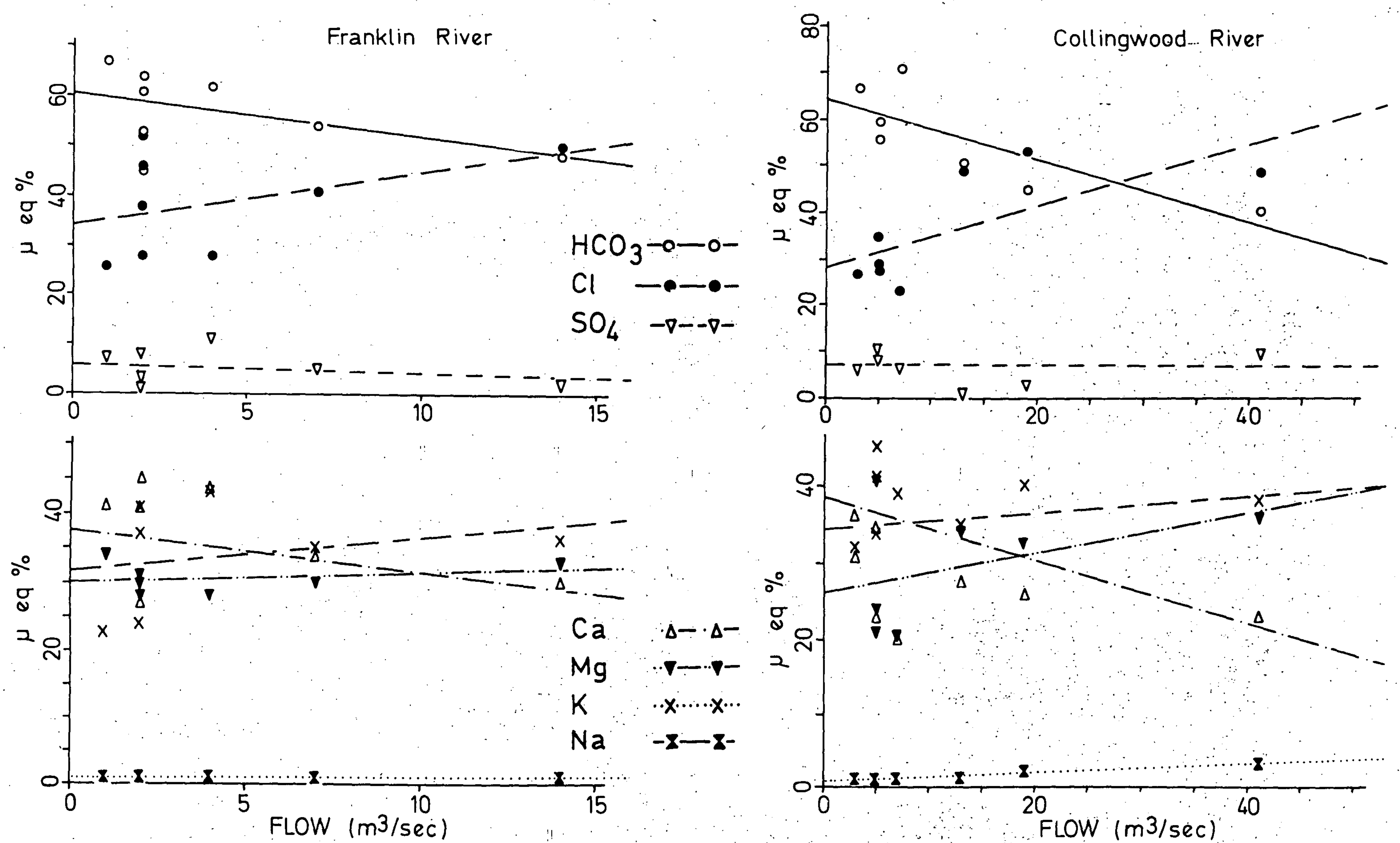


FIGURE 33

RIVER FLOW AND IONIC PROPORTIONS FOR THE UPPER FRANKLIN RIVER CATCHMENT. REGRESSION EQUATIONS FOR THE LINES FITTED ARE IN APPENDIX 4.

dramatic increase in sodium, unaccompanied by an concomitant rise in chloride in October 1977 can not be explained. Potassium was in low concentrations and showed only minor variations (Figure 35). Clearly, these two rivers experience considerable geochemical influence especially at low flows, and showed somewhat more affinity with World Average Freshwater than with seawater (Figure 34).

The relationship between river flow and salinity (Figure 35) shows that for both rivers very small increases in flow reduced the dissolved load considerably. In the Collingwood River, for example, salinity increased rapidly at flows below 10 $m^3\ s^{-1}$, and in the Franklin River below about 5 $m^3\ s^{-1}$. The Collingwood River carried a dissolved load of about 3 to 5 times that of the Franklin River at low flows, and at high flows about twice that of the Franklin River. Apart from this difference, the two rivers behaved very similarly throughout the study period (Figure 31 and 32). Probably, this is a consequence of the nearness and general similarity of their respective catchments.

6.2.4 Creeks

Seasonal samples were collected from Cataract Creek (3081041) (Plate 14), Roaring Creek (3081012) (Plate 15) and from the two creeks flowing into Lake Fidler, (both 3081061, see Figure 7). Seasonal variation in flow, concentrations of major ions, colour and other chemical parameters for Roaring and Cataract Creeks are presented in Figure 36. The relationship between flow and ionic composition for these two creeks is shown in Figure 37 and ternary diagrams show the ionic proportions of all four creeks (Figure 38). Figure 39 shows the relationship between flow and dissolved salts for Cataract Creek and Roaring Creek. The water chemistry data for Lake Fidler inflows is presented in Table 8.

Flow variation in the creeks was not great (Figure 36). There was reasonable correlation between flow and colour (gilvin) and in both creeks gilvin values dropped steadily after July 1977, as in the major rivers (see Figure 23).

All four creeks were always acid (pH 3.9-6.3) and no seasonal pattern was obvious. Their major ion chemistry was dominated by sodium and chloride at all times (Figures 37 and 38). And only these two, of the major ions, varied greatly in concentration, and then with no obvious seasonal pattern.

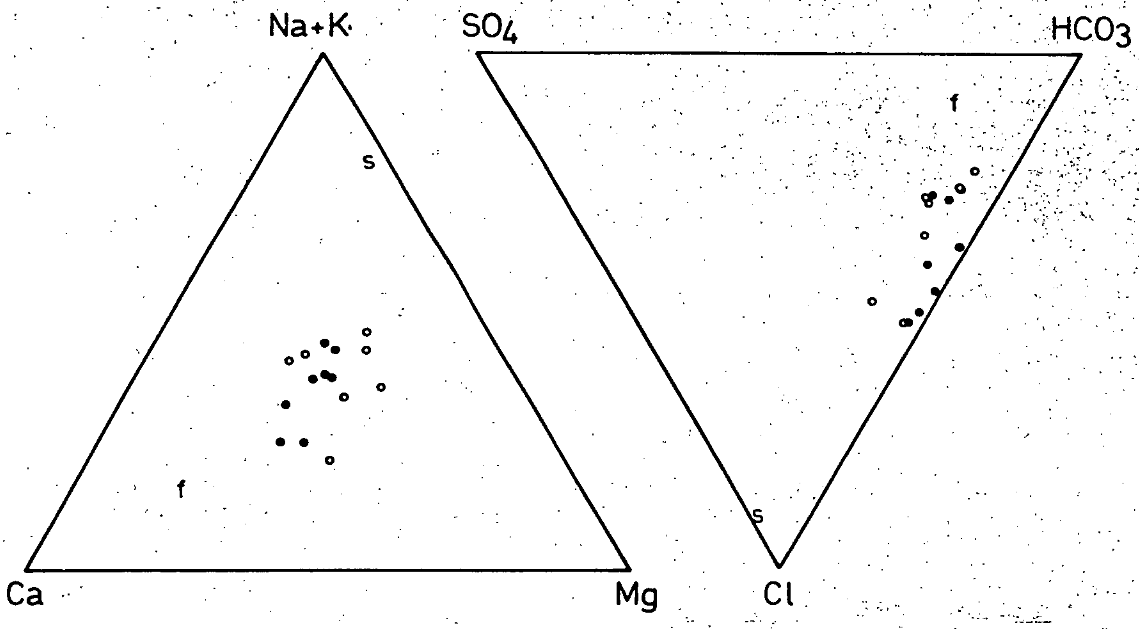


FIGURE 34

PROPORTIONS OF MAJOR IONS IN THE UPPER FRANKLIN RIVER (●) AND COLLINGWOOD RIVER (○).

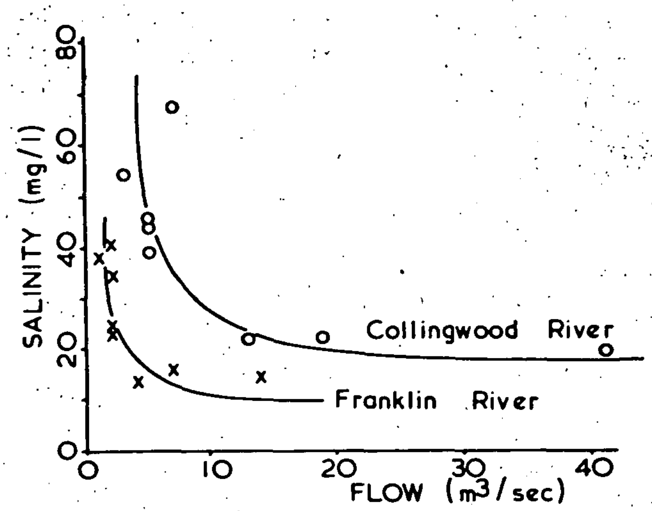


FIGURE 35

SALINITY AND FLOW IN THE HEADWATERS OF THE FRANKLIN RIVER.

PLATE 13

CATARACT CREEK AT SIR JOHN FALLS WHEN RIVER FLOW IS LOW.

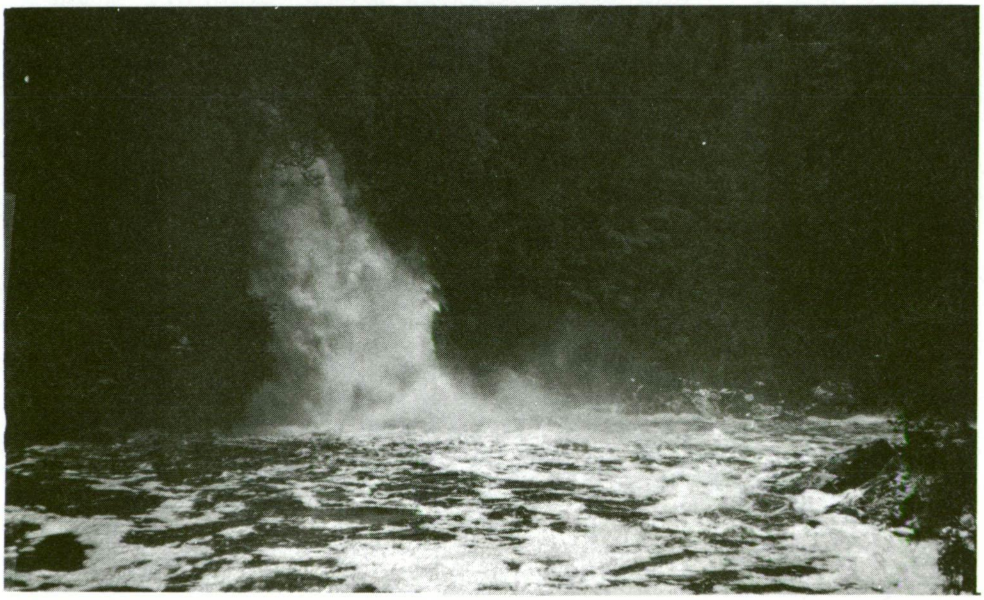


PLATE 14

CATARACT CREEK AT SIR JOHN FALLS DURING WINTER FLOODING.

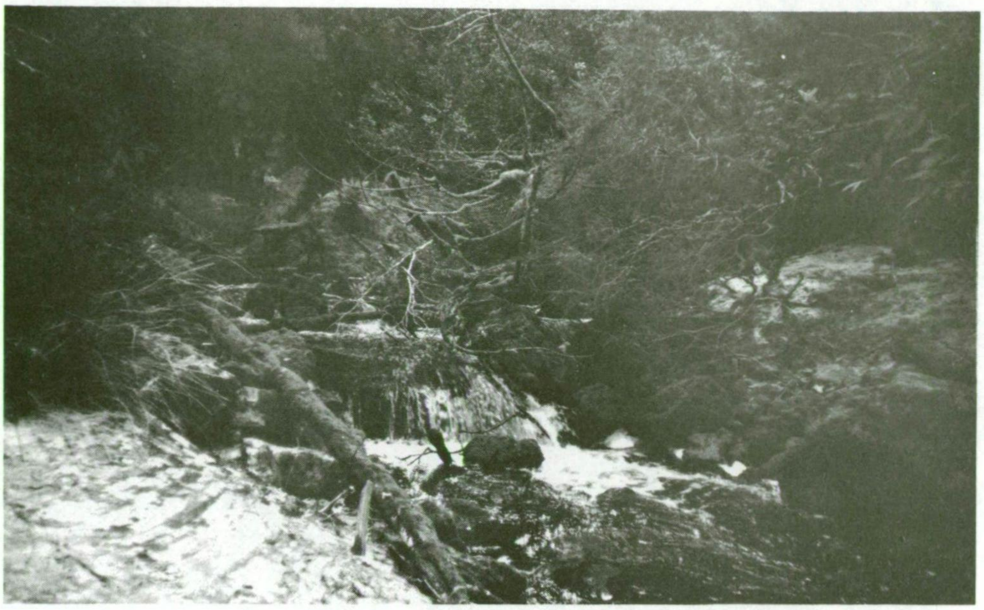


Plate 15

Roaring Creek, 1 km upstream from the Franklin Junction. Franklin River is just out of the picture on the bottom right.

Plate 16

Smith River, 2 km upstream from the Olga Junction in January 1977.

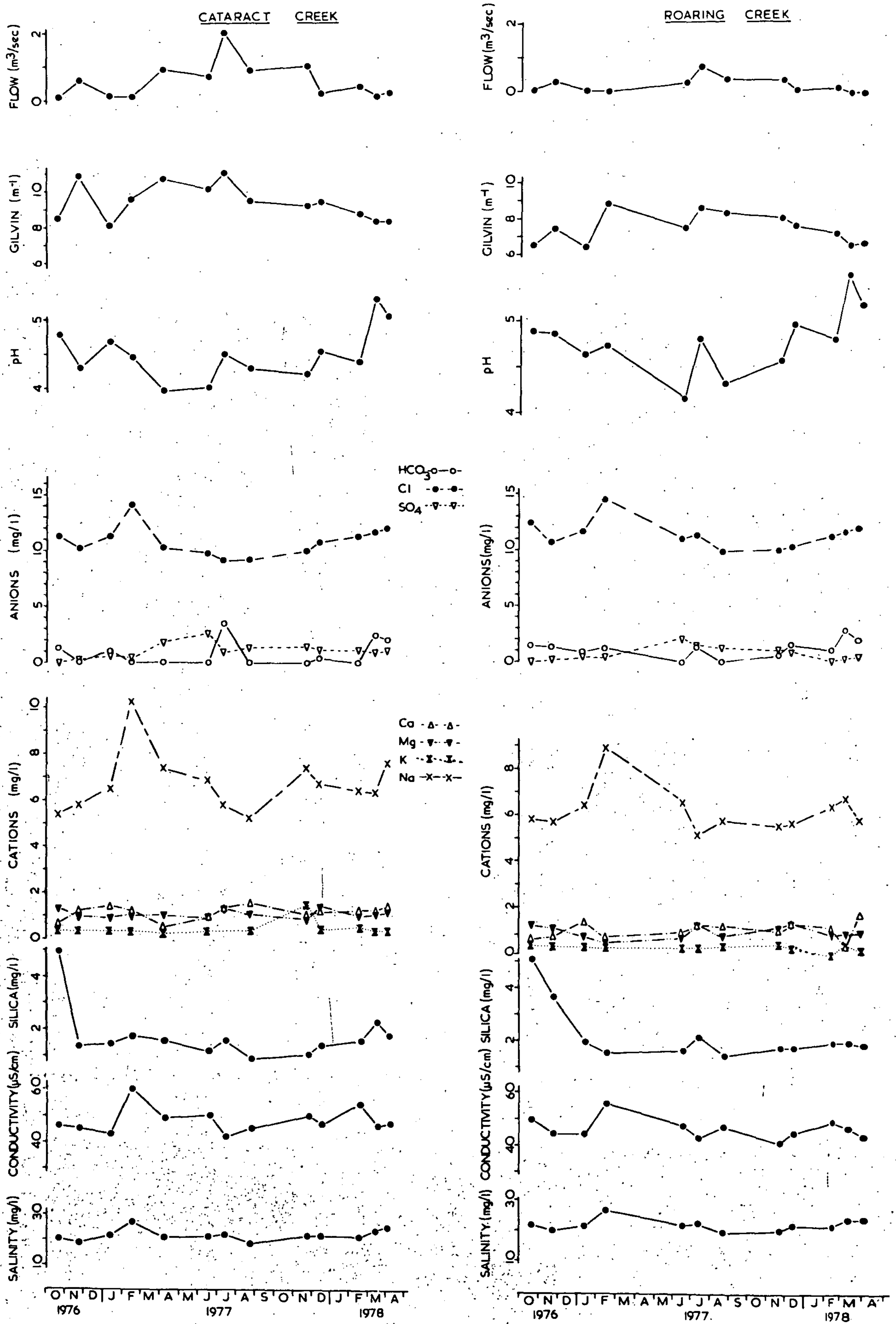


FIGURE 36

TEMPORAL VARIATIONS OF FLOW, GILVIN AND MAJOR IONS, AND OTHER CHEMICAL PARAMETERS IN CATARACT AND ROARING CREEKS.

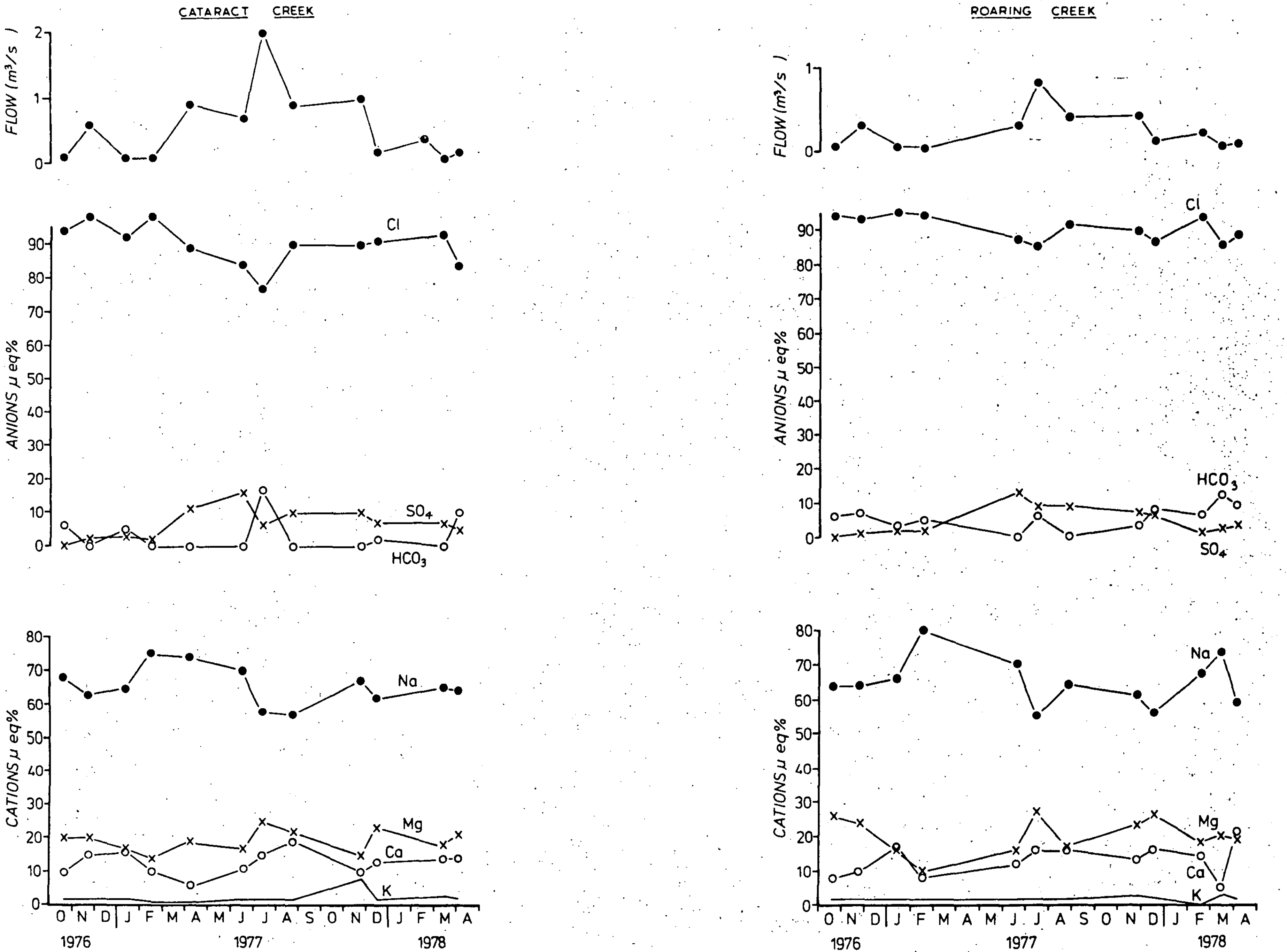


FIGURE 37

TEMPORAL FLOW AND PERCENTAGE IONIC COMPOSITION.

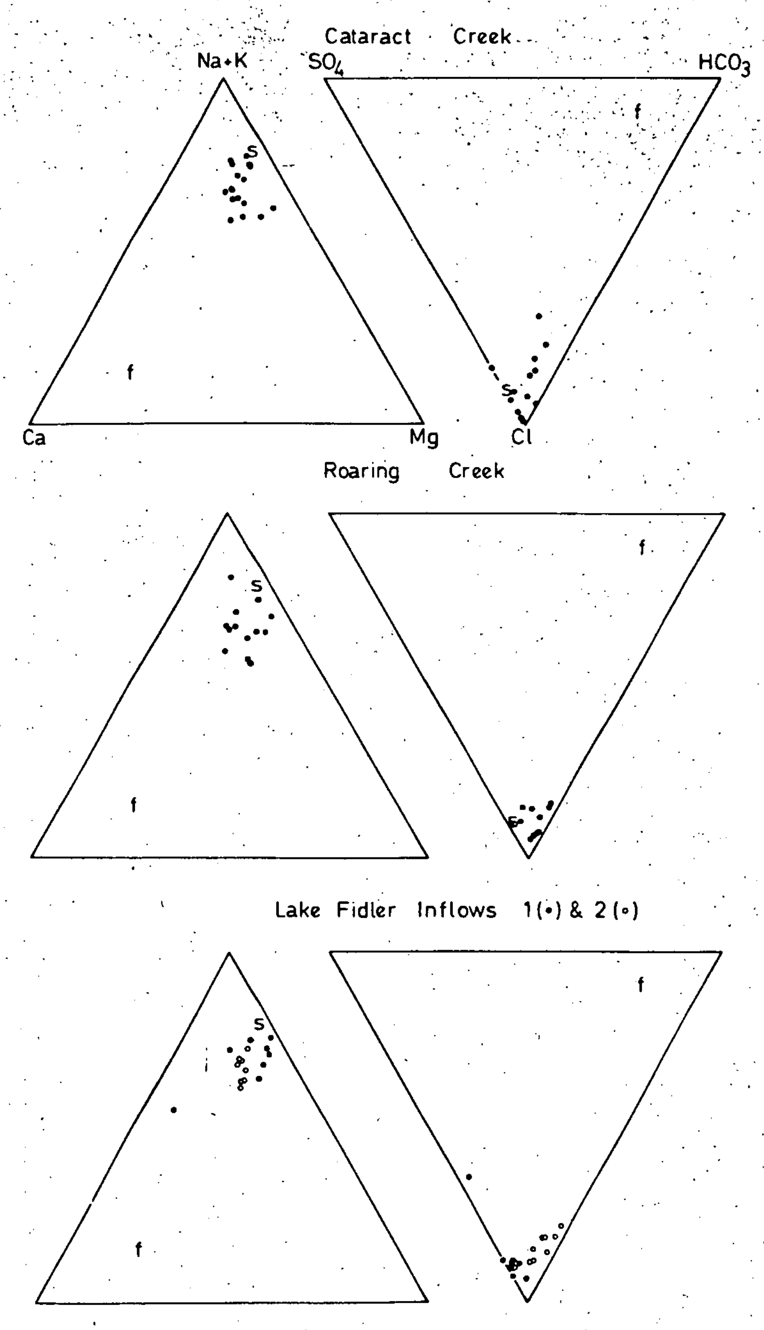


FIGURE 38

IONIC PROPORTIONS OF CREEK WATER. WORLD AVERAGE FRESH-WATER (f) AND SEAWATER (s) ARE INCLUDED FOR COMPARISON.

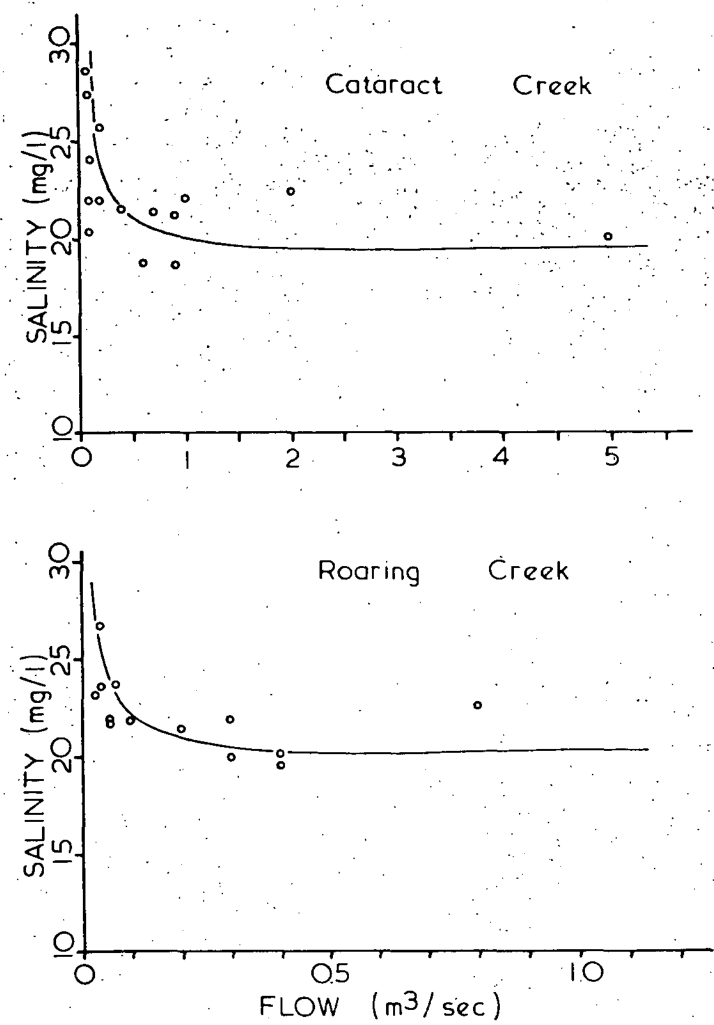


FIGURE 39

CREEK FLOW AND SALINITY IN CATARACT CREEK (○) AND ROARING CREEK (●).

TABLE 8

Water Chemistry Data for Lake Fidler Inflows

INFLOW 1

Date Taken	22.2.77	8.4.77	16.6.77	25.8.77	26.10.77	14.12.77	15.2.78	15.3.78
Lab pH	4.5	4.7	4.3	4.2	4.5	4.7	4.6	4.5
Gilvin G440 (m^{-1})	5.7	6.2	6.2	6.3	6.5	6.7	6.7	5.9
Alkalinity (HOC_3) mg/l	0	1.1	0	0	0	1.0	0.80	0.6
Chloride (Cl) mg/l	14.9	20.2	14.2	13.1	12.8	13.3	12.4	13.5
Sulphate (SO_4) mg/l	2.2	1.0	2.5	1.8	1.5	9.1	1.4	1.9
Calcium (Ca) mg/l	0.8	0.6	0.8	1.1	0.5	4.3	1.4	0.2
Magnesium (Mg) mg/l	1.1	1.8	1.4	1.5	1.3	0.6	0.8	1.1
Potassium (K) mg/l	0.4	0.2	0.4	0.5	0.4	0.4	0.3	0.2
Sodium (Na) mg/l	8.6	10.8	7.2	6.9	7.0	7.8	7.9	7.2
Silica (SiO_2) mg/l	7.3	5.0	5.3	2.1	2.6	2.1	12.5	2.6
Conductivity at 18 degrees Celsius (micro siemens cm^{-1})	57	67	56	59	54	80	64.5	54.5
Salinity (mg/l)	28.0	35.7	26.5	24.9	23.5	36.5	25.0	24.7

TABLE 8

Water Chemistry Data for Lake Fidler Inflows

INFLOW 2

Date Taken	22.2.77	8.4.77	13.7.77	25.8.77	26.10.77	14.12.77	15.2.78	15.3.78
Lab pH	5.7	5.4	5.3	4.9	5.0	5.3	5.7	6.3
Gilvin G440 (m^{-1})	6.6	8.3	9.0	8.1	7.7	7.5	7.6	6.5
Alkalinity (HCO_3) mg/l	4.4	3.6	2.9	1.7	2.0	2.7	4.7	6.7
Chloride (Cl) mg/l	15.8	15.3	11.0	13.5	13.8	14.5	13.5	15.6
Sulphate (SO_4) mg/l	1.4	0.5	1.0	1.0	0.9	1.4	0.5	0.6
Calcium (Ca) mg/l	1.9	1.6	1.1	1.9	1.1	1.8	2.1	1.4
Magnesium (Mg) mg/l	1.4	1.3	1.0	1.5	1.3	1.6	1.7	1.4
Potassium (K) mg/l	0.5	0.4	0.4	0.6	0.6	0.4	0.3	0.3
Sodium (Na) mg/l	9.7	9.5	6.8	7.3	9.5	8.6	9.5	8.0
Silica (SiO_2) mg/l	7.9	2.8	1.9	2.2	1.7	2.6	14.5	3.2
Conductivity at 18 degrees Celsius (micro siemens cm^{-1})	61	55	46.0	54	55	56.5	64.2	60.0
Salinity (mg/l)	35.0	32.2	24.2	27.4	29.1	30.9	32.3	33.9

Predictably, bicarbonate concentrations were very low in these acid waters. Sulphate was also scarce, as elsewhere in the catchment. Since sodium and chloride were such overwhelming dominants (Figure 38) it is not suprising that conductivity and salinity varied so positively with them (Figure 36). This ionic composition indicates only minor geochemical influence of the local rainfall by seepage water from the local Ordovician sedimentary rocks, and ionic proportions were close to those of seawater (Figure 38).

The relationship between salinity and flow in both Cataract and Roaring Creeks (Figure 39) showed a similar pattern to the Gordon and Franklin Rivers (Figure 28) and the upper Franklin and Collingwood (Figure 35), though the flow magnitudes were considerably smaller. The reason for increased salinities in the absence of significant geochemical contribution of ions (Figure 38) is not clear.

6.3 <u>"Pickup" Rivers</u>

This section deals with the rivers and creeks tributary to the Gordon and Franklin Rivers, which were sampled only occasionally. Their flow constitutes river "pickup" to the Gordon-Franklin junction (see Figure 4). The river inflow into Lake Gordon from the upper Gordon River will also be discussed.

Generally, only summer samples were collected (by helicopter, when river flows were low), from the normally inaccessible minor rivers. Therefore, the influence of groundwater discharge is likely to be more apparent than if sampling had been continued over the whole year. The chemical information for these pickup rivers is presented in detail in King and H.E.C. (1978), and here only a summary is presented.

6.3.1 Gordon River above Lake Gordon

The Gordon River headwaters were sampled below the Huntley Rivulet junction (308002). Flow in the Huntley Rivulet was insignificant in comparison to that in the Gordon River.

The upper Gordon River flows through the Vale of Rasselas which has extensive alluvial deposits overlying the Gordon Limestone. Chemical composition of the river below the Huntley junction was dominated by the alkine earths. At low flow bicarbonate dominated the anions but at higher flows chloride was dominant. The sample taken at low flow had a relatively high salinity, and though calcium plus magnesium dominated the cations, sodium still represented 36%. This probably reflects the marine origin of the underlying limestones. The pH ranged from 6.3 to 7.5.

There is a strong negative correlation (r = -0.95) between salinity and flow in the Gordon River below Huntley, where salinity ranged between 19-54 mg/l. All samples were light to moderately coloured and non-turbid (maximum turbidity of 1.7 FTU).

The chemistry of a single sample labelled "Gordon River east of Timbs Ridge" was sodium chloride dominated, moderate in colour (gilvin = 4.75 m^{-1}), low in turbidity (1.4 FTU) and unusually acid (pH = 4.1). There is some doubt as to whether this was the Gordon River itself or a tributary creek draining the Vale of Rasselas.

6.3.2 Huntley Rivulet (3091057)

The Huntley Rivulet drains similar terrain and geology to the Gordon River headwaters, with extensive buttongrass plains in its catchment. The water of a single sample was highly coloured (300 Pt, G_{400} = 9.8) and acid (pH = 5.8) probably because for most of its length it flows through buttongrass plains. Turbidity was low (1.7 FTU).

6.3.3 Albert River (3081016)

A single sample was collected in summer. The water was acid (pH = 4.45), darkly coloured (G440 = 17.55 m^{-1}) and had a cationic composition close to that of seawater, with only moderate additions of calcium and magnesium from the Precambrian rocks of the catchment. Since sulphates are low throughout the region, and the bicarbonate ion cannot exist below pH4.5, chlorides accounted for 94% of the anions.

6.3.4 Orange River (3081055) (=Albert Creek on some geological maps)

A single sample had an ionic composition dominated by alkaline earth bicarbonates, a pH of 7.2, and relatively high colour (G440 = 7.08). The cationic dominance order was unusual - Mg > Na > Ca > K. Magnesium dominance was also detected in the Jane and Maxwell Rivers (see below).

6.3.5 Maxwell River

Two autumn samples were taken from the headwaters of the Maxwell River from seepages draining Leptospermum, Bauera and Sprengelia scrub on shallow peat soil over alluvium (sites 3081049 and 3081050). They had pH values around neutral and were rich in dissolved organic matter (G440 values of 12.20 m^{-1} and 10.58 m^{-1} respectively), being much darker than the major rivers at this time. There is Precambrian dolomite in the catchment, and ionic composition suggested considerable geochemical influence:-

Order:	Mg >	Ca >	Na >	K ;	HCO_3 >	Cl >	SO_4
Mean ueq %	42	32	25	1	66	31	3

The reason for the 10% magnesium dominance over calcium is not known. It may be an inherent feature of the West Coast dolomites, though the mean molar ratio (Mg : Ca = 1.03 (Rao and Naqvi, 1977)) of local dolomites would suggest otherwise. Buckney and Tyler (1973a) found an approximately equimolar ratio for waters from Mt. Anne dolomites but heavy domination by magnesium in a creek draining serpentinite of the Sawback Range.

The mainstream flow of the Maxwell River was sampled at two sites (3081054 and 3081022) upstream from the Denison junction. Salinity and conductivity varied inversely with river flow (r = -0.97).

In three samples magnesium was the dominant cation, with sodium (2) or calcium (1) as second dominant. Bicarbonate dominated the anions in these samples. In the fourth sample cationic and anionic proportions were similar to those of seawater, so that it seems likely that the water chemistry of the Maxwell fluctuates as it does in the Gordon, Franklin and Jane Rivers. The Maxwell in summer was alkaline (pH 7.03 - 7.98) except for the one sample with sodium chloride dominance (pH = 6.64), and contained negligible turbidity. The characteristics of the river under flood conditions are not known.

6.3.6 Denison River

Water from the Denison River was collected from two sites - upstream of the Maxwell junction (3081021), and at Denison Camp (308013) - between

1976 and 1978.

The two samples from above the junction were basic (pH 7.50 and 7.74) and moderately coloured (G440 2.3 - 3.9 m^{-1}). Ionic dominance orders were Ca >Mg >Na >K: HCO_3 >Cl >SO_4.

A total of six samples from the river below the entry of the Maxwell had a pH between 7.02 and 7.85 and were alkaline earth-bicarbonate dominated.

At high flow sodium was the dominant ion but calcium plus magnesium bicarbonates together considerably exceeded sodium and chloride. At low flow either calcium or magnesium was dominant with sodium in second place. Ionic proportions are shown in Figure 40. The strong alkaline earth influence is clearly demonstrated by the position close to World Average Freshwater.

All the samples had relatively high colour (G440 2.3 - 8.0 m^{-1}) and low turbidity (0.42 - 0.90 F.T.U.).

The relationship between salinity and flow is shown in Figure 41. As with other rivers in the area (Figures 28, 35, 39) salinity increased exponentially with decreasing flow.

6.3.7 Smith River (3081025) and Harrison Creek (3081023)

These two rivers drain Precambrian rocks of the western slopes of the Nicholls and Princess Ranges (Plates 12 and 16). The valley floor is composed of siltsone shales. Though Harrison Creek flows over Precambrian metamorphic rocks for most of its length, Gordon Limestone and Precambrian dolomites near its mouth influence its chemical composition during low summer flows.

Both waters were alkaline (pH 7.2 - 7.7) and moderately coloured (G440 2.03 - 8.55 m^{-1}) during the summer. The anions were dominated by bicarbonate, in the mean proportions of bicarbonate 63%, chloride 34% sulphate 3%. However, as far as the cations were concerned, Smith River was dominated by sodium or calcium, with magnesium the second or third most numerous ion. Surprisingly, though this watershed is composed predominantly of Gordon Limestone sequences, the summer cationic composition is dominated by sodium. As low river flow implies an absence of

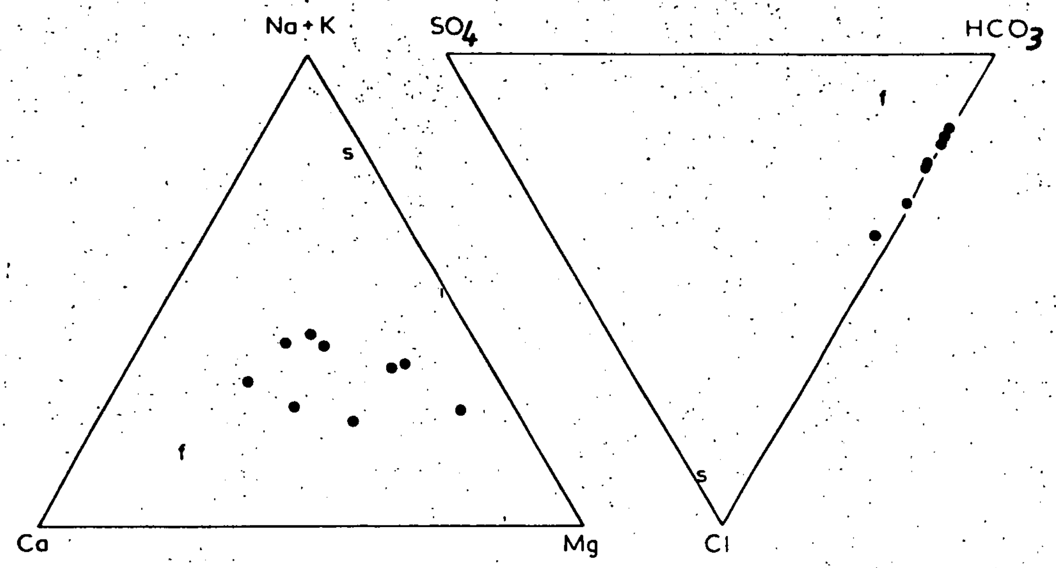


FIGURE 40

IONIC PROPORTIONS FOR THE DENISON RIVER AT DENISON CAMP.

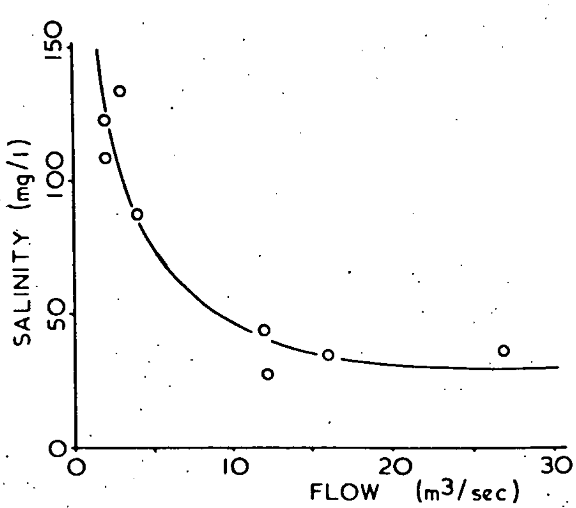


FIGURE 41

SALINITY AND FLOW IN THE DENISON RIVER AT DENISON CAMP.

rainfall in the catchment, this sodium probably has a geological origin, i.e. originates from marine limestone rocks. Though sodium was dominant on occasions, the sum of calcium and magnesium greatly exceeded sodium so that the waters were essentially of the alkaline earth bicarbonate type.

Harrison Creek was always dominated by magnesium or calcium. Though sodium may by second dominant, the sum of calcium plus magnesium bicarbonates always greatly exceeded sodium and chloride. Even so, the marine limestones probably contribute sodium as well as alkaline earths.

6.3.8 Olga River (3081030) and (3081027)

The Olga River was sampled several times during the three summer seasons of the survey, at two sites, namely four km upstream of the Gordon junction (site 3081030 Plate 3) and downstream from the Olga-Hardwood Saddle (3081027) Plate 4). Samples were also collected from two small influent creeks draining the Precambrian metamorphic rocks on the western flank of the Olga Valley, Upper Spur Creek, 3081028, and Lower Spur Creek, 3081029.

The influent creeks were acidic (pH = 6.4 - 6.5), moderately coloured (Pt 100 - 150) and non turbid (1.0 - 1.2 FTU). The cationic dominance order was that of seawater ($Na > Mg > Ca > K$) and the anionic order, $Cl > HCO_3 > SO_4$, suggested slight geochemical influence. This is reinforced by the fact that in Lower Spur Creek (3081028) bicarbonate was only 14% lower than chloride, and calcium and magnesium together contributed 34% of the cations. In Upper Spur Creek Mg + Ca contributed 42% of cations. Other evidence of geological contributions to the water chemistry of these creeks is that the molybdate-reactive silica concentrations were extremely high (up to 60 mg/l) for Gordon River Basin waters. Similar high silica concentrations were recorded in the Olga River further downstream but other rivers in the study area, draining similar Precambrian rock types, did not contain such high dissolved silica concentrations. Buckney and Tyler (1973) found that silica concentrations in the South West region of Tasmania rarely rose above 5 mg/l, well below the world average of 13 mg/l suggested by Davies (1964).

In the Upper Olga (3081027) the pH varied from 6.3 to 7.8 and the

G440 from 5.2 - 14.4 m^{-1}. Anionic dominance fluctuated between chloride and bicarbonate, and cationic dominance between calcium, magnesium and sodium in a way not related to flow but calcium plus magnesium equalled or exceeded sodium on all occasions. When chloride was dominant over bicarbonate the pH was less than 7.

The chemistry of the river from a point about 4 km from the mouth of the Olga, mostly taken on the same days as the upper Olga samples, was similar to that of the latter samples taken from both points on the same day did not necessarily have closely similar in water chemistry, implying that there can be horizontal variation in chemical parameters. A single sample from the mouth of the Olga was similar in chemistry to other Olga samples.

Several unusual ionic orders of dominance were recorded in the Olga River.

The following order of dominance has not previously been recorded in Tasmania (see Tyler, 1974):

$$Mg > Ca > Na > K:\ Cl > HCO_3 > SO_4.$$

An unfamiliar ionic order recorded was

$$Na > Mg = Ca > K:\ Cl > HCO_3 > SO_4$$

Turbidity values were less than 3.0 FTU, which indicates an absence of fluvial erosion in the drainage basin, the only suspended particulate material present in the waters being decomposing organic material washed from the vegetation litter layer and from the forest peats.

6.3.9 Sprent River (3081033)

The Sprent River drains the Precambrian quartzites on the steep southern slopes of the King Billy Range, and the buttongrass plains which lie between the D'Aguillar Range, Badger Ridge and Innes Peak.

Predictably, the waters were acid (pH 4.6 - 6.5) and fairly darkly coloured (G440 6.38 - 9.35 m^{-1}), with mininal turbidity (0.9 - 1.0 FTU). The water chemistry was dominated by sodium and chloride, and had a sea-water order of ionic dominance except on one occasion when calcium exceeded magnesium. The chemistry of this river would probably not alter significantly during winter except for a reduction in salinity.

6.3.10 Seepage Creeks - Franklin Junction (3081035, 3081036 and 3081037)

Three seepage creeks in the vicinity of the Franklin-Gordon confluence (sites 3081035, 3081036 and 3081037) were sampled occasionally. They were all acid, with pH values ranging from 4.02 to 6.60, and all were non-turbid and darkly coloured (from 200 to 300 Pt). Ionic proportions were broadly similar to those of seawater except that calcium was relatively more abundant. On one occasion potassium dominated magnesium and calcium. This is a most unusual order and is most likely an anlytical error. Because of the low pH values bicarbonate was absent or scarce. Sulphate was also present in low concentrations.

6.3.11 Surprise River (3081053)

This river drains the dolomites to the north and east of Mt. Ronald Cross in the upper Franklin River catchment. A single sample, collected in the spring of 1977 when river flows were high,was alkaline(pH=7.1) and low in dissolved organic acids ($G_{440} = 2.0\ m^{-1}$). The major ion chemistry clearly reflected the catchment geology with the ionic dominance order similar to world average freshwater except that, as often happens in the South-West (see also Section 3.3), chloride exceeded sulphate. The proportions of calcium and magnesium were almost equal, as expected for dolomite waters.

The chemistry of Shirleys Pool (3081046), which is situated in Mt. Ronald Cross dolomites and adjacent to the Lyell Highway, had a similar chemistry except that magnesium was always the dominant cation; occasionally calcium almost equalled magnesium. During the rainy season the concentration of sodium increased slightly, but it always remained the third most dominant cation.

6.3.12 Andrew River (3081046)

The Andrew River lies in a valley south west of the Engineer Range. The drainage basin above the sampling site is composed of volcanic Cambrian rocks. Three samples were collected from the upper reaches, on the Crotty Track, draining the mineralized volcanic rocks of the West Coast Range. Some limestone is also present.

The waters were acidic (pH = 4.6 - 6.4) and moderately coloured (G_{440} = 4.13 - 4.93 m^{-1}, Pt = 100 - 200). The chemical composition was dominated by chloride, but the cationic order of dominance was not necessarily that of seawater. In the spring sample (25th October 1977) calcium was more abundant than magnesium. Calcium + magnesium together twice equalled or exceeded sodium. Bicarbonate concentrations always exceeded those of sulphate. Between the Lyell Highway and Mt. McCall the Franklin River changes from sodium and chloride domination to an alkaline earth bicarbonate type of water. The Andrew River and Jane River are principal tributaries of the Franklin and it seems likely that they contribute Ca, Mg and HCO_3 from the seepage creeks as they flow to the Franklin, so changing the chemistry of that river.

6.3.13 Jane River (308011)

The Jane River flows through a considerable area of exposed Precambrian dolomites from the source in the Lightning Plains to the sampling point at Punt Hill (Plate 6), which is about 10 km from its confluence with the Franklin River. The topography in the headwaters is undulating to hilly and becomes very steep and rugged where the Jane River flows between the Norway and Surveyor Ranges. These ranges are composed of Precambrian metamorphic rocks overlying the dolomites. The river waters were alkaline under low flow conditions, and, as flow increased, so the pH decreased. At flows above about 50 m^3 sec^{-1} the waters became acid. The regression relationship between pH and flow is:

$$\text{Flow} = 7.46 - 0.009\ \text{pH}$$
$$n = 9$$
$$r = -0.76$$

This suggests that, during low flow, deep storage water emanating from the dolomites of the upper catchment constitutes the bulk of river flow, to be exceeded, as rainfall increases, by acidic surface waters and shallow groundwater storage. For example, for the lowest flow (1 m^3/sec) the pH was 7.88. At a flow of 121.8 m^3/sec the pH was 6.4. Further evidence for this is the significant correlations between flow and bicarbonate and chloride proportions (Figure 42). Relationships between river flow and major cation proportions are not significant (Figure 42).

The ionic composition under low flow conditions was dominated by

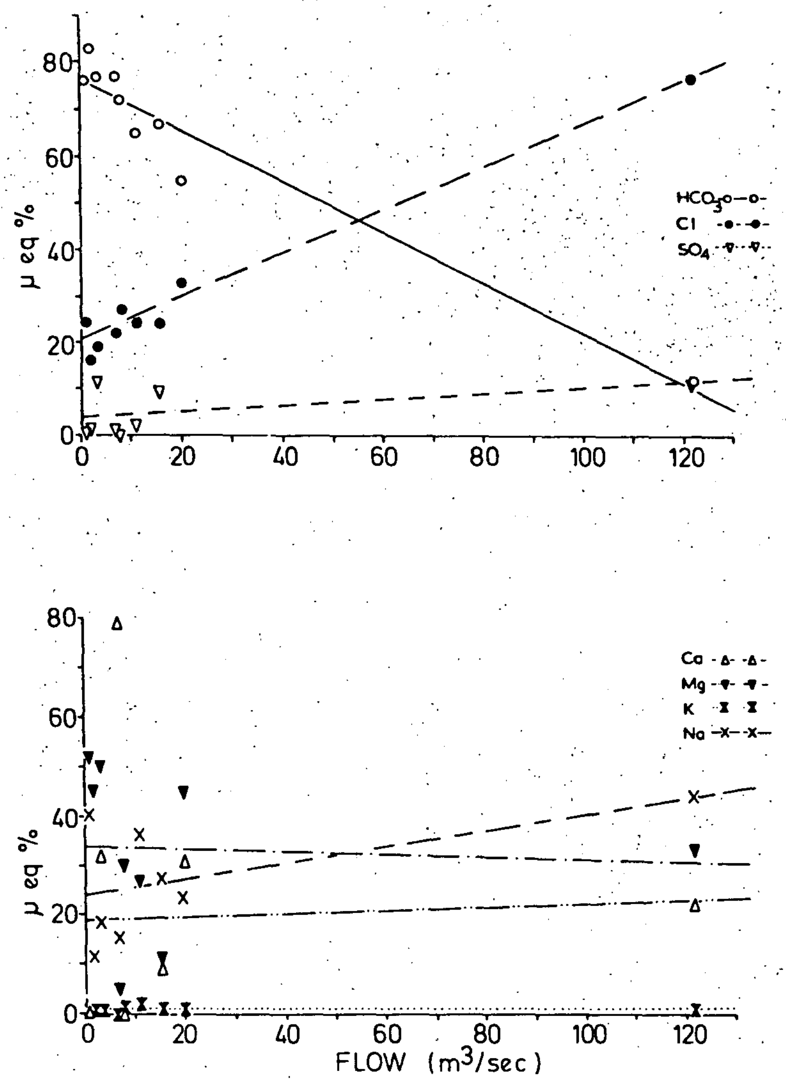


FIGURE 42

RIVER FLOW AND IONIC COMPOSITION IN THE JANE RIVER AT PUNT HILL. REGRESSION EQUATIONS OF THE LINES FITTED ARE IN APPENDIX 4.

alkaline earth bicarbonates. Only on one occasion, when the river was in flood (121.8 m^3/sec), did chloride exceed bicarbonate and sodium exceed calcium and magnesium. Similar ionic relationships occurred elsewhere in the Gordon River Basin, where rivers drain limestone rocks(Section 7.2).

Under moderate flow levels sodium sometimes became the second most dominant cation, for of the cations sodium was most significantly affected by river flow. River flow and salinity of the water were related in a similar way as for other rivers in the area(Figure 43). The relationship between river flow and salinity is given by the regression equation

$$\log \text{flow} = 2.213 - 0.4571 \log \text{salinity}$$
$$n = 9 \qquad r = -0.95$$

At very low flows salinity was high and variable. As flow increased, so salinity decreased and became less variable. Under flood conditions it would probably vary very little and tend to a minimum value similar to rainwater (Figure 43). The concentration of molybdate reactive silica was similarly correlated with flow, being higher at low flows.

The regression equation is

$$\log \text{flow} = 0.7321 - 0.2645 \log \text{Si} \qquad n = 9 \quad r = 0.87$$

With increased silicate and bicarbonate concentrations at low flows the pH became more alkaline. Both potassium and sulphate were present in very low concentrations and showed little response to flow.

6.4 Longitudinal Variation

Comparisons of the degree of variation in water chemistry along the length of the Gordon River on specific dates gave clear indication of the effect of the power station release on river chemistry. Springtime samples from 24th November 1976 have been compared with others for the 23rd November 1977, and the summer samples from the 12th January 1977 with those of 13th March 1978. The first samples of each of the above pairs of data were when Lake Gordon was filling, the latter data of each pair after release of water from Lake Gordon began. The data are presented in Figure 44. No data on chemical variation along the rivers are available for the period before construction of the Gordon Dam.

The flow pattern in the Gordon River has been significantly altered by construction of the Gordon Dam, while the tributary rivers still display their natural flow regimes (Figures 5 and 44). The natural mean monthly maximum flow has been decreased by 66.58 m^3/s and the minimum flow in-

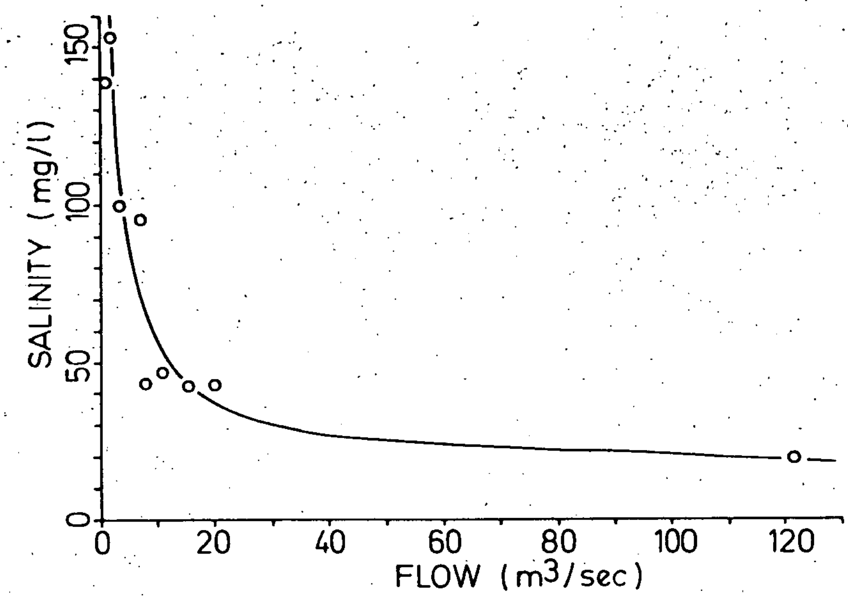


FIGURE 43

SALINITY AND FLOW IN THE JANE RIVER AT PUNT HILL.

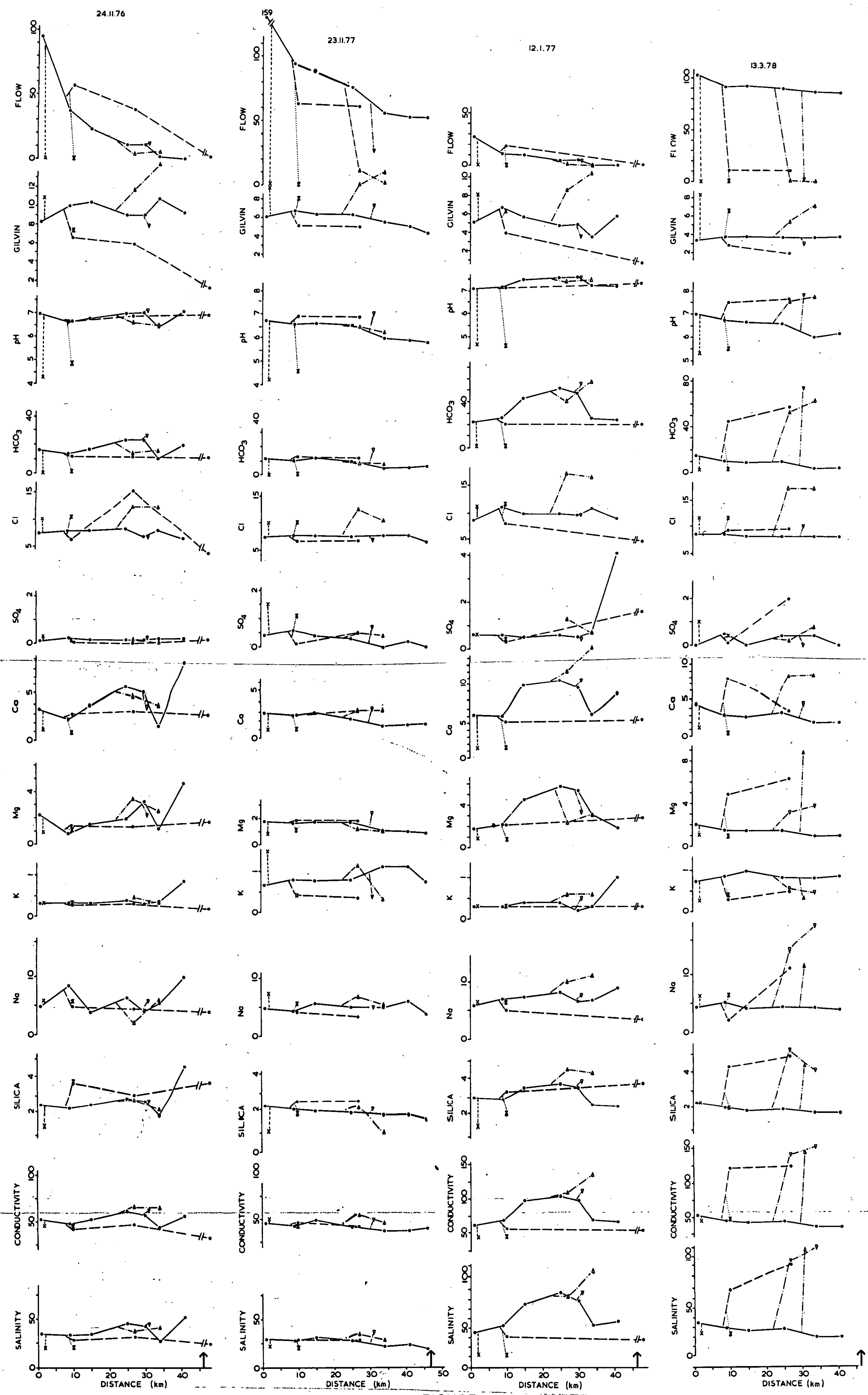


FIGURE 44

EFFECTS OF GORDON POWER STATION RELEASE ON WATER CHEMISTRY DOWNSTREAM OF THE GORDON DAM. UNITS OF MEASUREMENT ARE FLOW (m^3/sec), GILVIN ($G_{440}.m^{-1}$), pH UNITS, MAJOR IONS, SILICA AND SALINITY (mg/l) AND CONDUCTIVITY (μS/cm). SAMPLES COLLECTED ON 24.11.76 AND 12.1.77 WERE BEFORE POWER STATION RELEASE, AND 23.11.77 AND 13.3.78 AFTER POWER STATION DISCHARGE COMMENCED. RIVER FLOW IS FROM RIGHT (GORDON DAM, ↑) TO LEFT (BUTLER ISLAND, 0 km). RIVERS ARE INDICATED AS FOLLOWS: GORDON RIVER (●—●), FRANKLIN RIVER (●–●), OLGA RIVER (Δ···Δ), DENISON/MAXWELL RIVERS (∇···∇), ROARING CREEK (⧗––⧗), CATARACT CREEK (X···X).

creased by 112.54 m^3/s by the operation of the Gordon Power Station (Watson 1978a). The Franklin River flow exceeded that of the Gordon River at their confluence on the sampling dates before release commenced (Figure 44). However, this was for a period when Lake Gordon was filling, and had the Gordon been running freely, the reverse would probably have been true. The flow of the Olga and Denison Rivers was similar to that of the Gordon River on sampling dates before power station release began, but afterwards Gordon River flow greatly exceeded its previous summer values as well as the combined flow of the "pickup" rivers. Contribution of the tributary rivers to the flow of the Gordon River has, since Gordon Power Station release, become insignificant and consequently their influence on physical, chemical and biological conditions in the Gordon will have been all but removed.

6.4.1 Dissolved Organic Material

Before power station release commenced, the concentration of dissolved organic matter (gilvin) in the Gordon River was influenced by contribution of the darkly coloured tributaries and peat seepages along the length of the river. The Olga River and Cataract Creek were considerably darker than the Gordon River, while the Denison River, Franklin River and Roaring Creek contained less dissolved coloured organic material. This is probably in part related to soil differences. The headwaters of the Olga drain extensive buttongrass plains, with deep muck to spongy peats(Jarman and Crowden,1978; Tarvydas, 1978) and here the most coloured waters were found (G440 up to 14.4 m^{-1});$\geq$360 Pt). This contrasts with the shallower, more fibrous peats and forest of the Franklin River. From Figure 44 it appears that the Olga River increased the concentration of gilvin in the Gordon while the Franklin River had a diluting effect. After commissioning of the power station the colour of the Gordon River remained virtually unchanged or increased very gradually from the Gordon Dam to Butler Island.

6.4.2 pH

Figure 44 shows that before power station release commenced, the pH varied little, but erratically, along the length of the Gordon,fluctuating by about 0.5 pH units below (24th November 1976) or above (12th January 1977) neutrality. After discharge commenced pH varied gradually by about 1 unit along the length of the river from a value of about 6.0 at Gordon Dam to near neutrality at Butler Island (Figure 44).

6.4.3. Major Ions

Before discharge from the power station commenced, there was considerable variation in bicarbonate concentrations along the length of the Gordon River as the ion accrued from limestone or dolomite drainages or was diluted by acidic inflows. In general bicarbonate levels in the Gordon were similar to or greater than those in its tributaries except the Denison (Figure 44). After discharge, variations in bicarbonate were minimal and the river contained less bicarbonate than tributaries other than the two small creeks. The overwhelming influence of Lake Gordon water is clearly shown by the data for 13th March 1978 when the acidic waters of Lake Gordon (Steane and Tyler, 1978) were scarcely affected by inflow of bicarbonate rich water (Figure 44).

Chloride is a conservative element in the biosphere, often derived principally from rainfall and, perhaps for this reason, it varied only slightly in concentration along the Gordon River under natural flow regimes (Figure 44). What little variation took place would result from variations of chloride concentrations in local rainfall and from varying rates of accretion from marine limestones. After discharge from Lake Gordon commenced chloride concentrations were practically unaltered along the whole sampled length of the river and were almost identical with those of the discharge stratum of Lake Gordon (210 ueq/l or 7.5 mg/l, see Steane and Tyler 1978).

Sulphate concentrations, always low, varied minimally along the length of all the rivers, greatest variation being recorded in the Franklin and Olga Rivers. No geochemical influence on sulphate concentration was apparent, nor did the release of water from Lake Gordon have any significant effect. The single high sulphate concentration in the Gordon River below the dam on the 12th January 1977 could have arisen from pollutants being washed downstream from the construction site.

Variations in the concentrations of divalent cations along the length of the river were also dimished after discharge from Lake Gordon commenced. This is particularly apparent from a comparison of the values for calcium and magnesium on 12th January 1977 and 13th March 1978 (Figure 44) and, less dramatically, for 24th November 1976 and 23rd November 1977. Before discharge there was considerable accretion of these elements from the Gordon Limestone in the mid reaches of the river. After power station operation commenced neither calcium nor magnesium varied much, despite considerably higher levels in the tributaries than in the main river (Figure 44). There is no explanation for the drop in calcium, magnesium and bicarbonate levels, before discharge, between the Olga and Franklin Rivers (Figure 44, data for 12th January 1977), nor for the fact that calcium levels in the tailrace samples (Figure 44) are about double those of the discharge stratum (Steane and Tyler, 1978).

As with divalent cations, the variability of the monovalent ions sodium and potassium was diminished after power station operation commenced. An unusual result is that potassium concentrations were approximately doubled after release of Lake Gordon water commenced and were then similar to those in the released water. Sodium concentrations in the river were somewhat less than in the discharged water.

Variations in silica concentrations also showed the effects of power station discharge in much the same way as other chemical parameters (Figure 44). As expected conductivity and salinity tell the same story as other parameters, particularly major ions, that is, greatly diminished fluctuations along the length of the river when increased flows from power station discharge overwhelm any affect the tributaries might have had (Figure 44).

6.5 Effect of the Gordon Dam on Water Chemistry of the Gordon River - Further Considerations

Evidence presented above shows that before release of Lake Gordon water commenced, entry of a tributary river, with different chemical characteristics from the Gordon River, could alter the chemical composition of the latter below the point of entry of the tributary. Under these circumstances the downstream reaches would display a chemical composition dependent on the chemistry and volumes of all inflowing contributions. The main variables affecting the composition of the rivers are the concentrations of ions in rainfall, and the contact time between water and readily soluble rocks, such as limestone and dolomite, which contribute principally the alkaline earth bicarbonates. As shown above (Section 6.4) the effects of inflows on the Gordon were best evidenced by changes in concentrations of calcium, magnesium and bicarbonate as tributaries entered

(Figure 44). In addition, changes in concentration of one or more of the major ions relative to the others are revealed by changes in ionic proportions, conveniently compared with those of seawater and "World Average Freshwater". Viewed in either of the above ways the effects of the discharge of Lake Gordon water were readily apparent (Figures 25, 44).

It must be emphasized that the above comparison of the Gordon River chemistry, before and after discharge of Lake Gordon water, is of two periods both of which are unnatural. During the former, when Lake Gordon was filling, the influence of the tributaries on the main river would have been greater than had the Gordon been flowing naturally. However it is likely that conditions downstream before filling commenced, at least at low flows of the Gordon River, were more like those during filling than those after discharge commenced (Figure 5).

This Section considers further the effects of discharge on river chemistry and includes H.E.C. data from before the dam constructed.

Figure 45 shows the ionic proportions of 4 sets of samples taken along the length of the Gordon before and after discharge commenced. They are the same samples discussed above (Figure 44). The samples fall fairly obviously into two groups on the ternary diagrams, those before discharge occupying a position towards World Average Freshwater, with calcium and magnesium in more or less equal proportions. This clearly demonstrates the influence of the major tributaries with limestone and dolomite in their catchments. In contrast, the samples taken after discharge commenced cluster more towards the seawater position, corresponding almost exactly with those of Lake Gordon (Figure 22 - 24 of Steane and Tyler, 1978).

Over a longer time scale, the seasonal variability of water chemistry has been changed by discharge from the Gordon Power Station. Variability of chemical parameters can be illustrated by the standard deviation of the number of determinations (Buckney, 1976) and the range of variation (Timms, 1970; Williams, 1965). Figure 46 shows the mean, range, and standard deviation for a number of chemical parameters before dam construction during dam filling, and after discharge commenced. For most parameters, it appears that variability was greater during filling, when pickup rivers constituted most of the flow in the Gordon River, than under natural

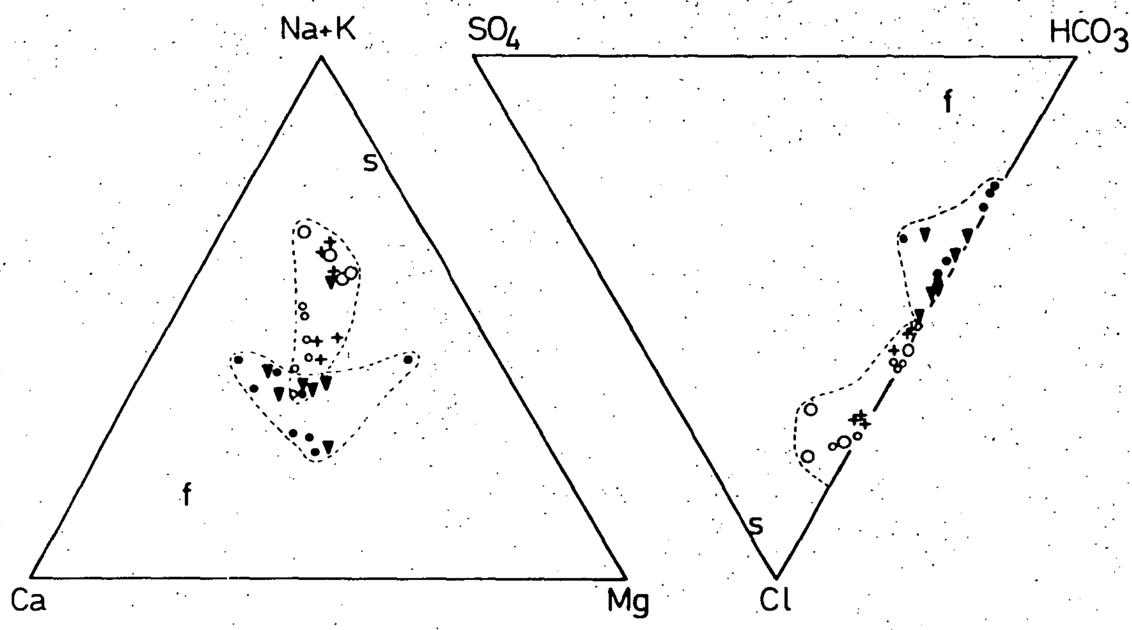


FIGURE 45

IONIC PROPORTIONS OF THE GORDON RIVER BEFORE RELEASE OF WATER FROM LAKE GORDON [24.11.76 (▼), 12.1.77 (●)], AFTER POWER STATION DISCHARGE COMMENCED [23.11.77 (+), 13.3.78 (o)], AND LAKE GORDON WATER AT 50 m (O). (Data for Lake Gordon from Steane and Tyler 1978.)

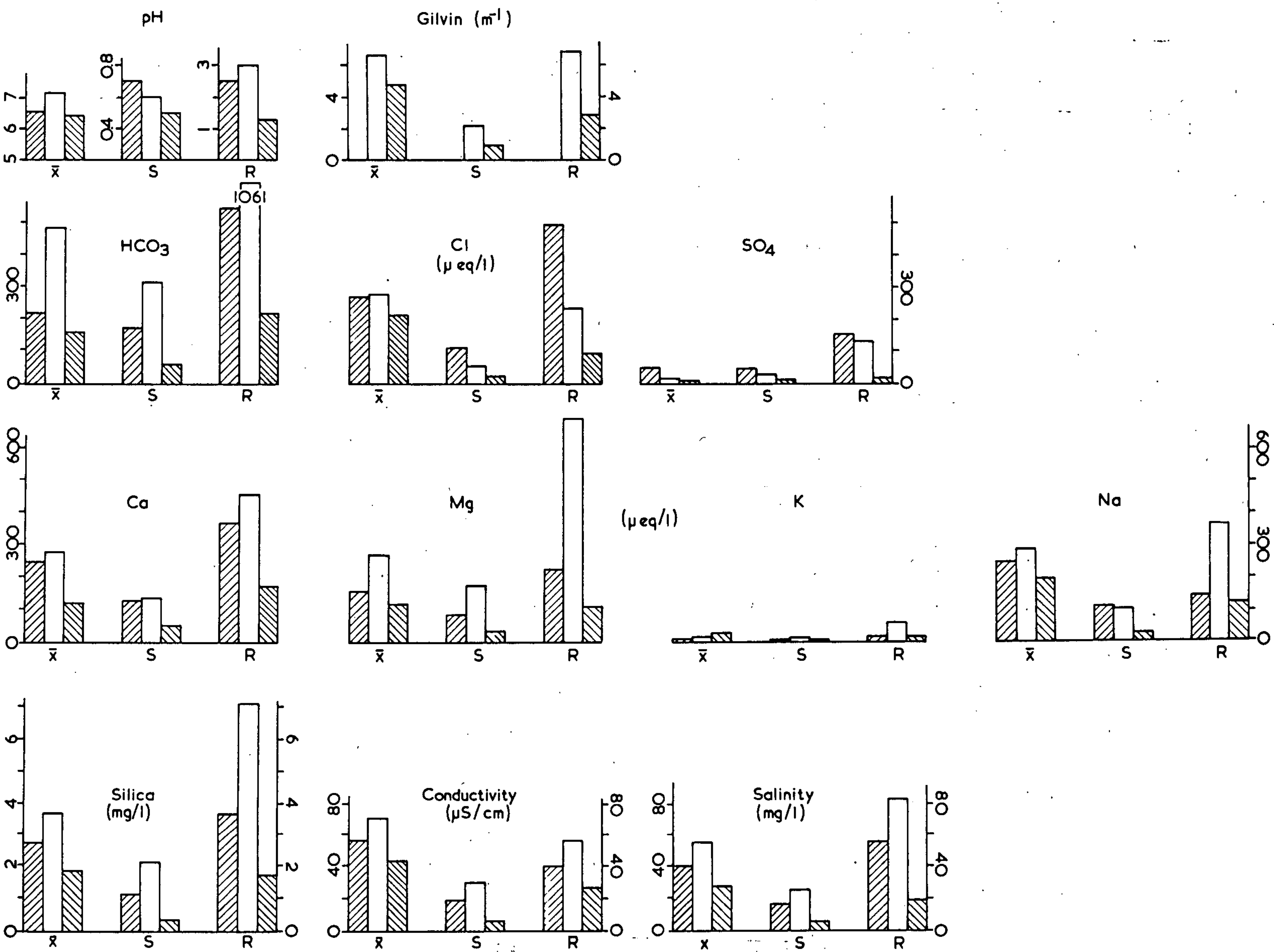


FIGURE 46

MEAN (X), STANDARD DEVIATION (S) AND RANGE (R) OF COLOUR AND WATER CHEMISTRY IN THE GORDON RIVER, BEFORE CONSTRUCTION OF THE GORDON DAM (▨), WHEN LAKE GORDON WAS FILLING (□) AND AFTER POWER STATION DISCHARGE (▧).

flow conditions. However, discharge of the stored water has considerably reduced variability, to a level less than that before construction. This effect is also shown by the reduced range of variability in ionic composition (Figure 47). For most rivers in the Gordon Basin, salinity decreases exponentially with flow and this was true for the Gordon before discharge commenced (Figure 28). Since then salinity, and chemical composition, have been relatively stable at values close to those for Lake Gordon. These events, together with alteration of river flow, must have produced substantial changes to the aquatic habitats of the river (Coleman, 1978).

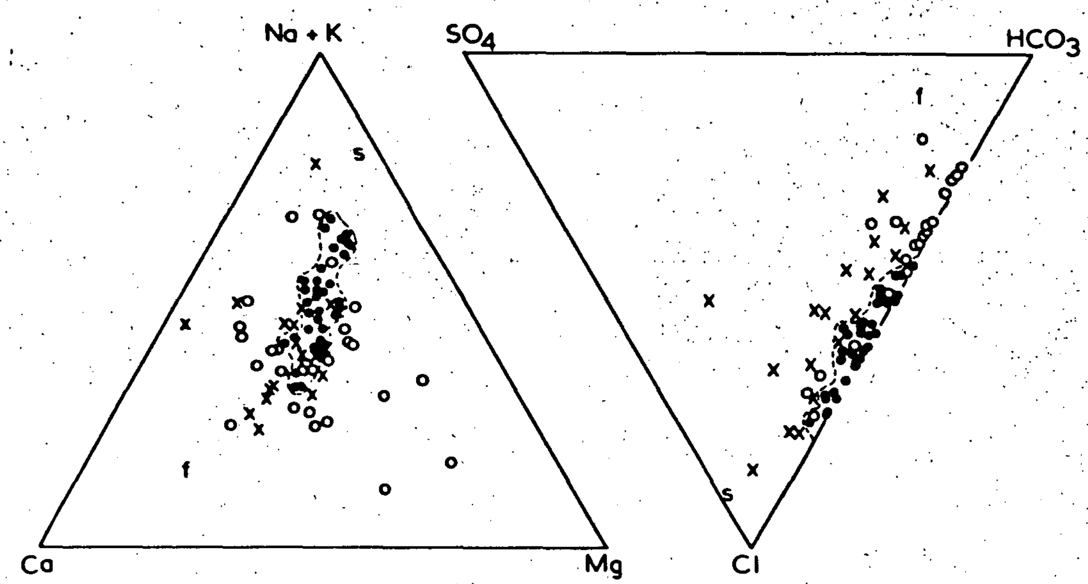


FIGURE 47

IONIC PROPORTIONS IN THE GORDON RIVER BEFORE CONSTRUCTION OF THE GORDON DAM (X), WHILE LAKE GORDON WAS FILLING (O) AND AFTER POWER STATION DISCHARGE (●).

7.0 CONCLUSIONS

The Gordon River Basin, in South West Tasmania, has a temperate maritime climate, with rainfall increasing from about 1600 mm on the West Coast to over 3000 mm along major mountain barriers lying at right angles to the prevailing westerly winds.

The geology of the basin is complicated, with limestones and/or dolomites occurring in most of the river catchments.

Vegetation in the basin forms a complex mosaic which can be interpreted in terms of fire history (Jarman and Crowden 1978, Kirkpatrick et al 1978). Soils are variable with profile development minimal or absent but peats are prevalent. Organic material leached from these peats produces the dark brown (dystrophic) waters so characteristic of South West Tasmania (Buckney and Tyler, 1973 a,b).

The hydrological regime of the Gordon River has been modified by diversions to the upper Franklin River and the addition of the upper Huon River into the Gordon Basin, and more significantly by construction of the Gordon Dam and subsequent pattern of power station discharge (Watson, 1978a).

Air temperature is the major factor influencing water temperatures of natural rivers. Discharge of water from Lake Gordon has reduced the variability of temperature in the Gordon River and summer temperatures have been lowered and winter ones raised. There is now a slight and gradual temperature rise downstream from the dam to Butler Island, and ambient temperatures in the river are determined principally by events in Lake Gordon. The tributaries now exert little influence on temperatures in the main river.

Temperature stratification occured in downstream reaches because of the intrusion of saline water from Macquarie Harbour. Since discharge of Lake Gordon water commenced this has no longer been evident.

Solar radiation at river level is limited by mountainous topography, valley mists and shading by riparian vegetation.

Light pentration in the river water is severely restricted by the strong absorbing properties of dissolved organic matter (colour, gilvin) and in comparison light scattering by suspended material is insignificant. Discharge of water from Lake Gordon has reduced the colour of the river but the nett effect of higher river levels is a reduction of light available for photo-synthesis by benthic algae of shingle banks and former shallows. For this reason production within the river has most likely been reduced.

The chemical composition of river waters in the Gordon River Basin is dictated by the degree to which minerals of soluble rocks augment those present in rainfall. The considerable influence of dolomite and limestone in the area is apparent from the position between seawater and world average freshwater occupied by most samples on ternary diagrams of ionic composition. These rocks contribute calcium and magnesium bicarbonates to percolating rainwater, so altering its composition from the seawater characteristics of rain and of many lakes in the South West, (Buckney and Tyler 1973 a,b). Because of their marine origin the rocks also contribute sodium and chloride.

The waters of some creeks, where minimal geochemical influence occurs, are dominated by sodium and chloride, and alkaline earth bicarbonates are insignificant (e.g. Cataract and Roaring Creeks). These have an ionic composition akin to seawater.

The chemical composition of Lake Gordon discharge water is also similar to seawater, with slight bicarbonate enrichment, and a fairly constant salinity (Steane and Tyler, 1978). Power station discharge resulted in a seawater ionic dominance order prevailing in the river when previously, under low flow conditions, alkaline earth bicarbonates dominated and tributaries could influence composition considerably. The Gordon River below Lake Gordon will now resemble Lake Gordon water at all times when the power station is operating. The Franklin may, at times, still exert a slight influence.

In natural rivers, salinity decreases exponentially with increases in flow. This was true for the Gordon River until discharge from Lake Gordon commenced. Thereafter salinity was fairly constant at a value close to that for Lake Gordon.

Chemical concentration and variability in the Gordon River increased during dam construction and filling of Lake Gordon and then decreased to levels below the natural state (before construction commenced).

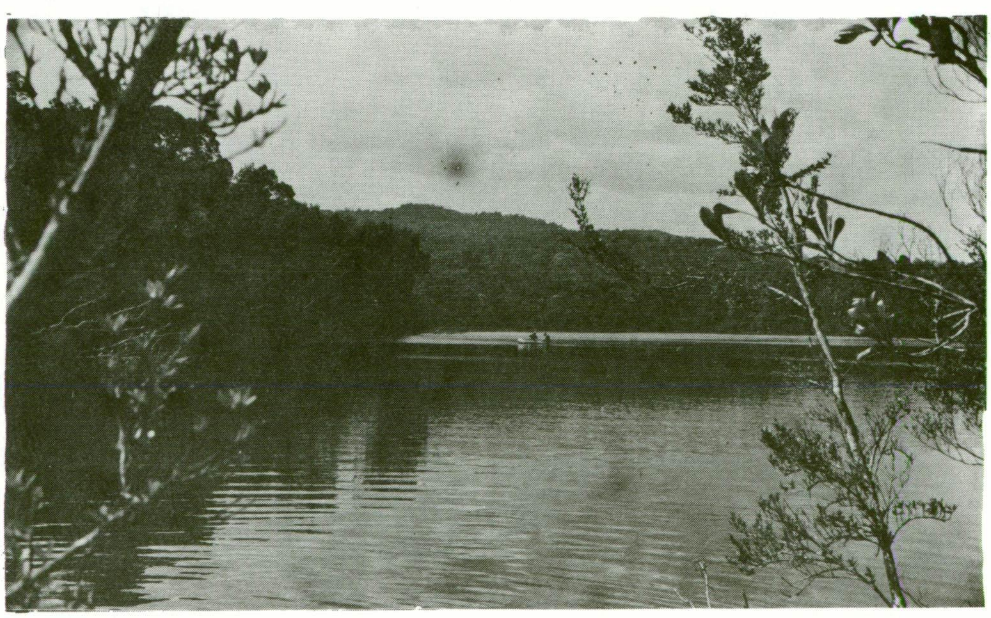
CHAPTER 3

Limnology of Perched Lake

FRONTESPIECES

Above: View west over Perched Lake to the Gordon River and Butler Island, with the base of Mt. Discovery in the background left.

Below: Typical view from ground level, showing the characteristic forested shoreline of Perched Lake.



CONTENTS

FIGURES

TABLES

PLATES

1. INTRODUCTION

The Lower Gordon Scientific Survey was initiated by the Hydro-Electric Commission as a fact-finding survey to assess the natural resources of the lower Gordon River area (Figure 48). The main aim of the survey was to investigate hitherto unstudied areas.

The study area was that part of the South West likely to be affected by the proposed Stage 2 of the Gordon River Power Development, and, in some cases, adjacent territory where necessary for interpretation of results.

Limnological investigations in the area covered as many lentic and lotic sites as possible. The objectives of the present study were to characterise the small lake near Butler Island known as Perched Lake. Preliminary investigations in February 1976 were followed by regular sampling at approximately six-week intervals from October 1976 to April 1978.

2. THE STUDY AREA

2.1. Location

Perched Lake is situated on the east bank of the Gordon River, 0.8 km due east of Butler Island. Grid co-ordinates of the lake are 5286500 N 392000 E on the 1:100 000 series maps of Tasmania. The lake is approximately 17 m above the Gordon River which is at sea level, and is 33.5 km from the mouth of the river in Macquarie Harbour. The area of its catchment is not known but is in the vicinity of four times the lake area (Figure 49).

2.2. Geology

The geology of the area around Perched Lake is complex. Impure argillaceous limestones are interbedded with sandstones and siltstones. Sandstone hills occur to the north of the lake and to the west are limestone outcrops and caves. The origin of the lake is not known but its shape and elevation do not suggest that it is a sinkhole. One possibility is that it occupies a depression in the bed of a former course of the river.

2.3. Climate

Perched Lake and surrounding areas come under the influence of the prevailing westerly winds. The nearest climatic monitoring stations are at Strahan on the coast 55 km to the north west, and Strathgordon

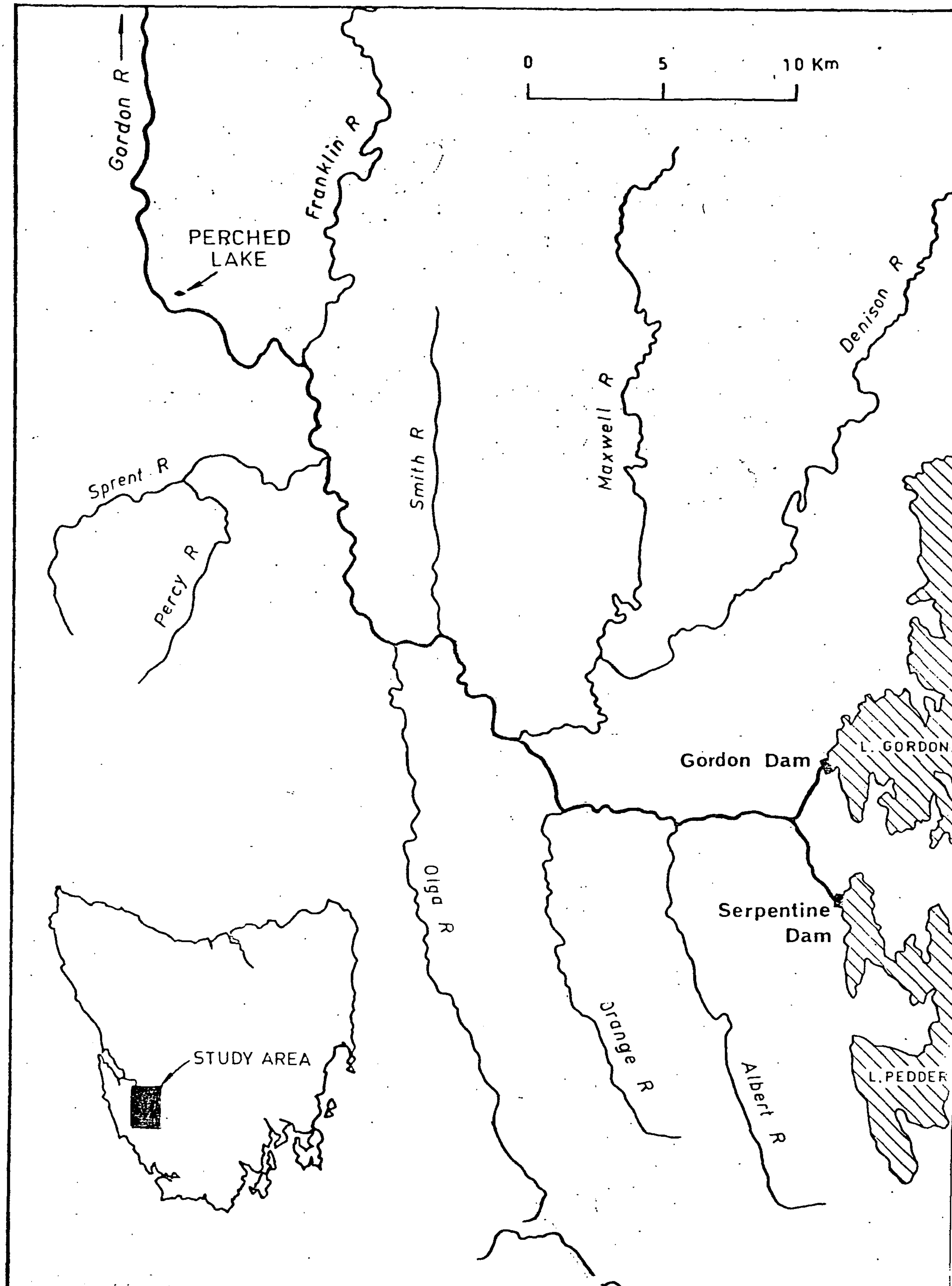


FIGURE 48

LOWER GORDON RIVER SCIENTIFIC STUDY AREA, IN THE SOUTH WEST OF TASMANIA, SHOWING THE POSITION OF PERCHED LAKE.

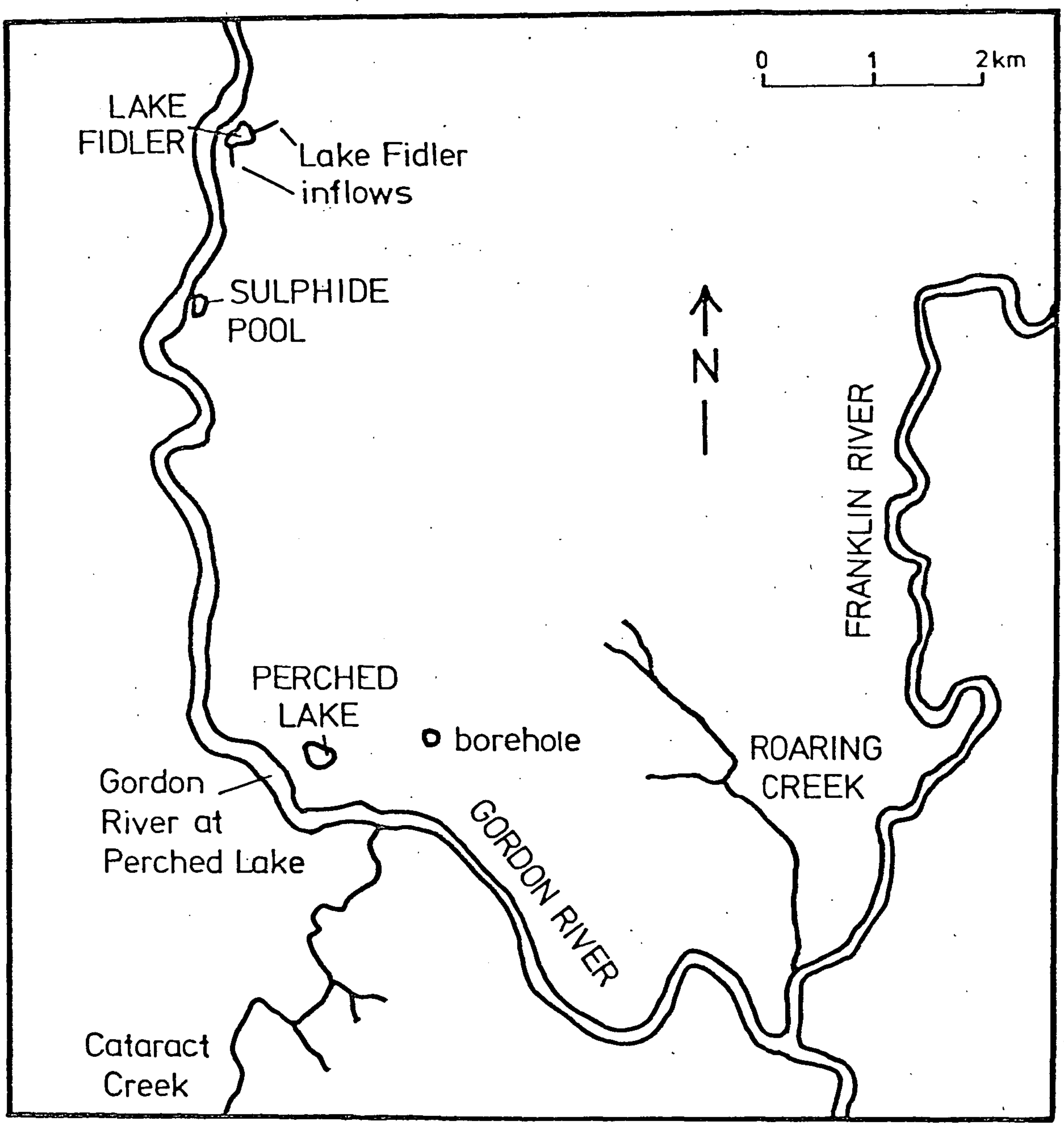


FIGURE 49

LOCATION PLAN OF PERCHED LAKE AND ENVIRONS IN THE LOWER GORDON RIVER AREA. OTHER SITES SAMPLED HAVE BEEN INCLUDED.

(elevation 370 m) 41 km to the south east.

The climatic environment of Perched Lake lies somewhere between that of these two stations, but the maximum/minimum air temperatures are about 4°C higher than either station, probably due to the sheltering effect of the rugged terrain and the surrounding rainforest. The mean annual rainfall for Strahan is 1750 mm and for Strathgordon 2580 mm, with maximum rainfall during the winter months (Figure 6A+B). The mean nett precipitation (minus evaporation) for Strathgordon is 1630 mm. The number of sunshine hours shows a definite seasonal pattern, increasing from a minimum in May - June to a maximum in January - February (Bureau of Meteorology, 1978). Due to the severity of the prevailing westerlies the weather can change rapidly over a short period. Detailed climatic data are given by Faircloth (1978).

2.4. Hydrology

There are no well defined surface or sub-surface inflows into the lake but water may enter the lake in the following ways:

(a) by precipitation onto the surface of the lake;

(b) by precipitation through the forest canopy seeping through the forest litter layer into the lake;

(c) through joints by artesian or sub-artesian flow resulting from hydraulic head generated in the hills to the east (H.E.C. Geology Section, pers. comm.).

Water may be removed from the lake by:

(a) evaporation from the surface;

(b) seepage downwards during drier summer months when the groundwater table may be lower;

(c) lateral seepage through the forest litter and soil during winter months when the lake level rises.

A salt water wedge extends up the Gordon River and undercuts fresh dystrophic water (Kearsley 1978). It often extends upstream to Butler Island, and may even reach Big Eddy, 38.2 km from the mouth. When present at Butler Island the salinity discontinuity is between 2.0 m and 4.0 m from the river surface, with salinities of up to 16‰ in the bottom water. Because of its elevation, Perched Lake is unlikely to be influenced by the salt wedge via groundwater.

2.5. Bathymetry

During the study maximum variation in lake water level was 40 cm. The bathymetric map (Figure 50) was constructed by measuring water depth with a weighted graduated line along transects laid out on compass bearings. The lake outline was traced from aerial photographs. The morphometric parameters (Table 9) were obtained from this map. Volumes were calculated for each contour interval and plotted with the area/depth curve in Figure 51.

The lake basin generally has steeply sloping north and south sides, flatter, more sedimented east and west sides, and a flat central area. The 0 m to 3 m zone and that below the 9 m isobath together account for 64% of the lake surface area. The north and south littoral zones have many fallen, submerged trees covered with liverworts and algae. The less steep east and west areas have rooted macrophyte stands. Below 2 m depth the lake bottom is covered with anaerobic organic oozes derived from decaying plant material falling into the lake, material from the forest litter layer entering by seepage inflow, and autochthonous organic material.

TABLE 9

Morphometric Parameters for Perched Lake

Elevation (m)	*c.* 17
Maximum length (m)	378
Maximum width (m)	165
Maximum depth (m)	13
Mean depth (m)	6
Area (ha)	4
Volume (m^3)	241,310
Length of shoreline (m)	903
Shoreline development	1.2

2.6. Vegetation

A superficial study was undertaken of the vegetation at the western end of the lake (Jarman, pers. comm.). A dense fringing zone of forest occurs around the lake, with low closed mixed forest of *Nothofagus cunninghamii* (Hook.) Oerst. and *Phyllocladus aspleniifolius* (Labill.) Hook. occurring at the western end. Species diversity is relatively

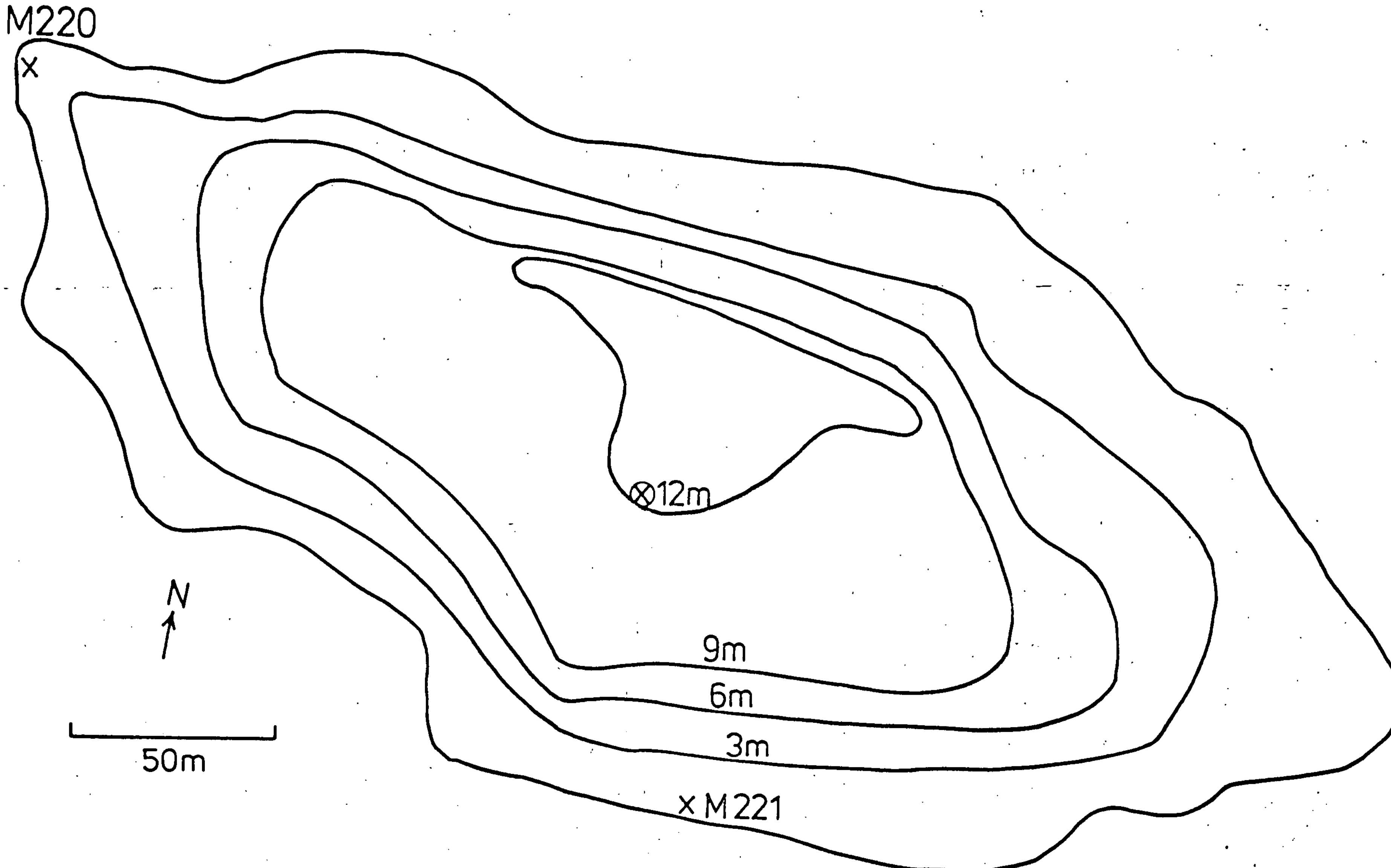


FIGURE 50

BATHYMETRIC MAP OF PERCHED LAKE SHOWING THE SAMPLING SITE (⊕) AND THE LOCATIONS OF THE MAXIMUM/MINIMUM THERMOMETERS

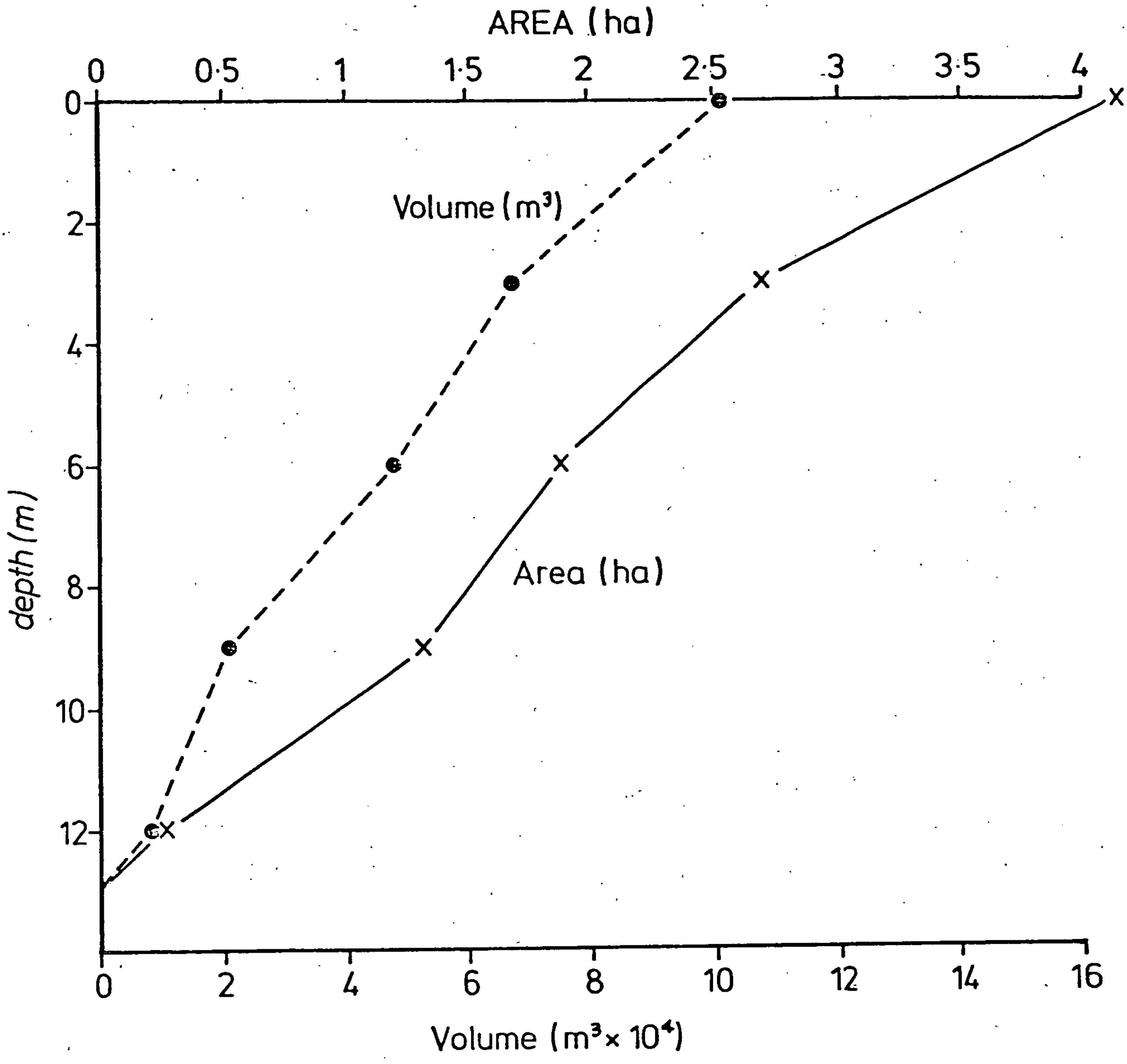


FIGURE 51

MORPHOMETRIC CURVES FOR AREA AND VOLUME OF PERCHED LAKE.

high in this forest. Common species are *Dacrydium franklinii* Hook.f., *Eucryphia lucida* (Labill.) Baill., *Eucryphia milliganii* Hook.f., *Leptospermum scoparium* J.R. & G. Forst., *Anodopetalum biglandulosum* A. Cunn. ex Hook.f., *Phebalium squameum* (Labill.) Engler and *Monotoca* spp. This forest grades into a low forest of *Leptospermum* sp. at the eastern end of the lake, interspersed with patches of closed forest of *Nothofagus cunninghamii* and *Acacia melanoxylon* R.Br.

The forest is more open immediately behind the fringing zone, and species diversity is lower. The dominant species, *Nothofagus cunninghamii* and *Eucryphia lucida*, form a low closed forest with an open understorey in which *Anodopetalum biglandulosum* and the fern *Blechnum wattsii* Tindale are the most common species.

Emergent aquatic species *Triglochin procera* R.Br., *Baumea rubiginosa* (Spreng.) Boeck. and *Eloecharis sphacelata* R.Br. occur at the eastern end of the lake in the shallows where the lake bottom is gently sloping and the water is about 1 m deep, several meters from the forest edge.

3. METHODS

3.1. Sampling

Water samples were collected by dipping detergent-washed polyethylene bottles about 10 cm below the surface. Samples from 5 m and 10 m were collected using a modified 1ℓ van Dorn bottle. There was generally a delay of a few days before samples reached the laboratory, during which time they were stored in as cool a place as possible. In the laboratory samples were stored at 5^{o}C.

3.2. Field Measurements

Temperature profiles were determined electrometrically with a Wheatstone Bridge thermistor. Littoral temperatures were measured with mercury-filled maximum-minimum thermometers placed in submerged polyethylene pipes, in the shade of the overhanging rainforest. Dissolved oxygen was measured by the azide modification of the Winkler method (Anon., 1971). Field pH was measured electrometrically with a portable Pye Unicam pH meter. Water transparency was measured using a standard 25 cm Secchi disc and a water telescope. The penetration of photosynthetically active radiation (PAR) was determined using a Li-Cor LI-185 Quantum meter (400-730 nm) and its spectral composition by using a Techtum QSM 2500 Quantaspectrometer.

3.3. Analysis

In the laboratory pH and alkalinity (bicarbonate) were measured using a Radiometer pHM26 pH meter coupled to an auto-titrator. An endpoint of pH = 4.5 was used with 0.01N HCl (Golterman and Clymo, 1967). Conductivity was measured electrometrically at 18°C. Turbidity was measured with a Hach turbidimeter calibrated against formozan standards (FTU = Formozan Turbidity Units).

The remaining determinations were on filtered samples (0.45 μm pore size). Particulate material was gently brushed from the filters for microscopic examination of phytoplankton by the Utermöhl method (Lund *et al.*, 1958). To estimate biomass, cell numbers were counted and volumes calculated from actual measurements of the organisms. Absorbance at 440 nm (G440) was measured on a Cecil 292 spectrophotometer using 40 mm silica cuvettes, and "Gilvin" calculated for a 1 m path length (Kirk, 1976). Chloride was measured by automated conductimetric titration with silver nitrate (Golterman and Clymo, 1969). Sulphate was determined turbidimetrically using barium chloride. Calcium concentrations were measured colorimetrically using Glyoxal-bis-(2-hydroxyanil) (Kerr, 1960). Silica concentrations were measured as "molybdate reactive silica" using the molybdate yellow method (Anon., 1971). All cations except calcium were determined on a Varian AA5 atomic absorption spectrophotometer. Salinity was calculated as the sum of the major ion concentrations in mg/l.

4. PHYSICAL-CHEMICAL LIMNOLOGY

4.1. Temperature

Perched Lake is a dystrophic, warm monomictic lake. Stratification, in phase with seasonal air temperature variations, probably relies on the shelter of surrounding hills and rainforest.

The lake was almost isothermal during June and July of both years with a temperature difference of about 4°C between top and bottom in 1976, and 1.3°C in 1977. The surface waters began warming in early August 1976 and reached a maximum between December and February (Figure 52). A thermocline was established between 2.0 m and 4.5 m. In February 1977, at maximum stratification, there was a 14°C difference between surface and bottom water. The deepening of the thermocline in March was

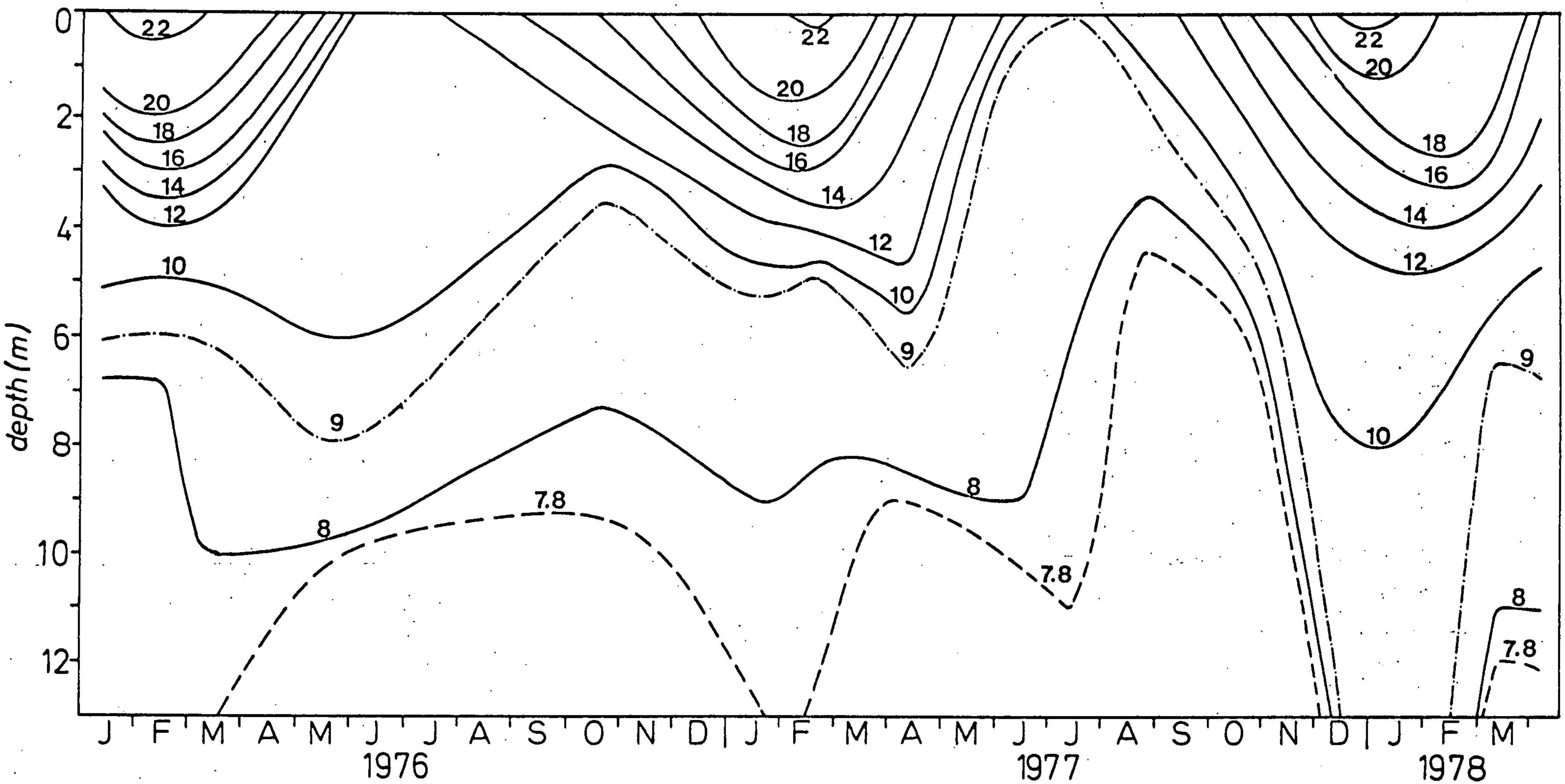


FIGURE 52

SEASONAL TEMPERATURES IN PERCHED LAKE.

probably due to wind action. When cooling commenced the surface waters lost heat at about 3°C per month from April to July.

As the water column approached isothermy in June the bottom waters, below 4 m, commenced a period of cooling which lasted until August, during which time surface waters had commenced rapid heating. The only likely explanation for this anomalous behaviour is the entry of cold subterranean water at intermediate or lower levels of the lake.

From July to December, 1977, surface water warmed at about 2.3°C per month. Between August and December wind-induced turbulence carried heat to deeper strata before stratification set in, about December, with a thermocline at about the 5 m depth.

The drop in surface water temperature in February probably resulted from local weather conditions. A summer fall in temperature has also been recorded in Lakes Sorell and Crescent (Cheng and Tyler, 1973), Risdon Brook Reservoir and Arthurs Lakes (Tyler, 1974) and Lake St. Clair (King, unpublished). In Perched Lake the depression of surface temperatures affected only the top 0.5 m of water.

Between February and March 1978 the autumnal cooling began. As in 1977, but more dramatically, there was an anomalous drop in temperature in the lower strata (Figure 53). Again, the only likely explanation is the influx of cold, subterranean water at intermediate levels.

The littoral water temperatures followed the ambient air curves for Strahan and Strathgordon, showing a pattern characterised by periods of heating and cooling with temperature differences greatest in the summer and least in the winter (Figure 54). The minumum winter temperatures were similar to those of the bottom waters of the lake throughout the study period (excluding the anomaly of hypolimnetic heating in the summer of 1977-78). The maximum summer values were about 5°C higher than those of the open lake surface waters. Littoral temperatures were commonly higher than open water temperatures in summer.

The temperature discrepancies between the two maximum/minimum thermometers placed in the lake along the shoreline were probably due to their aspect. Thermometer M220 was situated at the west end of the lake and thermometer M221 on the southern shore, which would receive more sunlight. This explains the broader summer maximum temperature peaks for M221.

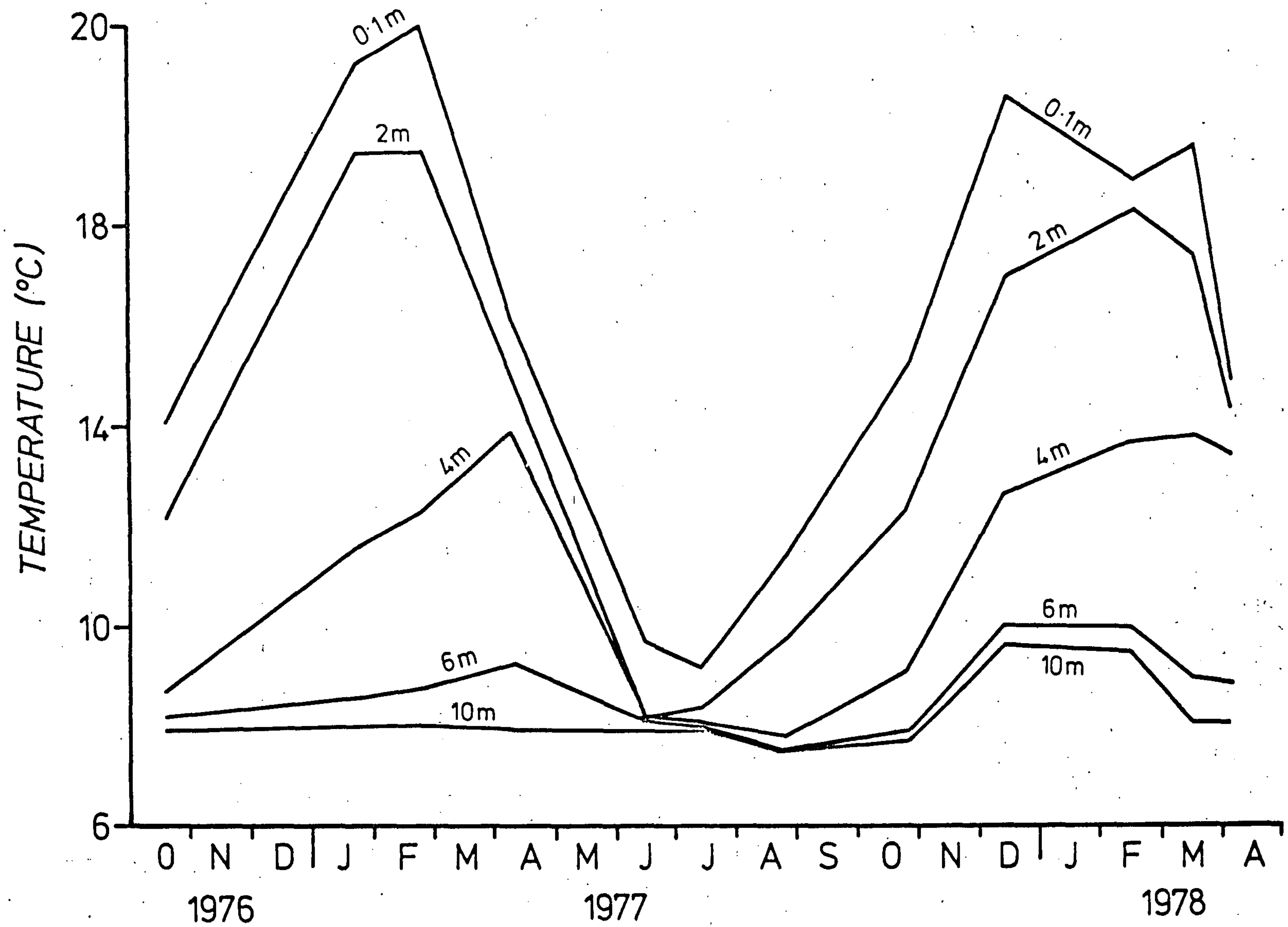


FIGURE 53

TEMPERATURE FLUCTUATIONS AT VARIOUS DEPTHS IN PERCHED LAKE.

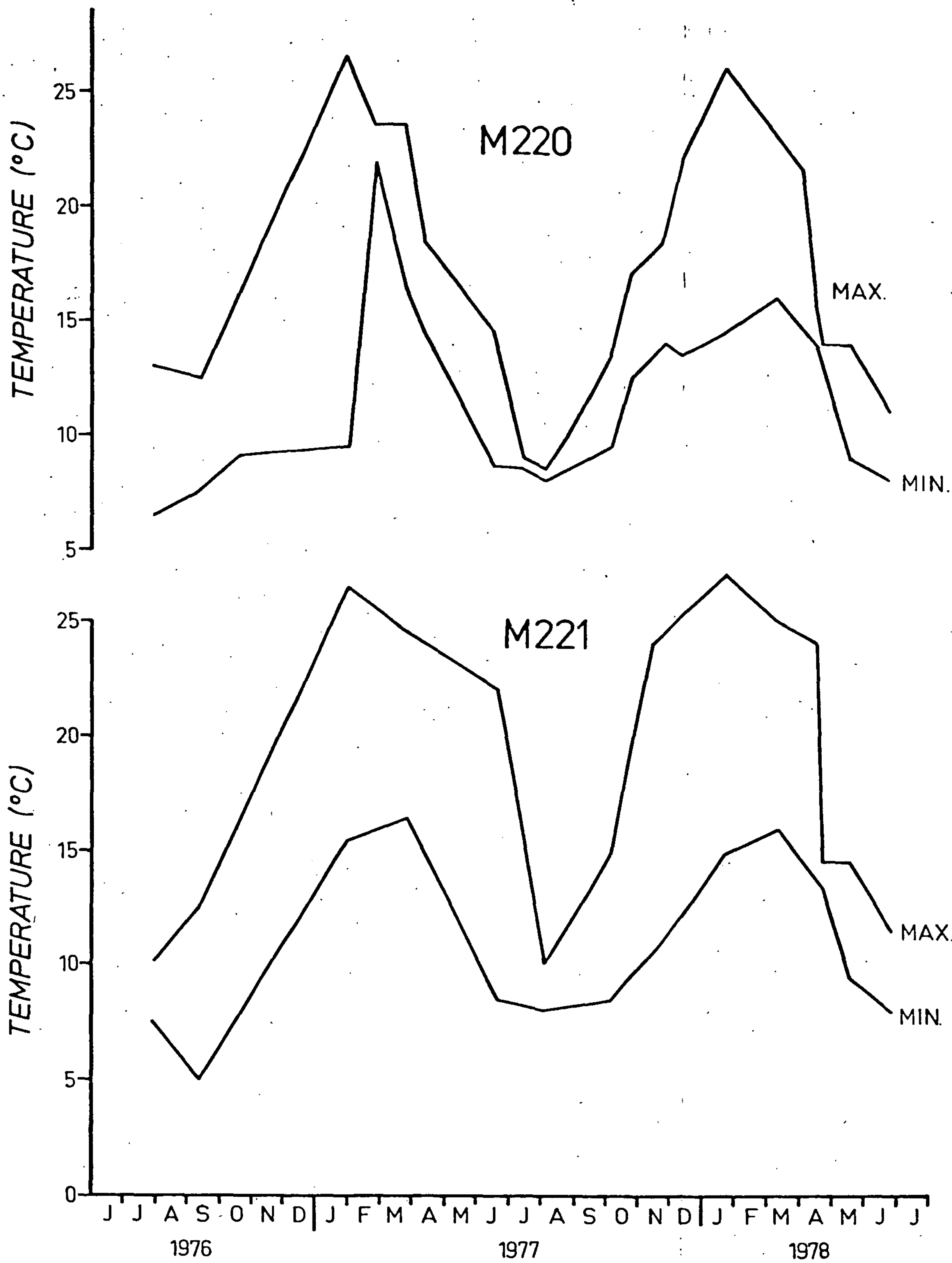


FIGURE 54

LITTORAL WATER TEMPERATURES FOR TWO STATIONS ALONG THE SHORES OF PERCHED LAKE. LOCATIONS OF STATIONS ARE INDICATED IN FIGURE 50.

4.2. Dissolved Oxygen

The seasonal variation of dissolved oxygen in Perched Lake is illustrated in Figure 55. The dissolved oxygen follows a regular pattern related to the thermal regime. When the lake was approximately isothermal the bottom waters were well ventilated (DO concentration > 60% saturation). Thermal stratification did not influence hypolimnetic dissolved oxygen concentrations until late in the period of stratification. Oxygen consumption began in the hypolimnion in about January/February, DO reaching values of < 20% by March/April. The depth of the oxycline corresponded to the depth of the thermocline.

At this time, when maximum surface water temperatures were reached (*c.* 22^{o}C), saturation values occurred down to about 0.5 m. The depth to which saturation values occurred varied from year to year, as did the period for which the surface waters remained saturated.

The ventilation of the bottom waters began in April, coinciding with the breakdown of thermal stratification. Dissolved oxygen concentrations greater than 60% were again achieved by the end of July.

The principal factor causing hypolimnetic deoxygenation was the effect of thermal stratification, which reduces vertical water movement, and hence replenishment of oxygen consumed during microbiological decay of organic material.

4.3. Water Chemistry

The chemistry of Perched Lake is summarised in Table 10. Complete analytical data may be found in King, H.E.C (1978b). The variation of certain parameters with time is shown in Figure 56.

The waters of the lake were acidic, with pH values ranging between 4.0 and 6.58, but usually below 5.0. This was to be expected, for as rainwater percolates through the forest litter, organic acids are released into the water resulting in the typical brown west coast water. Such waters are widespread in the South-West (Buckney and Tyler, 1973*a,b*) and usually have very low bicarbonate alkalinity. This was true for Perched Lake most of the time, but peaks of bicarbonate did occur (Figure 56).

Table 10 shows that the waters of Perched Lake are dominated by sodium and chloride ions and for most samples the ionic order of dominance is that of seawater, Na > Mg > Ca > K : Cl > SO_4 > HCO_3, the

Parameter		Depth 0.1 m Mean	Range	Sx	n	Depth 5 m Mean	Range	Sx	n	Depth 10 m Mean	Range	Sx	n
Field pH		4.8	4.20 - 6.10	0.50	13	4.60	4.50 - 4.80	0.20	3	4.57	4.00 - 4.70	0.60	3
Laboratory pH		5.27	4.48 - 6.34	0.36	15	5.06	4.60 - 5.33	0.22	14	5.04	4.30 - 6.58	0.50	14
Gilvin (G440)		2.16	1.70 - 2.65	0.30	12	2.42	2.28 - 2.65	0.14	11	2.42	2.25 - 2.65	0.14	11
Alkalinity	mg/l	1.92	0.95 - 5.15	1.08	17	1.60	1.10 - 2.90	0.46	14	2.01	0.80 - 8.40	1.97	14
	μeq %	8.40	4 - 19	4.3	17	6.4	3 - 11	1.9	14	7.9	3 - 28	6.4	14
Chloride	mg/l	11.17	9.93 - 13.50	0.77	17	11.88	10.37 - 21.60	2.83	14	11.13	10.46 - 11.70	0.41	14
	μeq %	84.1	73 - 87	3.7	17	79.9	75 - 83	2.6	14	80.3	65 - 88	5.3	14
Sulphate	mg/l	2.2	0.8 - 3.6	0.7	17	2.8	1.8 - 5.1	0.8	14	2.2	1.0 - 3.1	0.6	14
	μeq %	11.6	4 - 20	3.5	17	13.6	10 - 18	2.1	14	11.9	6 - 16	3.0	14
Calcium	mg/l	1.00	0.56 - 1.76	0.32	17	0.95	0.47 - 1.13	0.31	14	1.02	0.50 - 1.88	0.40	14
	μeq %	11.0	7 - 21	3.7	17	12.1	23 - 97	4.4	14	12.5	7 - 23	4.0	14
Magnesium	mg/l	0.99	0.60 - 1.90	0.39	17	0.9	0.5 - 1.82	0.25	14	0.89	0.60 - 1.80	0.3	14
	μeq %	19.3	11 - 34	6.8	17	17.3	41 - 131	3.2	14	17.9	12 - 27	3.5	14
Potassium	mg/l	0.46	0.30 - 1.80	0.35	17	0.37	0.30 - 0.38	0.05	14	0.35	0.30 - 0.47	0.05	14
	μeq %	2.7	2 - 10	1.9	17	2.1	9 - 13	0.3	14	2.2	2 - 3	0.4	14
Sodium	mg/l	6.16	4.00 - 8.80	1.36	17	6.89	5.40 - 13.00	1.92	14	6.14	5.20 - 6.90	0.57	14
	μeq %	65.8	48 - 78	8.5	17	68.1	60 - 78	5.2	14	67.1	56 - 72	5.6	14
Silica	mg/l	0.7	0 - 2.1	0.6	16	1.1	0.5 - 2.9	0.6	13	1.4	0.8 - 2.9	0.6	13
Conductivity	μS/cm at 18°C	40.9	36.0 - 46.2	2.98	16	42.3	29.4 - 68.0	8.6	13	40.9	30.8 - 48.4	4.0	13
Salinity	mg/l	23.89	20.05 - 29.09	2.20	15	25.46	21.68 - 44.14	6.14	12	23.75	21.51 - 25.79	2.75	14

TABLE 10

Water Chemistry of Perched Lake: mean, range, standard deviation (Sx) and number (n) of samples of some characteristics of Perched Lake at various depths from February 1976 to

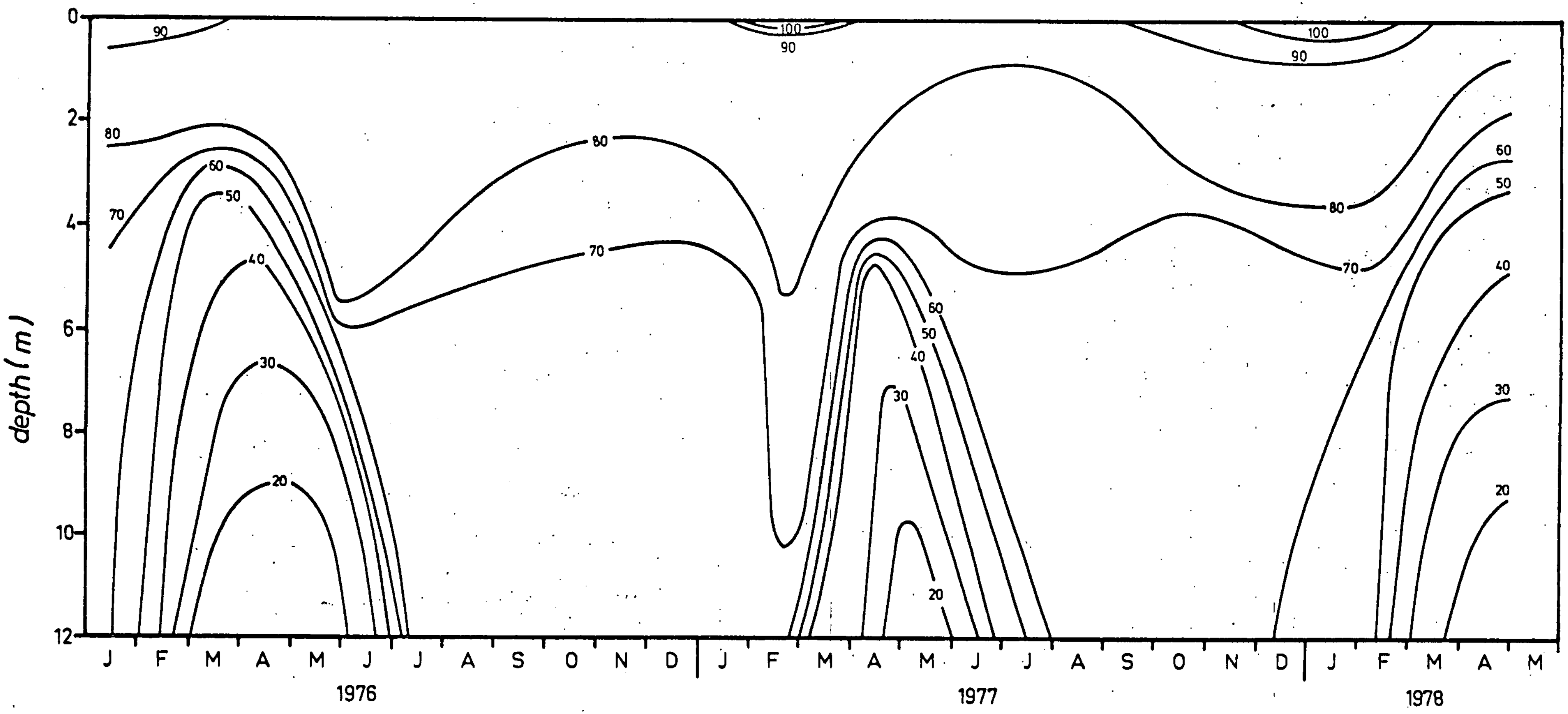


FIGURE 55

DISSOLVED OXYGEN ISOPLETHS, IN % SATURATION, FOR PERCHED LAKE.

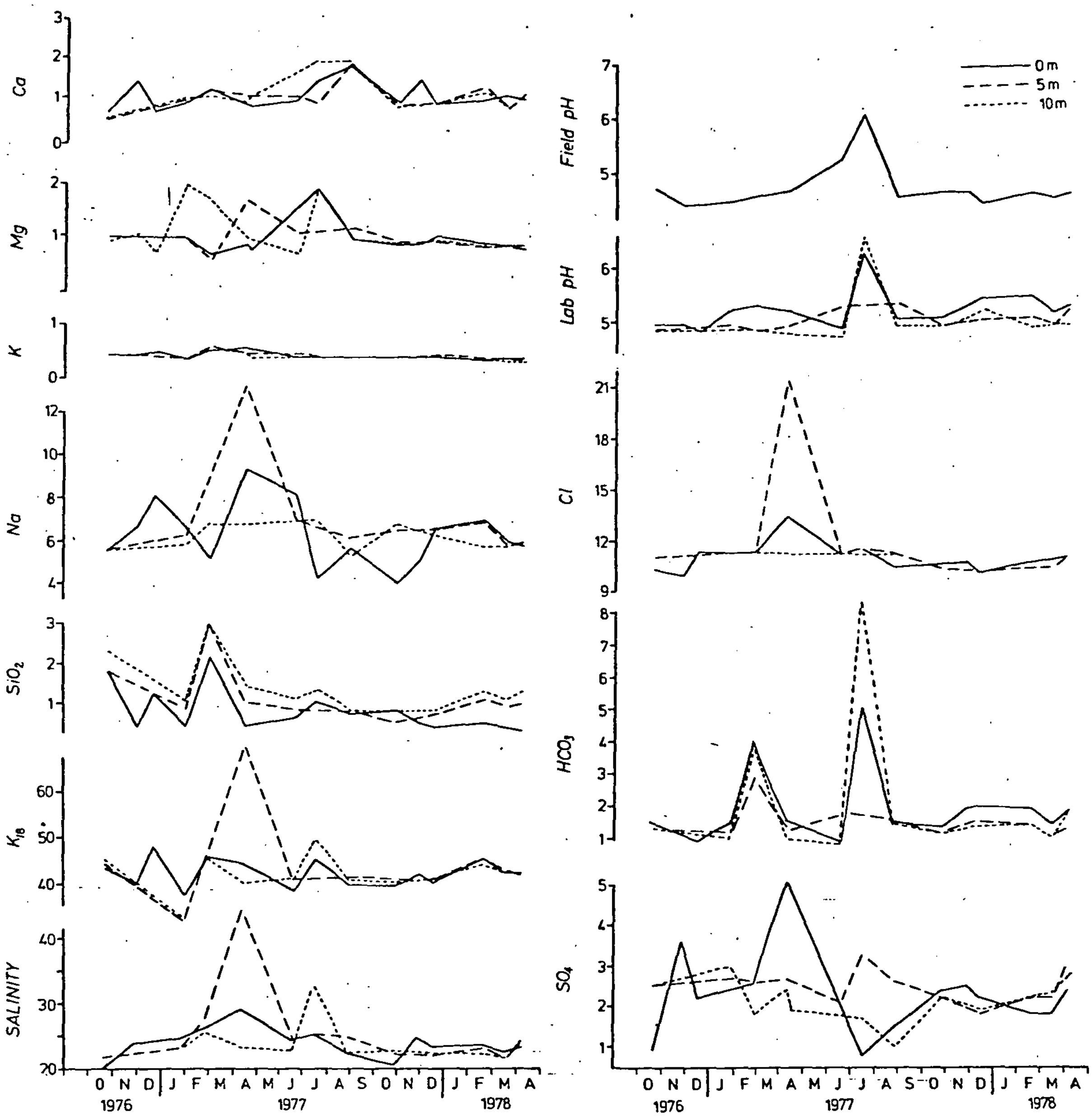


FIGURE 56

SEASONAL VARIATION OF CHEMICAL PARAMETERS OF PERCHED LAKE AT VARIOUS DEPTHS (0.1 m, 5 m and 10 m in mg/l, μS/cm and pH units).

mean proportions of ions being chloride, 81.4%; sulphate, 12.4%; bicarbonate, 7.6%; sodium, 67.0%; magnesium, 18.2%; calcium, 12.2%; and potassium, 2.3%. On a few occasions calcium equalled or slightly exceeded magnesium and bicarbonate exceeded sulphate. The maritime nature of the waters is revealed by the clustering of points close to seawater proportions in the ternary diagrams (Figure 57). Some Perched Lake samples show moderate geochemical influence through accretion of alkaline earth bicarbonates and are consequently displaced from the seawater towards "World Average Freshwater" in the ternary plots. Not surprisingly, groundwater from a borehole plots very close to "World Average Freshwater". The prevailing character of Perched Lake water, then, is that of dilute, coloured seawater, a precipitation dominance type in the notion of Gibbs (1970). Such waters are common in many parts of the world in the path of prevailing maritime winds (Buckney and Tyler, 1973*a,b*).

Generally, in this set of analyses, cations exceeded the anions by about 10% which is the reverse of previous analyses of Tasmanian waters (Buckney and Tyler, 1973*a,b*; Cheng and Tyler, 1973). A probable explanation is that in this survey the turbidimetric method for sulphate was used in place of the tedious ion-exchange/conductimetric method of previous work. As the turbidimetric method is the less sensitive one, it is probable that sulphate has been underestimated. The magnitude of error is not sufficient to have significant effect on the conclusions drawn.

No strictly seasonal fluctuation is evident in any of the chemical parameters measured (Figure 56). Instead, there are erratic fluctuations of some species at certain depths, in a manner which suggests complex subterranean inflows, already inferred from the thermal data. In April 1977, sodium, chloride and conductivity all showed large increases in the 5 m stratum, while in February 1977 silica increased at all depths. In July 1977 there was a pronounced increase in bicarbonate, alkaline earths and consequently pH at the surface and at 10 m, but not at 5 m. No explanation of this perplexing behaviour is possible with the scant data available but, again, the possibility of stratified inflows is suggested. Figure 58, in which mean values of major ions are plotted with depth, also indicates the probability of subterranean inflows. The 5 m stratum shows significant differences from strata above and below, a phenomenon perhaps explained by entry of a different

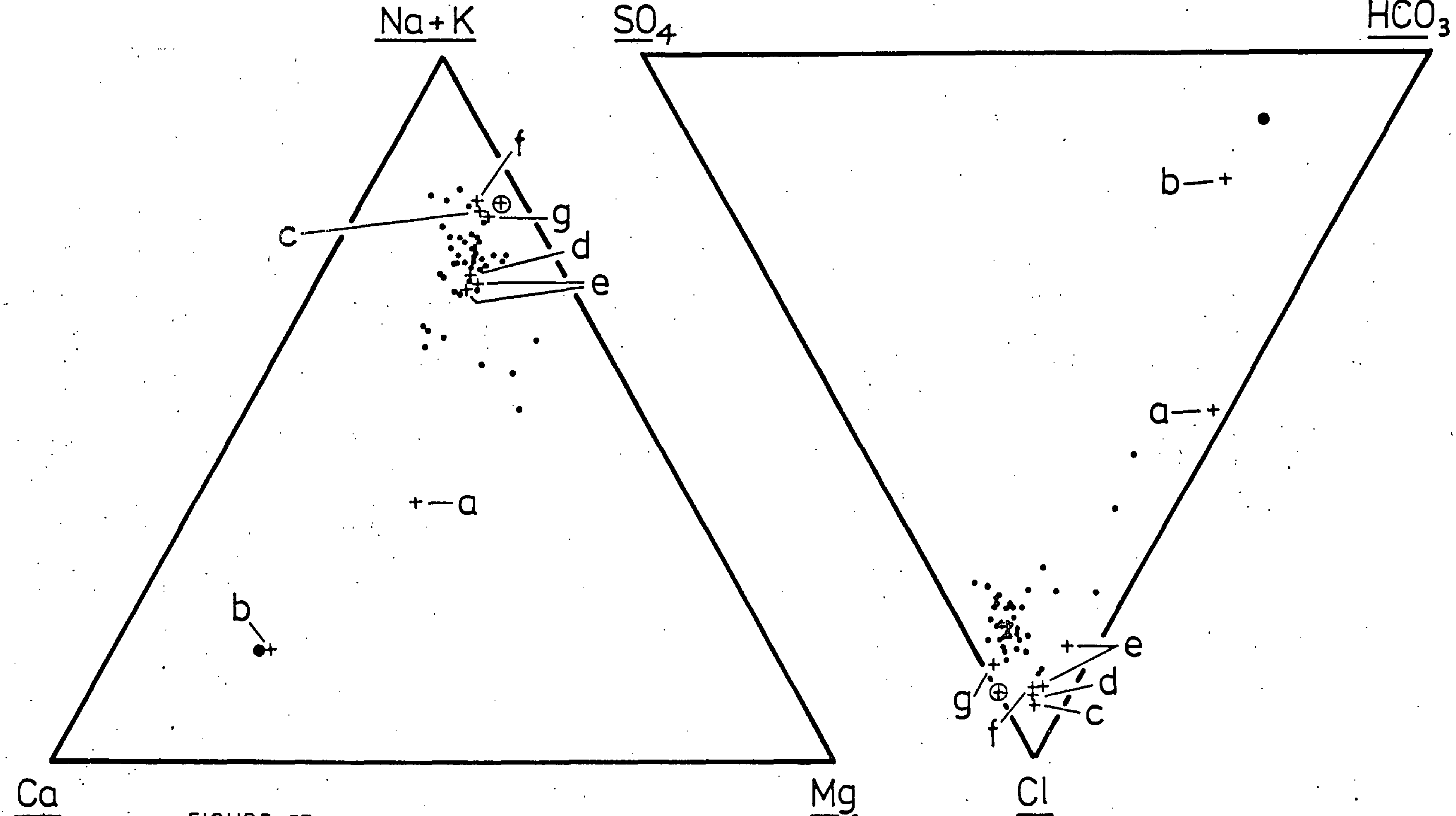


FIGURE 57

TERNARY DIAGRAMS FOR ALL SAMPLES COLLECTED FROM PERCHED LAKE (in μeq%). SAMPLES FROM OTHER WATERS IN THE VICINITY HAVE BEEN PLOTTED FOR COMPARISON

a - GORDON RIVER AT BUTLER ISLAND
b - BOREHOLE NEAR PERCHED LAKE
c - RAINFALL AT CAPE GRIM *
d - ROARING CREEK
e - LAKE FIDLER INFLOWS
f - LAKE FIDLER SURFACE
g - SULPHIDE POOL SURFACE

WORLD AVERAGE SEAWATER (⊕) AND "WORLD AVERAGE FRESHWATER" (⊛) HAVE ALSO BEEN PLOTTED FOR COMPARISON.

* DATA FROM DEPARTMENT OF THE ENVIRONMENT, HOUSING AND COMMUNITY DEVELOPMENT (pers. comm.).

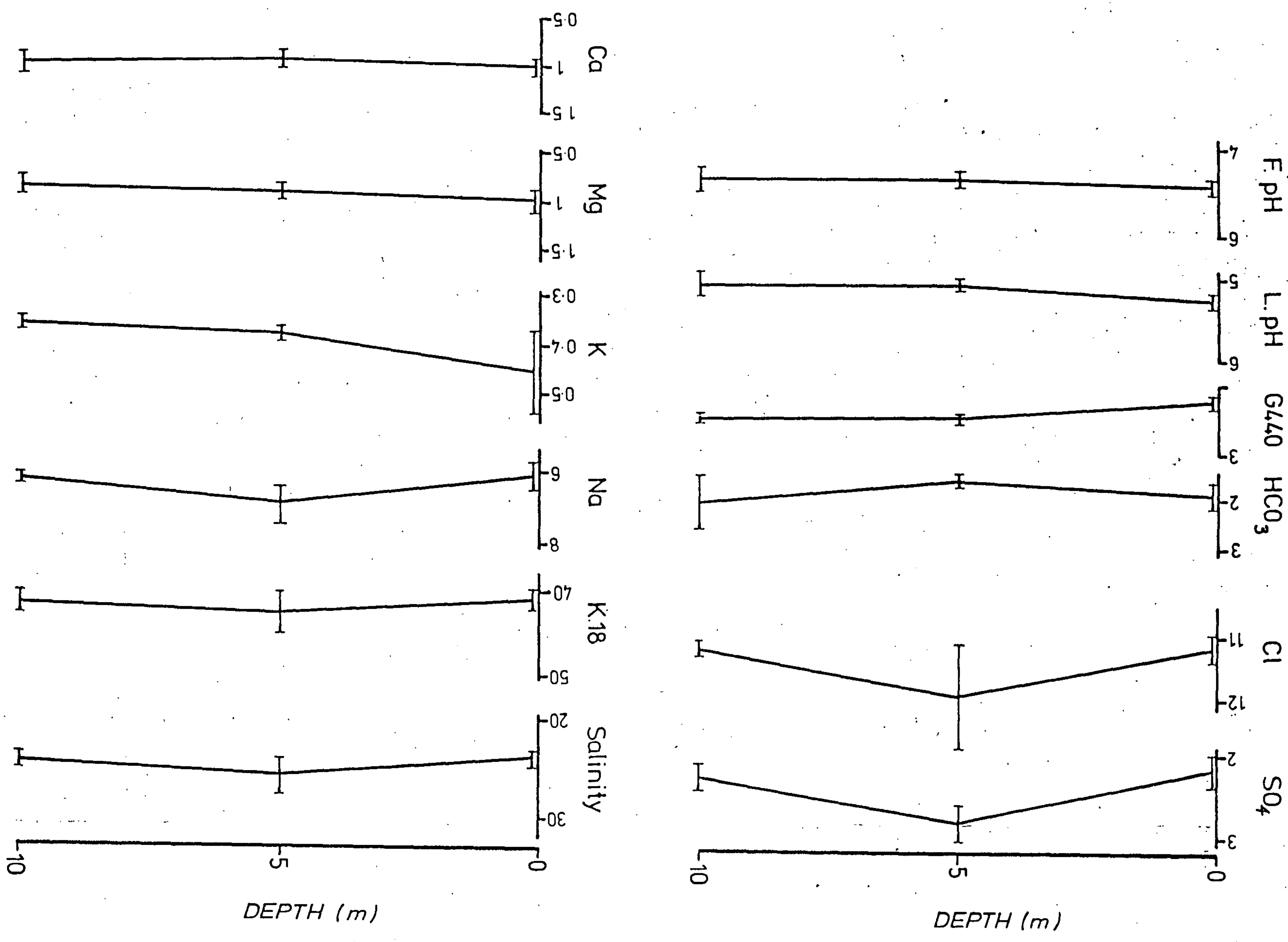


FIGURE 58

MEANS AND STANDARD DEVIATIONS OF CHEMICAL PARAMETERS WITH DEPTH IN PERCHED LAKE. MAJOR ION CONCENTRATIONS (in mg/l).

water at intermediate depths. However, if artesian water does enter the lake at 5 m one might expect it to be enriched with calcium, like the borehole water (Figure 57). This is not so. However, not all borehole samples in the area show calcium bicarbonate dominance.

4.4.

4.4. Light Penetration

The amount of primary production (carbon fixation) that occurs in any body of water, and hence, in most cases, the productivity of the whole system, is intimately related to the amount of light entering the water, and its fate as it passes downwards through the water column. Practical methods of measuring and interpreting this have changed profoundly in recent years. Modern instruments are designed to measure the biologically-significant portion of the solar spectrum, photosynthetically-active radiation (PAR). Its waveband is approximately 400-730 nm, almost coinciding with the visible spectrum ('light'). The radiant flux of PAR is measured in microeinsteins (μE) per sq. cm per sec., where 1 μE = 6.023×10^{17} quanta (photons). Theory and practice are lucidly treated by Kirk (1977*a,b*).

Light striking the surface of the lake is either reflected or refracted at the interface, so entering the water. The proportion of incident light which enters the water depends on the solar angle and state of the water surface (smooth or ruffled); the depth to which it penetrates and its spectral composition at any depth depend also on the characteristics of the water. Though the water itself modifies the nature of light reaching deeper strata, turbidity and colour exert greater, profound influences.

In very clear lakes, water itself absorbs long wave red light and blue light penetrates furthest, and to great depths. The brown colour caused by humic materials in solution [= gelbstoff or gilvin (Kirk, 1976)] absorbs blue wavelengths strongly and in this case red light penetrates furthest, but only to slight depths. Suspended material, causing turbidity, rapidly attenuates light. Its effect on spectral properties of the penetrating light is complex (Kirk, 1979).

The concentration of humic substances, or gilvin, has been measured traditionally by comparing the colour with that of solutions of chloroplatinate (Pt units). Recently, Kirk (1976) has proposed another vicarious measure, the absorbance at 440 nm (G440) of a 1 m column of the water relative to distilled water. The correlation between the two for waters of South West Tasmania is given by King and H.E.C. (1978).

As Perched Lake has moderate concentrations of gilvin (colour = 40-100 Pt units) but low turbidity (< 2 FTU), the former is likely to be the most significant attenuator of light in the lake.

A rough measure of light penetration is the depth at which a black and white disc (Secchi disc) is no longer visible from the surface. Figure 13 shows the seasonal fluctuations of gilvin (G440, m^{-1}) and of Secchi disc transparency in Perched Lake. The data for gilvin suggest a seasonal pattern in surface water of high values in winter and low values in summer. This seasonal trend probably results from the increased rainfall of winter leaching more humic materials from soils and forest litter. There is no obvious relationship between Secchi transparency and either gilvin (Figure 59) or phytoplankton biomass (Figure 64) and the periodic changes are unexplained. The main value of Secchi readings lies in comparisons of lakes of widely differing character rather than in small amplitude fluctuations within any one lake. Perched Lake is then seen as a lake of moderate transparency compared with other Tasmanian lakes (Cheng and Tyler, 1973; Croome and Tyler, 1972; Tyler, 1974). Lake Gordon, also a brown water lake, has comparable gilvin and transparency (colour = 80-100 Pt units, Secchi = 2.1-3.0 m).

Perched Lake is not the brown water body that might be expected from a knowledge of other waters in the South West. Figure 60 shows the absorption spectra of Perched Lake and some other waters from the Gordon River area. The moderate absorbance of Perched Lake is in contrast to such waters as Cataract Creek, Roaring Creek and heavily coloured coastal lagoons with absorbances greater than those illustrated in Figure 60.

The penetration of light into the lake was measured with a Li-Cor quanta meter, which measures the downwelling irradiance as total quanta per unit area and time over the 400-700 nm waveband ($\mu E\ cm^{-2}\ sec^{-1}$). Despite theoretical imperfections, it is usually found that the attenuation of total quanta with depth is adequately described by the Beer-Lambert Law, where the intensity at any depth Z is given by:

$$I_Z = I_o e^{-kz}$$

so that

$$k = \frac{1}{Z} \ln \frac{I_o}{I_Z}$$

The exponent, k, is the vertical attenuation coefficient used as one

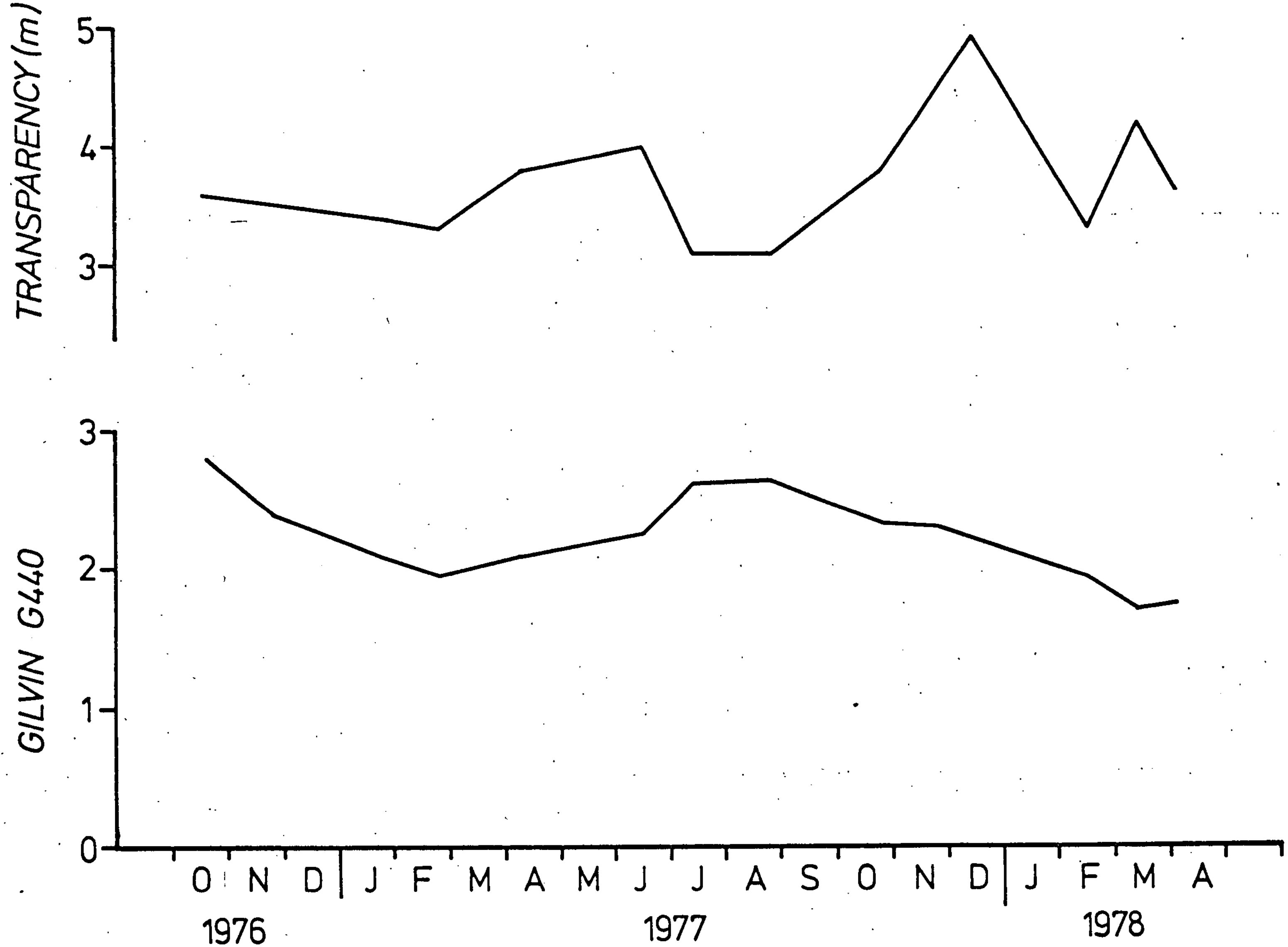


FIGURE 59.

SEASONAL VARIATION OF SECCHI DISC TRANSPARENCY, AND OF GILVIN IN SURFACE WATER, FOR PERCHED LAKE.

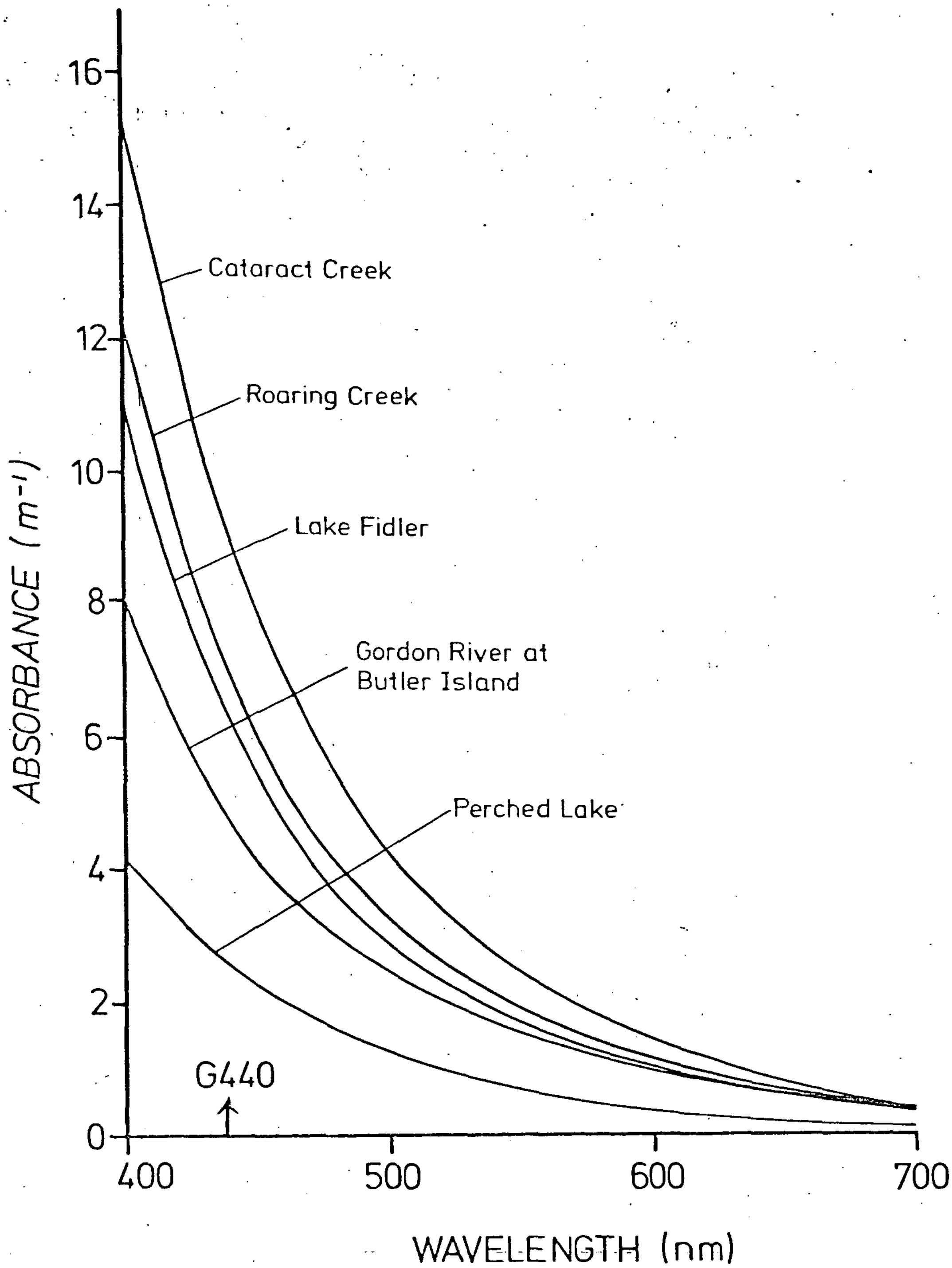


FIGURE 60

ABSORPTION SPECTRA OF VARIOUS WATERS IN THE VICINITY OF PERCHED LAKE. ABSORPTION VALUES ARE FOR A 1 m PATH LENGTH.

expression of the optical properties of a lake. In practice, base 10 logarithms are preferred and the exponent is given the symbol *E*.

Figure 61 shows the results of measurements of downwelling quantum irradiance in Perched Lake on three dates. The values of *E* (the slope of the line) are typical of a moderately dystrophic water. Higher coefficients are typical of the more coloured lakes in the vicinity, such as Sulphide Pool (E = 1.74-2.55), Lake Morrison (E = 1.41-1.76) and Lake Fidler (E = 1.11-1.62). Lake Rhona, a moderately dystrophic montane lake in the Denison Range, has *E* values of 0.43 to 0.75, while Lake St. Clair, which is slightly coloured, has values of 0.17 to 0.24. A clear-water montane lake on dolerite would have much lower values as does, for example, Lake Perry on the Hartz Mountains (E = 0.09).

The photic zone of a lake is the upper portion of the water column where there is sufficient light for adequate photosynthesis. Its lower limit is theoretically defined as the compensation level where photosynthesis just balances respiration. Practically this is arbitrarily taken to correspond with the level where irradiance is 1% of surface values. The compensation level is at greater depths than the Secchi transparency and various authors have used factors between 2 and 5 to relate the two (Bindloss, 1976). In Perched Lake the 1% level was found at depths 1.01x to 1.36x the Secchi depth.

Figure 62 shows the spectral distribution of downward quantum irradiance in Perched Lake. As is to be expected of a dystrophic lake with moderate gilvin concentrations, there was marked attenuation of the short wavelengths. All radiation below 500 nm was quenched in the first 1.5 m of water. The heavy quenching of the infra-red (> 700 nm) occurs in all waters, whether coloured or not. The reasons for lateral shifts in the transmission peaks (indicated by the dotted line in Figure 60) are not clearly understood. The diminution in red irradiance (650-700 nm) between 0.1 m and 2.5 m roughly coincided with the absorption band of chlorophyll-*a* so that phytoplankton was the likely cause. The unequivocal information to be derived from Figure 62 is that, typical of a dystrophic lake, orange-red wavelengths penetrate furthest, but not very far.

The significance of such information is that the ability of algae to photosynthesise at any given depth depends on their ability to harness light energy. From Figure 62 it is clear that algae possessing only

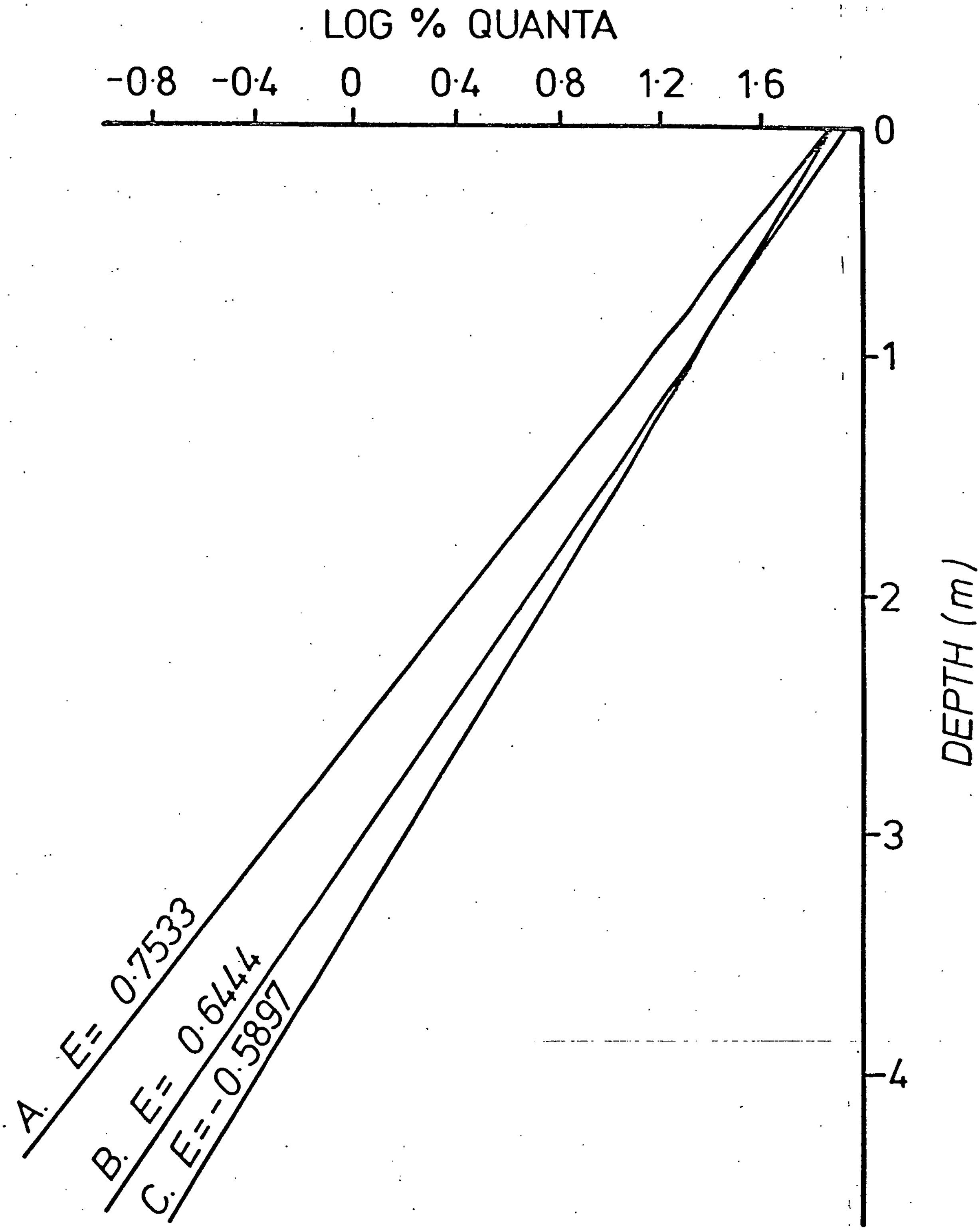


FIGURE 61

ATTENUATION OF LIGHT IN PERCHED LAKE. THE PLOT IS OF QUANTUM IRRADIANCE (E cm^{-1} sec^{-1}) AT DEPTH AS A PERCENTAGE OF IRRADIANCE JUST ABOVE THE SURFACE. THE SLOPE OF THE LINE GIVES THE COEFFICIENT E. THE QUANTUM WAVEBAND IS 400-700 nm.

A = 6/77 B = 4/78 C = 2/78

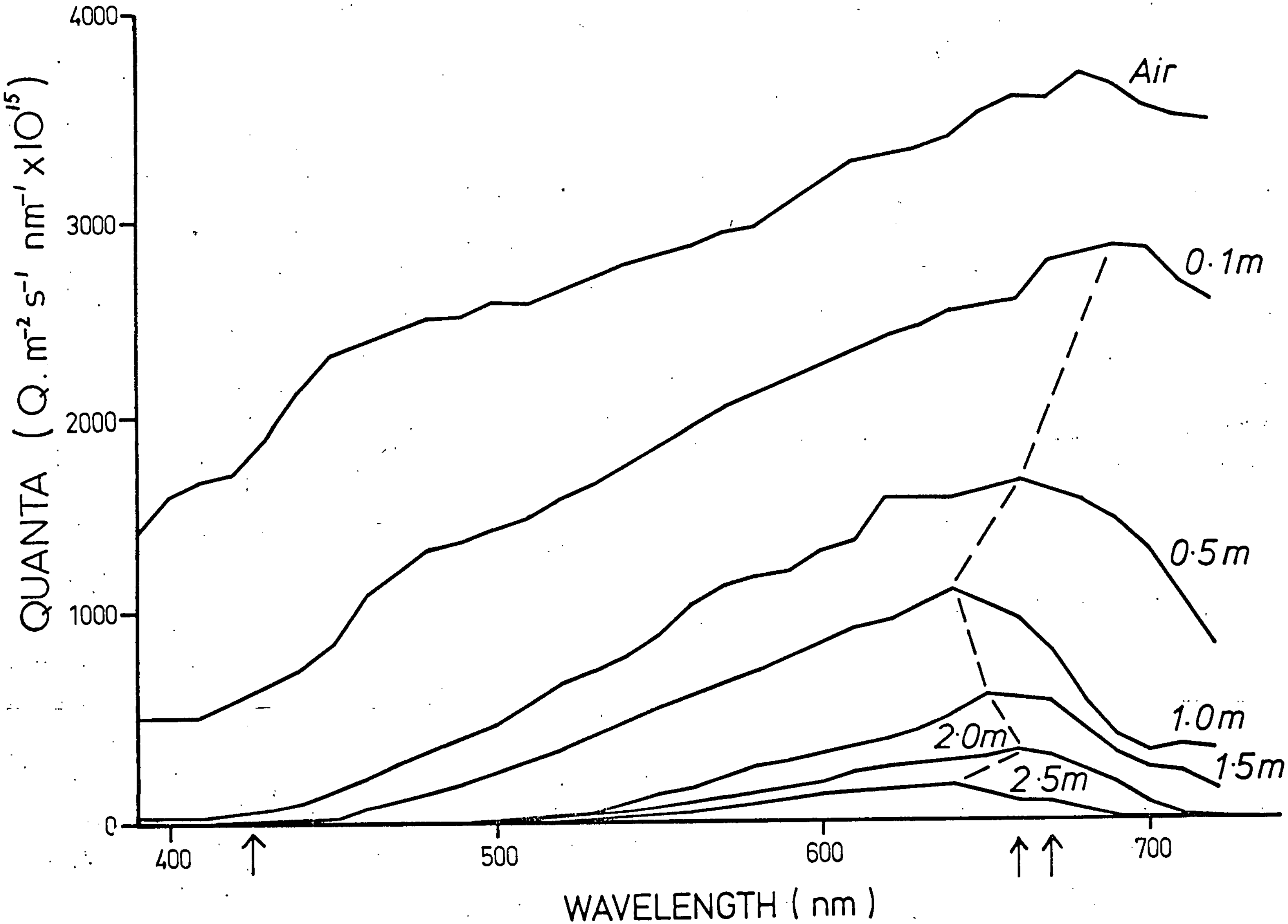


FIGURE 62

SPECTRAL DISTRIBUTION OF DOWNWARD QUANTUM IRRADIANCE MEASURED ON 14TH DECEMBER 1977. CHLOROPHYLL-A ABSORPTION PEAKS ARE INDICATED (↑).

chlorophyll-*a* would be at great disadvantage at depths greater than about 2.0 m in Perched Lake. In fact, the phylogenetic groups of algae possess a variety of accessory photosynthetic pigments absorbing at various wavelengths, and the possibility exists of different types of algae positioning themselves in the water column such that their pigment array is in harmony with the prevailing light climate.

This theory of chromatic adaptation (Boney, 1966) has obvious relevance to the zonation of different seaweed species, according to depth, on a rock platform, but exploration of its relevance to planktonic populations is in its infancy. The coloured lakes of the South West offer tempting opportunities, for in Lakes Fidler, Morrison and Sulphide Pool algae and photosynthetic bacteria are known to be severely stratified at discrete depths in the water column.

5. PLANKTON

5. 1. Sampling

Samples for taxonomic investigation were taken with a 25 µm pore-size plankton net. Population biomass was estimated from samples taken at 0.1 m and 5 m from October 1976 to April 1978.

5. 2. Taxonomy

The taxonomy of Perched Lake algae is incomplete and requires further study. Thirty-two species of algae have been noted. A list, almost certainly incomplete, is presented in Appendix together with cells volumes of thirteen species contributing more than 1% to the total biomass. Some species are illustrated in Plate 14.

The freshwater phytoplankton of Tasmania is too poorly known to allow serious comment on floristic relationships of Perched Lake. However, a flora dominated by *Dinobryon, Mallamonas, Peridinium* and desmids accords with other dystrophic lakes and lagoons in the State. The unidentified *Staurastrum* sp. 1 (Plate 14,O) occurs in other riverine lakes and coastal lagoons in the South West and was present in old Lake Pedder. It also occurs in Lake Laura which is not dystrophic.

The most surprising discovery is the occurrence of a predominantly marine dinoflagellate (Plate 14,A) in Perched Lake, other Gordon River lakes, and West Coast lagoons. Taxonomic treatment is incomplete but according to Bourrelly (Natural History Museum, Paris, pers. comm.) it is probably a species of *Prorocentrum* which has not been recorded previously in freshwater.

A plankter presenting taxonomic problems is *Arthrodesmus triangularis* (Plate 14,K). Most Perched Lake specimens resemble it as described by West and West (1911). However, some specimens resemble *A. pingue*, also described by West (1909) from Yan Yean Reservoir, Victoria, but lack of a very deep sinus and the parallel nature of the spines is more in keeping with *A. triangularis* than *A. pingue*. There is also the possibility that the morphology of *A. triangularis* will vary from season to season, year to year and lake to lake. The identification of colonial algae of the Chlorococcales is difficult and the name *Sphaerocystis schroteri* is used with some caution. The plankton contained many diatom genera, e.g. *Eunotia, Nitzschia, Synedra, Frustulia, Pinnularia,* etc., but in very low numbers.

Perched Lake, and other lakes and lagoons in the area, have as the dominant zooplankter the calanoid copepod *Calamoecia tasmanica* (Smith). This species has a wide distribution in dystrophic lakes and lagoons, both coastal and inland, and was present in a pool of the old Lake Maria complex.

5.3. Biomass

One measure of algal biomass is the volume of cellular material per unit volume of water. This is derived from counts of the numbers of individuals present and the volumes of cells computed from microscopic measurements of cell dimensions. A cell is then approximated to a geometric shape or a number of them, so that the volume can be calculated from standard mathematical formulae. It is not unusual for workers in different parts of the world to arrive at widely different estimates of volume for the same species (Cheng and Tyler, 1973). Nonetheless, the method allows some insight into the wax and wane of populations.

Fluctuations of total algal biomass in Perched Lake are shown in Figure 63. The contributions of individual species are shown in Figure 64 and the percentage composition of the population presented in Figure 65. The chrysophyte *Mallamonas* was a constant member of the plankton but its cells broke up on fixation so that its contribution could not be estimated.

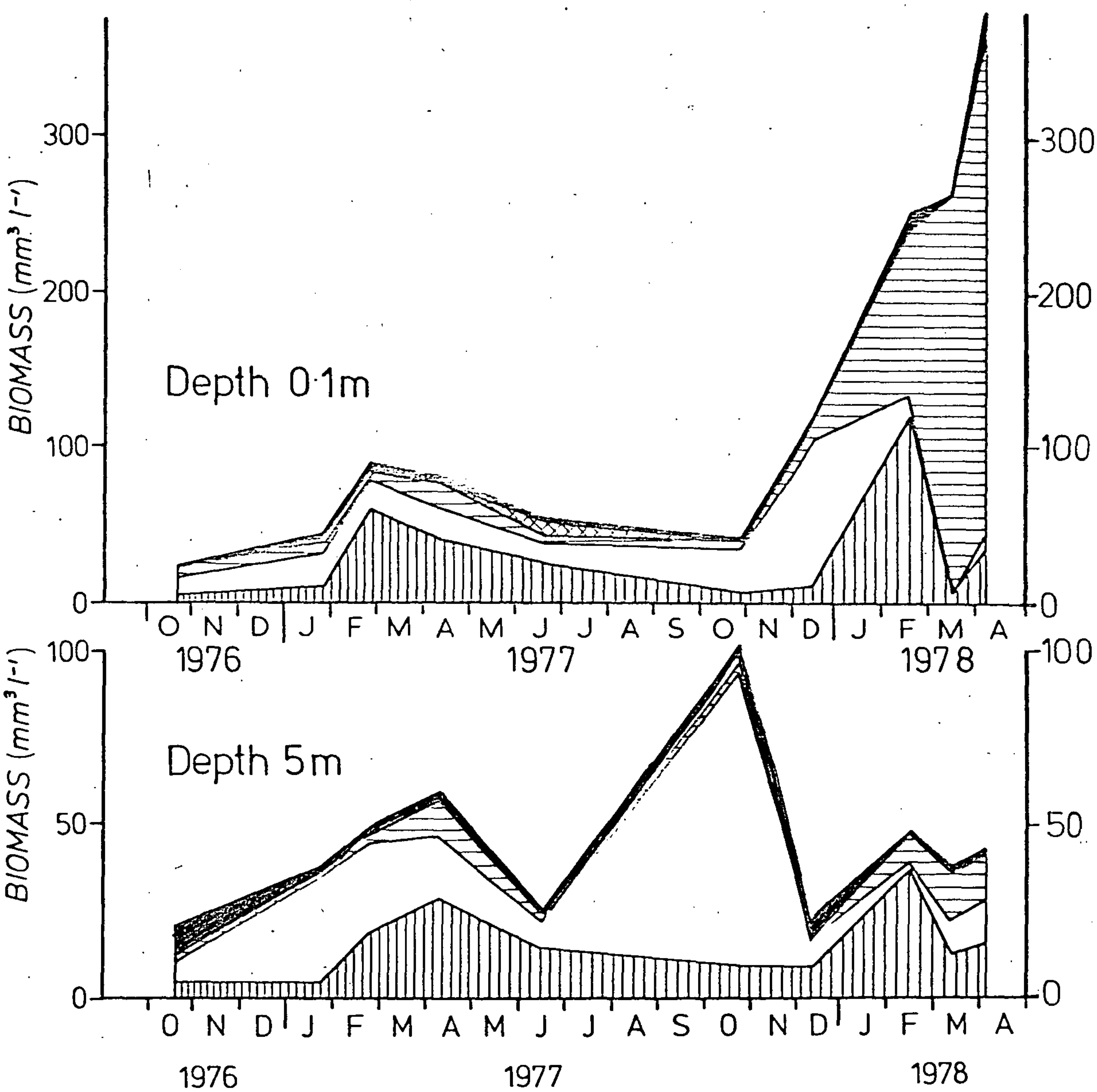
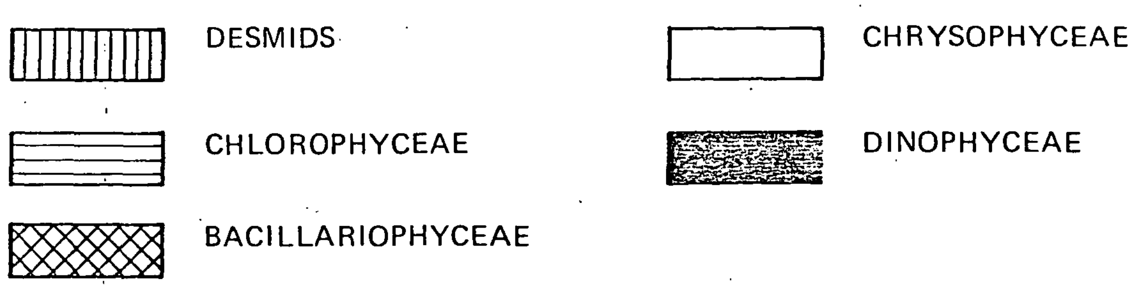


FIGURE 63

SEASONAL VARIATION OF BIOMASS OF MAJOR PHYTOPLANKTERS OF PERCHED LAKE.



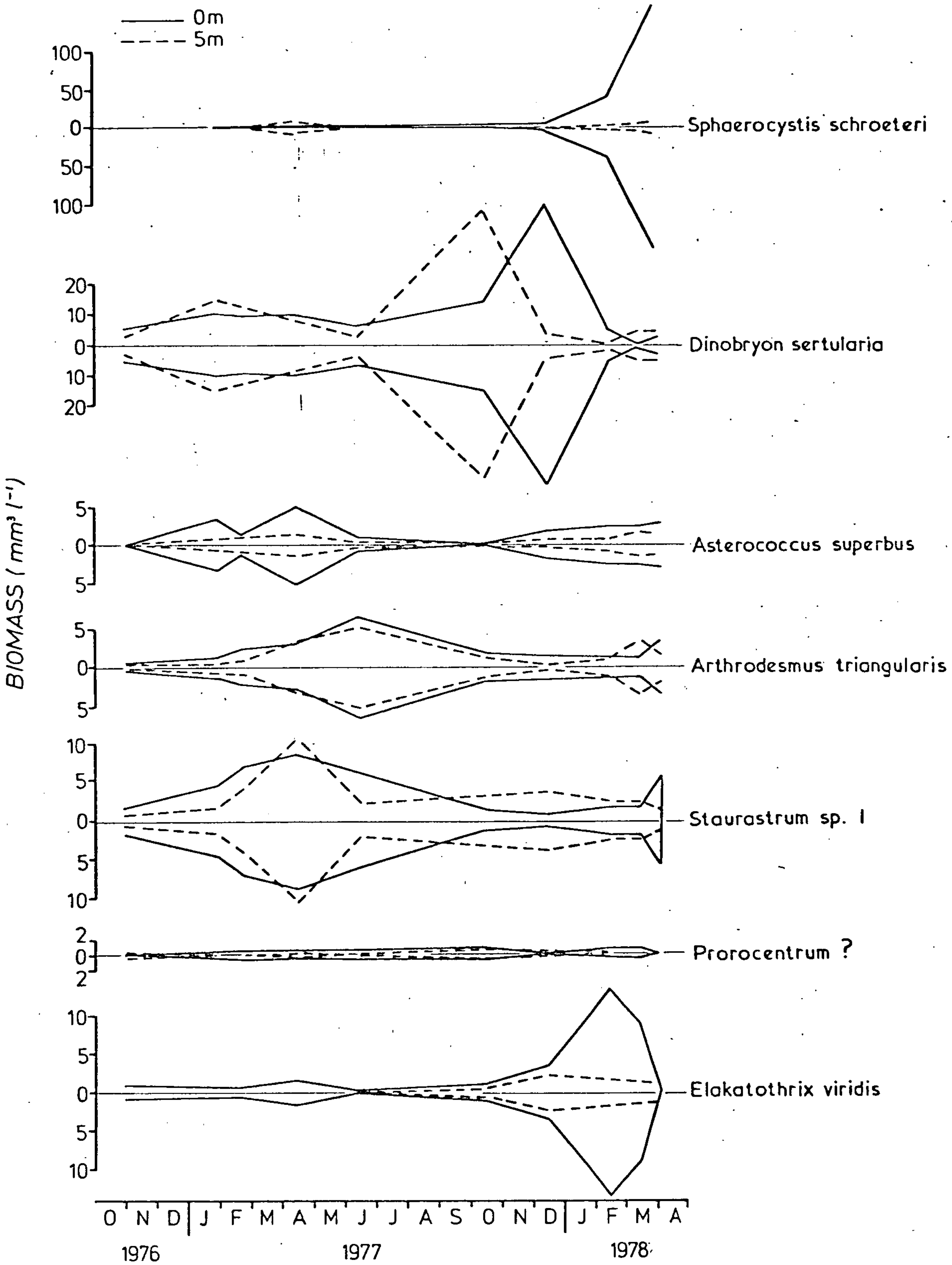


FIGURE 64

SEASONAL VARIATION OF BIOMASS OF THE DOMINANT PLANKTERS OF PERCHED LAKE. THE BIOMASS IS OBTAINED FROM THE SCALE ON ONE SIDE OF THE CENTRE LINE, MULTIPLIED BY TWO.

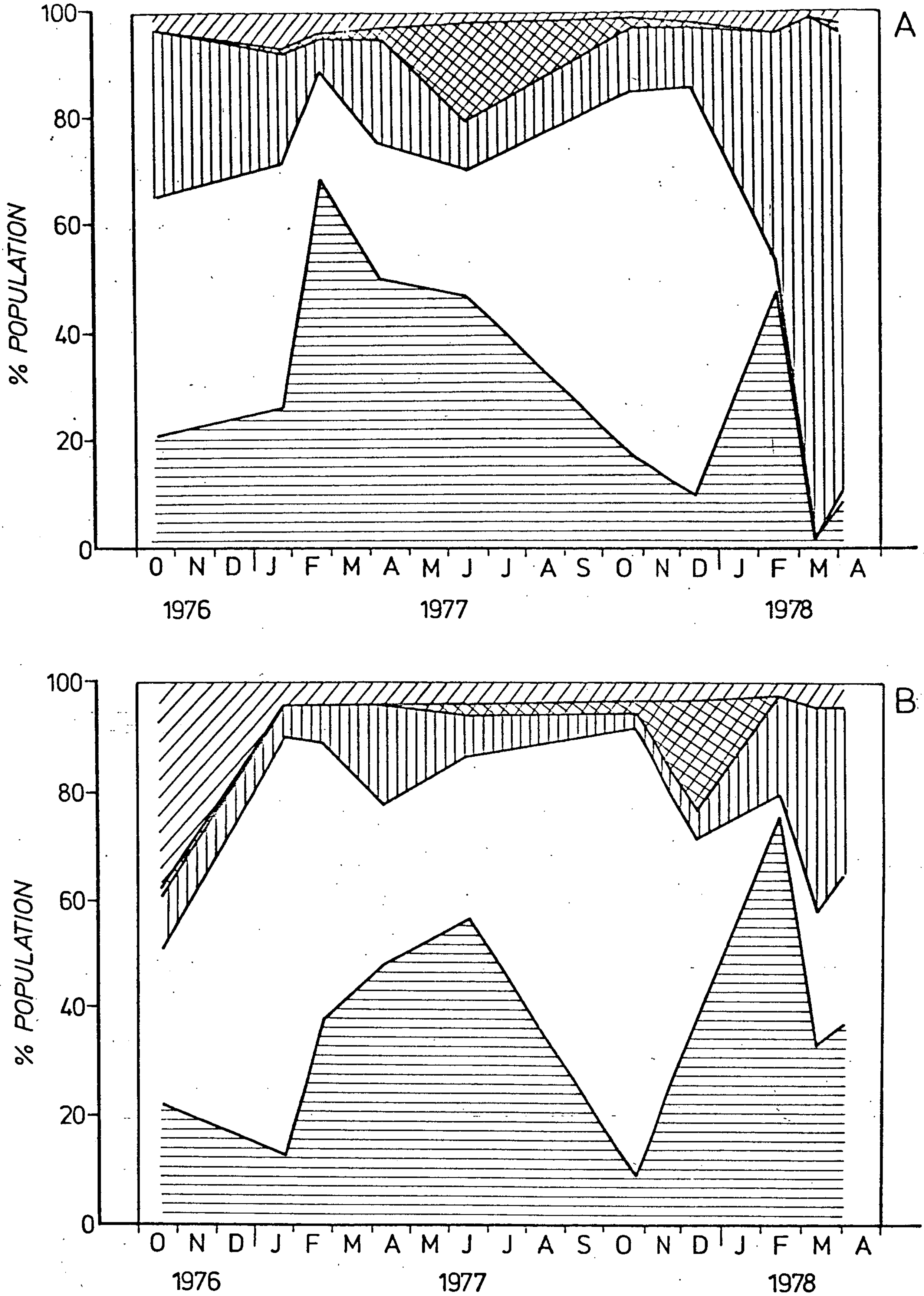
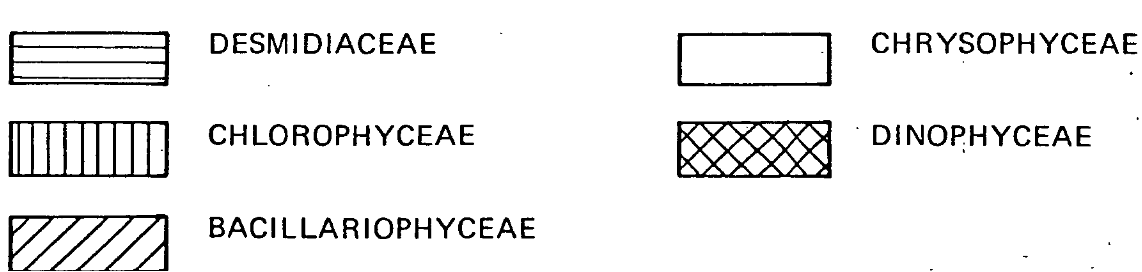


FIGURE 65

SEASONAL VARIATION IN THE RELATIVE CONTRIBUTION OF TOTAL BIOMASS OF VARIOUS TAXA (at 0.1 m (A) and at 5.0 m (B)):



The biomass for both depths sampled in the lake increased gradually from spring 1976 reaching a peak in late summer (Figure 63). The standing crop at 0.1 m then declined gradually to a low in late winter, but at 5 m depth a large increase in biomass in the late winter of 1977 occurred dominated by *Dinobryon sertularia*. This population had generally waned by December 1977, thereafter showing an increase to late summer of 1978. As the waters began warming and light penetration into the water increased due to the increased elevation of the sun about November 1977, so the phytoplankton population began increasing again in the surface waters.

The maximum total summer biomass values for the two summer periods studied were markedly different. In the surface waters the 1978 peak, which was due to a bloom of cf. *Sphaerocystis schroteri* during the summer and autumn, was four times the 1977 maximum. All other groups reached approximately the same standing crops as in 1977.

Figure 65 shows that the plankton of Perched Lake was dominated by desmids and chrysophytes for most of the year. It is noticeable that diatoms (Bacillariophyceae) usually contribute less than 10% of the total biomass. In addition to a small but relatively constant population of *Prorocentrum* (?) another dinoflagellate, *Peridinium* sp., produced a small population in the winter of 1977 which apparently migrated down the water column in subsequent months (Figure 65).

The chrysophyte *Dinobryon sertularia* (Plate14B) showed an interesting fluctuation (Figure 64). A relatively large population (*c.* 91 $\mu m^3 l^{-1}$) was present at a depth of 5 m in early spring. Later it was present in surface waters, suggesting a vertical migration.

Among the Chlorophyceae, cf. *Sphaerocystis schroteri* and *Elakatothrix* cf. *viridis* produced bursts of growth (Figure 64) and came to dominate the plankton population for a short period.

With only two years of data from samples collected at undesirably long time intervals, it is not possible to make firm conclusions on the nature of phytoplankton population dynamics. The limited data do suggest that there was no clearly defined seasonal pattern of the diacmic type common in some northern hemisphere lakes. Instead, there seems to be a rise in biomass in spring and summer followed by a decline in winter. Populations of the algae contributing to total biomass fluctuate in a random and capricious manner.

PLATE ~~14~~ 17

SOME PHYTOPLANKTON FROM PERCHED LAKE

A: *Prorocentrum* sp. (?)

B: *Dinobryon sertularia* Ehr. colony

C: *Mallomonas* sp.

D: *Frustulia rhomboides* (Ehr.) DeT.

E: *Tabellaria flocculosa* (Roth.) Kütz.

F: Planktonic diatoms *Frustulia rhomboides* (Ehr.) DeT. and variety *capitata* (arrows). C - *Cyclotella stelligira* Cleve and Grun., N - *Nitzschia* spp. and CO - *Cocconeis* sp.

G: *Pinnularia* sp. and *Eunotia* sp.

H: *Asterococcus superbus* (Cienk.) Scherffel.

J: cf. *Sphaerocystis schroteri* Chodat.

K: *Arthrodesmus triangularis* Lagerh.

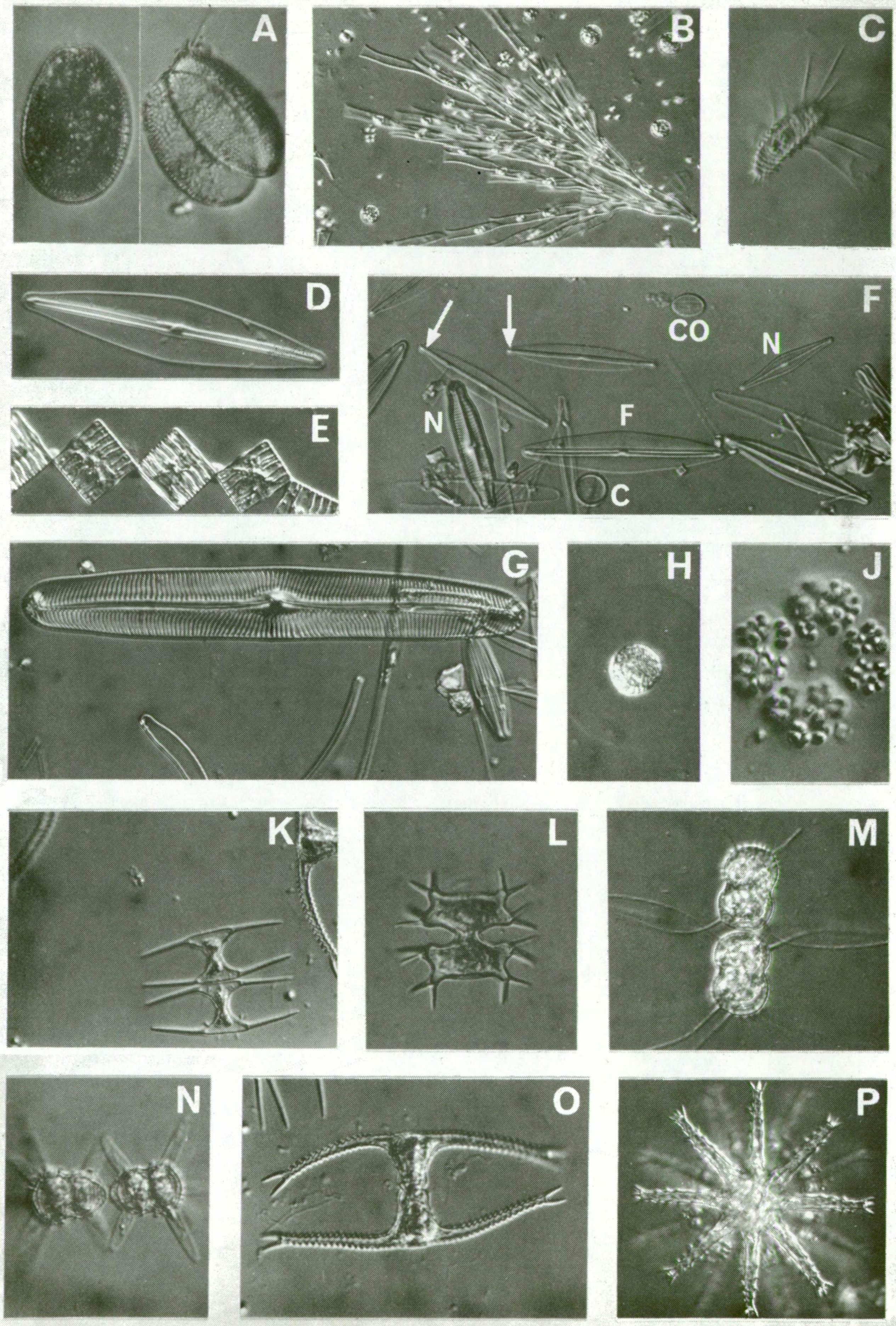
L: *Xanthidium* sp.

M: *Cosmarium* sp.

N: *Staurastrum aureolatum* Playfair

O: *Staurastrum* sp. 1

P: *Staurastrum sagittarium* Nordst.


A
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6. DISCUSSION

Dark, humic waters are generally considered to be most characteristic of tropical rainforest regions (Sioli, 1975; Lewis and Caufield, 1977), where rivers such as the Congo, Rio Negro and Amazon yield large quantities of 'black' water. Although there is no equivalent of this in the temperate zone, humic waters are by no means rare, especially in areas of extensive bog or swamp. Both in tropical and temperate regions, refractory organic acid compounds discussed by Shapiro (1957) are leached from vegetation or podzolic soils to give a humic water poor in electrolytes (Sioli, 1965; Klinge, 1967).

South West Tasmania is very much a dark water province and for this reason it was easily recognised as a distinctive region by Buckney and Tyler (1973*a,b*) in their survey of water chemistry in the State. The steady maritime rainfall, and the peats derived from dense rainforest, scrub, or *Gymnoschoenus* sedgeland, ensure that most waters have abundant humic material and low electrolyte concentrations. Limestone and dolomite rocks significantly modify water chemistry of the rivers. Fuller discussion of water chemistry of the South West will be presented in another report in this series.

Lewis and Caufield (1977) give data on the dark waters of the Venezuelan Rio Carrao. With an absorbance at 440 nm of 6.2 m^{-1} it must have considerable amounts of humic material, gilvin, in solution. Most rivers and montane lakes in the South West have values of this order and some west coast lagoons have considerably higher values.

Though set in a dark water province, Perched Lake is not the humic water that might be expected. Its absorbance and colour (Pt scale) indicate only moderate amounts of gilvin, sufficient nonetheless to restrict light penetration and specify a blue-deficient spectrum. In all probability, the relatively low gilvin values are a result of the limited catchment area where inflowing waters have scant contact with forest soils. Suspected inflows of artesian water may also introduce low-colour water. Probably for the same reasons, Perched Lake, despite being set in limestone country, has a water chemistry akin to seawater like many surface waters in the South West (Buckney and Tyler, 1973*a,b*). The influence of readily soluble alkaline-earth metals is slight. The slight differences in water chemistry at intermediate depths are circumstantial evidence for artesian inflow.

The temperature regime of Perched Lake is typically warm monomictic, with summer stratification followed by free circulation at temperatures above 4°C. However, there are some anomalies. The apparent hypolimnetic heating suggests that occasional gales may mix warm surface water downwards after stratification has occurred. The phenomenon of apparent hypolimnetic cooling is more difficult to explain, but a cold artesian inflow springs to mind. The low sampling frequency prevents further interpretation.

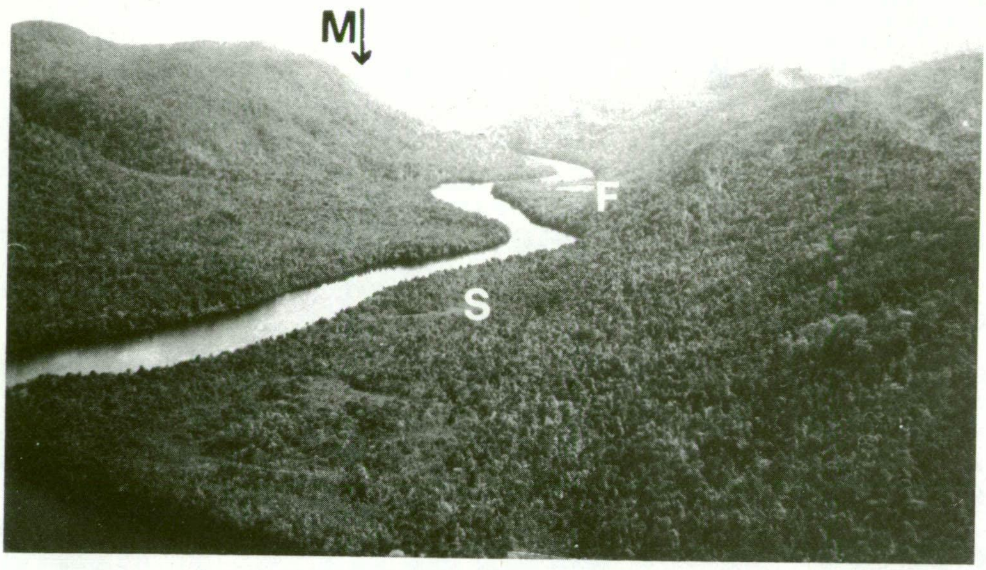
Thermal stratification in Perched Lake has predictable effects upon oxygen concentrations in bottom waters. However, significant consumption of hypolimnetic oxygen lags thermal stratification considerably in contrast to many lakes, for example Risdon Brook Reservoir (Tyler, 1974) where thermal stratification is closely followed by hypolimnetic oxygen deficits. The lag indicates low or moderate productivity with only moderate oxygen demand generated by dead plankton or litter.

A reasonable picture of the general limnology of Perched Lake has been sketched, but knowledge of its biota is less satisfactory. All that can be said is that the flora has obvious relationships with coastal lagoons, old Lake Pedder and other lowland dystrophic waters in Tasmania. While montane dystrophic waters are chemically similar, and support some of the same species as Perched Lake, it is suspected that they may differ in other respects. The contrast between Perched Lake and large lakes of the Central Plateau and Eastern Tiers, however, is very marked (Cheng and Tyler, 1973; Croome and Tyler, 1973).

Data gathered from infrequent sampling over only two years does not allow a firm opinion on whether population size and structure are typical of dystrophic waters in all years, though this seems likely. In all events the low total biomass and limited species diversity of Perched Lake plankton is likely to be normal not only for Perched Lake in most years, but also for most lowland dystrophic lakes in Tasmania. The overriding influence of gilvin in attenuating light militates against anything other than low productivity if only phytoplankton is considered. That secondary productivity might be high, supported by heterotrophic bacteria utilising humic materials, is a possibility worthy of investigation in the numerous dystrophic waters of Tasmania. For the present our knowledge of Perched Lake, however imperfect, is a significant advance on the other, formally published study of dystrophic waters in the South West, a slight work on old Lake Pedder (Buckney and Tyler, 1973*b*).

C H A P T E R   4

Meromictic lakes of the Gordon River



FRONTISPIECE

VIEW LOOKING NORTH ALONG LIMEKILN REACH; CAMERONS FLATS ARE ON THE MIDDLE LEFT AND LAKE FIDLER (F) AND SULPHIDE POOL (S) ON THE RIGHT HAND BANK OF THE GORDON RIVER. THE CRACROFT HILLS AND MT McCUTCHEON CAN BE SEEN IN THE BACKGROUND. LAKE MORRISON (M) IS OUT OF THE PICTURE AT THE END OF LIMEKILN REACH.

CONTENTS

FIGURES

Page

TABLES

FRONTISPIECE

1. INTRODUCTION

Lake classification has generated considerable debate during the relatively recent history of limnological investigation. Classification criteria are paramount in order to formulate a universally applicable scheme. Hutchinson and Löffler (1956) grouped lakes according to thermal characteristics and annual ciruclation patterns, the primary basis was whether a lake underwent no vertical circulation at all (amictic lakes), partial and restricted circulation (meromictic lakes), or complete vertical circulation (holomictic lakes). These various circulation patterns exhibit a continuum, and accepting that lakes undergo changes in these patterns throughout their existence, classification may have no practical value (Walker and Likens 1975) due to the reality of transitional types (e.g. Culver 1975 described the initiation and destruction of biogenic meromictic Hall Lake - Washington). This paper deals specifically with three meromictic lakes on the banks of the lower Gordon River.

The state of meromixis (Findenegg 1935) can be defined simply as incomplete mixing in a body of water, where some part of the water mass remains completely isolated throughout the year. An integral characteristic of these lakes is a chemically produced density gradient which overrides the seasonal thermally induced density fluctuations (Likens 1967). A specific terminology has developed for these lakes: the permanently stagnant anoxic bottom layer, containing quantities of dissolved sulphides and/or methane, as well as much larger concentrations of dissolved substances than do the surface waters, is called the monimolimnion (Findenegg 1935); the upper mixolimnetic layer (Hutchinson 1937) which is oxygenated and much more dilute, is mixed by wind action and may display seasonal changes similar to those of a holomictic lake (Cole 1975). Between the mixolimnion and monimolimnion is a zone where the concentration of solutes increases rapidly with depth, the chemocline (Hutchinson 1937).

Striking chemical differences may develop between the upper and lower layers (Likens 1967) as well as a unique layering of various bacteria and algae which are able to tolerate, and no doubt thrive in, these seemingly adverse conditions, to produce a bacterial plate (see Northcote and Halsey 1969, and Figures 109 and 110). Variations to this generalized picture of meromictic lakes in terms of their classification have been discussed by Walker and Likens (1975).

Meromictic lakes have been classified according to their mode of origin, and Hutchinson (1937) divided them into ectogenic[1], crenogenic[2] and biogenic[3]. Walker and Likens (1975) have recently revised Hutchinson's scheme, by recognizing two principal groups, namely ectogenic meromixis which originates primarily from factors external to the lake basin (incorporating ectogenesis and crenogenesis in Hutchinson's classification), and endogenic meromixis (biogenesis sensu Hutchinson 1937), where internal factors are of primary importance. Walker and Likens recognize two types of ectogenesis, and the Gordon River lakes can be classified as type 1b ectogenesis, where a surface inflow of saline water of marine origin underlies a pre-existing fresh layer, resulting in a well developed chemocline. Marked density differences between the mixolimnion and monimolimnion inhibit vertical circulation, thereby creating the state of meromixis within the lakes.

Walker and Likens (1975) have compiled a list of 120 meromictic lakes worldwide. Several lakes have been omitted from this list due to insufficient information, while others have been excluded because they were no longer meromictic at the time of compilation (e.g. Hall Lake, Washington - Culver 1975). Three Gordon River meromictic lakes can now be added to the world list. Of the total of 123 lakes, 107 occur in the northern hemisphere

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CLASSIFICATION OF HUTCHINSON (1937)

1. Ectogenic meromixis results from an external event bringing salt water into a freshwater lake, or vice versa, producing a layer of freshwater overlying more dense salt water.
2. Crenogenic meromixis results from submerged saline springs delivering dense water into the deep portion of the basin.
3. Biogenic meromixis results from accumulation of salts in the bottom of a lake, usually liberated from bacterial decomposition in the sediments and released to the overlying water. No noticeable accumulation of marine salts. Similarities and differences between the lakes are investigated as well as the effect on the lakes of the altered flow pattern of the Gordon River by Stage 1 of the Gordon Power Development. The inaccessibility of this area has precluded closer sampling intervals, and in some cases (particularly Lake Morrison) only limited information was collected, mainly due to adverse weather conditions.

(4 within the tropics and 103 outside) and only 16 in the southern hemisphere (6 tropical and 10 subtropical), five from Australia and 5 from Antarctica. Meromictic lakes occur widely throughout the world, being most abundant in the U.S.A. and Europe, with significant numbers also reported from Japan and the U.S.S.R. This global occurrence may well reflect the intensity of limnological investigation, and therefore meromictic lakes could be more widespread. Clearly the Gordon River lakes contribute significantly to the worldwide distribution of meromictic lakes.

This chapter describes three meromictic lakes discovered in 1977 which occur just outside the lower Gordon River Scientific Survey area on the river banks along the lower Gordon River (Figures 66 and 68). Seasonal observations have helped to characterise these lakes with respect to physical chemical and biological characteristics.

2. BACKGROUND

2.1 Lake Formation

The suggestion that an alteration in flow direction facilitated levee formation and the formation of the Gordon River lakes (Figure 67, stage 1) particularly Lake Fidler and Sulphide Pool, is supported by geological information (Figure 68). From just downstream of Butler Island the Gordon River flows directly due north along Gordon limestone sequences, and in order for alluvial deposition to occur along the river banks some force must have been exerted to permit meandering and thus deposition. The causitive factor producing the alteration to river flow direction cannot be stated with certainty, but could be due to local geology or possibly a landslide.

The Gordon River meromictic lakes were probably formed when depressions remained behind these river deposited levee banks (Figure 67, Stage 2). Alluvium was deposited on the inside of a bend in the river (Wetzel 1975) which then progressively extended the levee further downstream (Figure 67, Stage 3). The levee opposite Tuan Gabby Flats exhibits a feature at this particular stage and is believed to be presently forming such a lake; the zone between the river and the impending lake is presently about 1.0 - 1.5 m deep, depending on river height, and is colonized by a band of *Triglochin procera* and *Baumea rubiginosa* extending from the tip of the levee to the downstream river bank (Figure 67, Stage 4; chapter 2 Plate 10). The rooted aquatic macrophytes appear to stabilize the river bed alluvium bridging the levee tip and the bank until the sickle-shaped levee develops sufficiently to separate a lake from the river (Figure 67, Stage 5).

The formation of Lake Morrison is not at all clear, because of its

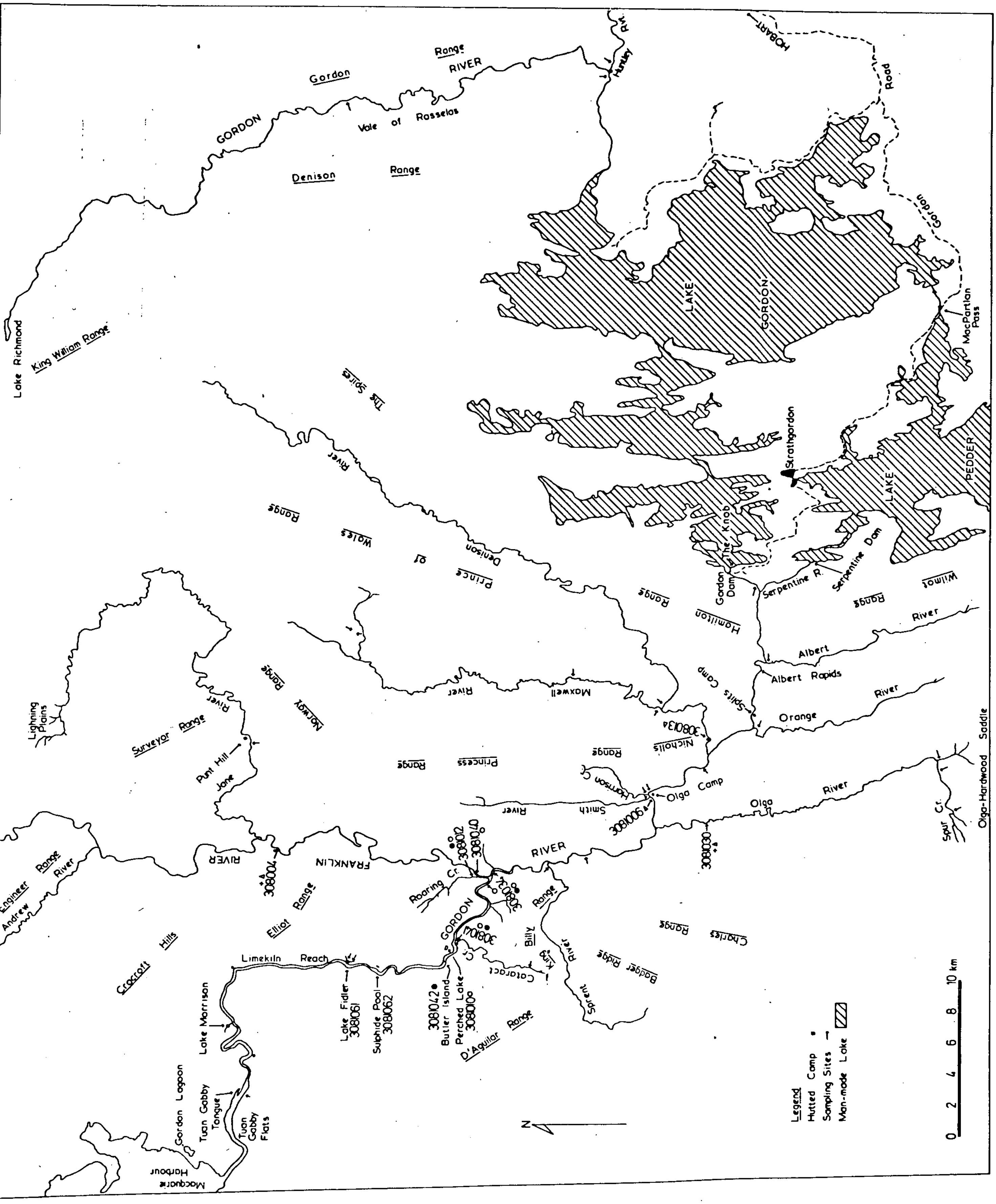

FIGURE 66: LOCATION OF THE LAKES AND THE LOWER GORDON RIVER SCIENTIFIC SURVEY AREA.

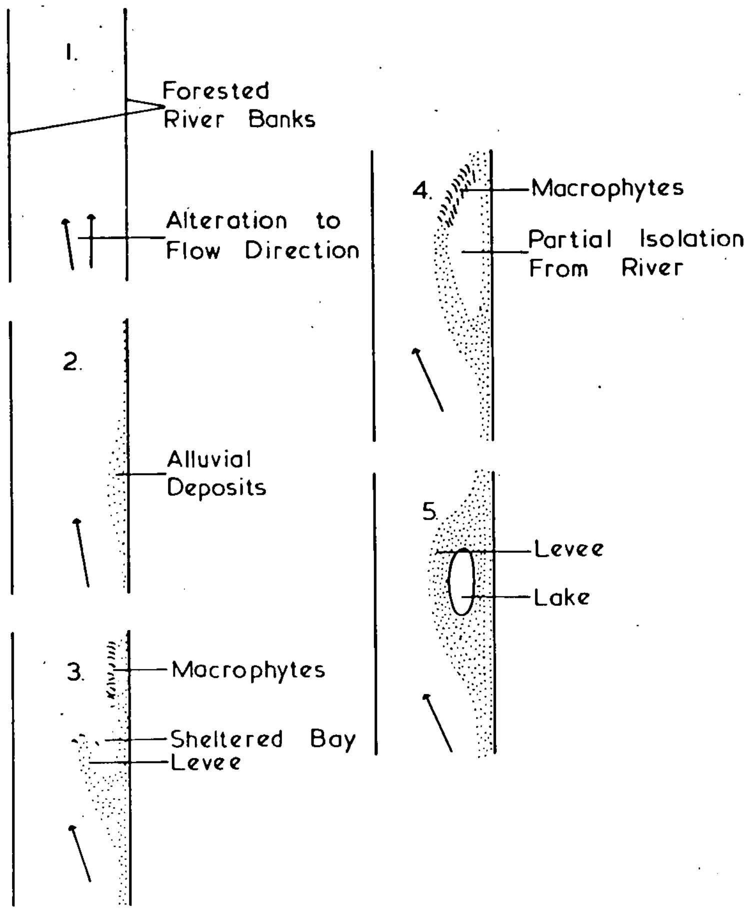

FIGURE 67: SCHEMATIC REPRESENTATION OF THE FORMATION OF GORDON RIVER LEVEE LAKES. 1 TO 5 INDICATE PROBABLE SEQUENCE STAGES OF LAKE FORMATION.

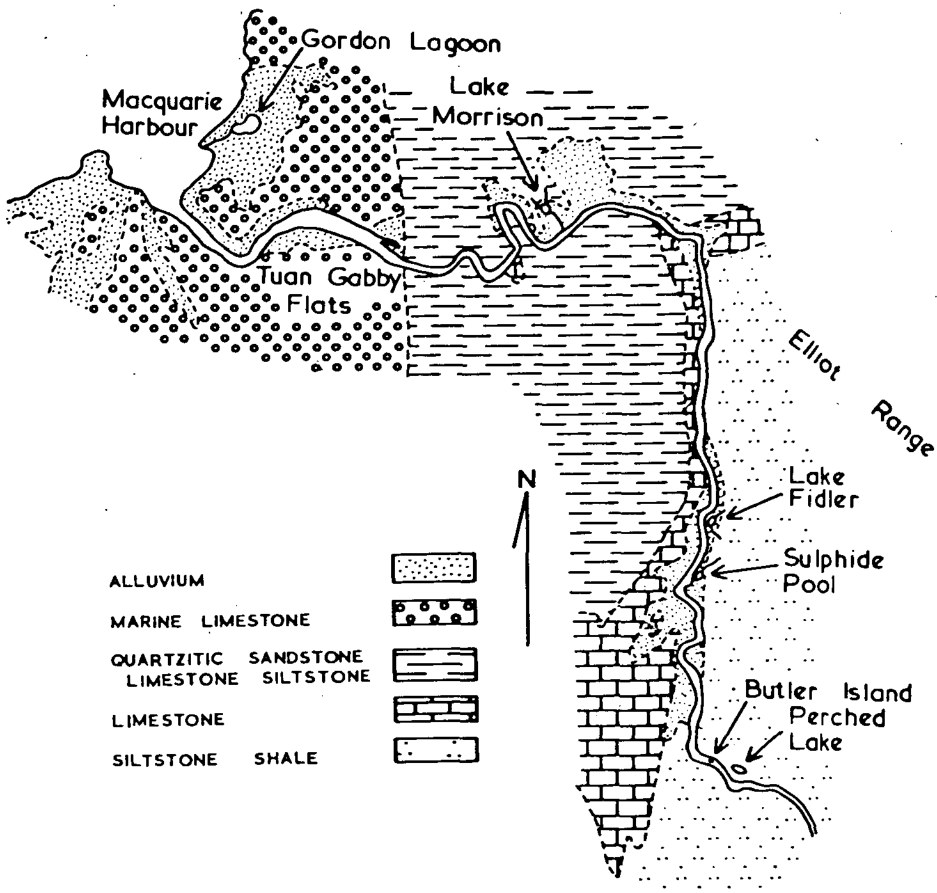

FIGURE 68: GEOLOGY OF THE LOWER GORDON RIVER AREA SHOWING THE LOCATION OF THE MEROMICTIC LAKES. PERCHED LAKE AND GORDON LAGOON HAVE ALSO BEEN INCLUDED. (MODIFIED FROM TASMANIAN DEPARTMENT OF MINES, 1976).

distance from the Gordon River and the configuration of the river itself in this region. However alluvial deposits in the region suggest a similar sequence of formation when the Gordon River took a course unlike that at present.

2.2 Physiography

The lakes are sheltered from prevailing westerly winds by hilly terrain and surrounding temperate rainforest (Plates 20, 21, 23 and 25). They occur at river level, and are in the tidal section of the river which extends for a distance of about 48 km upstream from the mouth (Kearsley, 1978). The lake basins all occur behind river bank levees composed of Holocene alluvium. The underlying geology at Lake Morrison is Lower Devonian - Silurian siltstone-shale sequences, and at Lake Fidler and Sulphide Pool, Ordovician Gordon limestone sequences. The lakes receive water directly from rainfall, from small creeks and peat seepages draining the temperate rain-forest, and through small inflow-outflow creeks which connect directly to the Gordon River (Figures 69 and 70). As this lower section of the Gordon River is tidal the lake levels are also tidally influenced. The inflow-outflow creeks are shallow and only about 1 m wide, therefore this source of river water is unlikely to be sufficient to effect all the observed lake level rises of about 0.05 m per hour, representing a flow rate of about 1.8 m^3/sec. As these lakes (Lake Fidler and Sulphide Pool) are in close proximity to the Gordon River and lie in alluvium, river level fluctuations could also influence lake levels by percolation through the levee banks. No information exists to substantiate this theory and further work will be required to confirm or reject this theory of subterranean flow.

Bathymetric maps of the meromictic Gordon River Lakes are presented in Figure 70, the bathymetric curves in Figure 71, and the morphometric data in Table 11.

The aquatic herb fields surrounding the lakes to the inside of the rainforest are flat and become inundated when the lake level rises. The lake waters sometimes extend beyond the forest perimeter when river levels are high. From the inner perimeter of the herb fields the lake bottoms drop off suddenly to a depth of approximately 1 m, and this fringing zone is colonized by *Triglochin procera*, and *Baumea rubiginosa*. These areas of rooted macrophytes are most extensive in Lake Morrison and to a lesser extent in Lake Fidler and Sulphide Pool. The basins of both Lake Morrison and Sulphide Pool are very flat and shallow. Published morphometric data from meromictic lakes (mostly from Walker and Likens 1975) suggest that

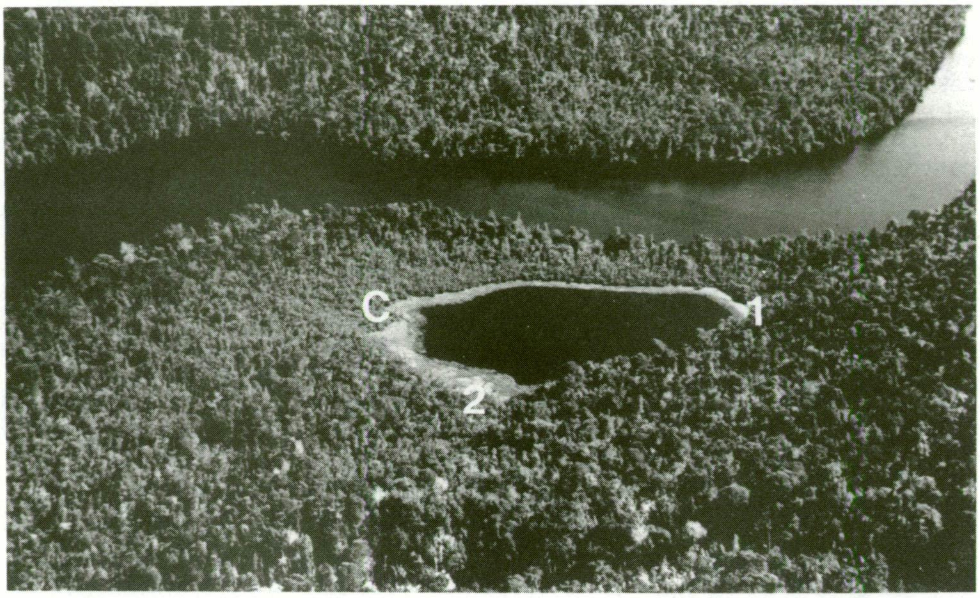

PLATE 19: LAKE FIDLER FROM THE AIR WITH THE GORDON RIVER BEHIND. THE POSITIONS OF INFLOW CREEK 1 AND 2 AND THE CHANNEL CONNECTION WITH THE GORDON RIVER (C) ARE MARKED.

PLATE 20: THE WESTERN SHORE OF LAKE FIDLER WITH THE FORESTED RIVER VALLEY RIDGE IN THE UPPER LEFT OF THE PICTURE. INFLOW CREEK 1 IS VISIBLE IN THE LEFT FOREGROUND. *TRIGLOCHIN PROCERA* AT THE MOUTH OF THIS CREEK HAS BEEN CROPPED BY NATIVE ANIMALS, AND HERBFIELDS ARE IN THE FOREGROUND.

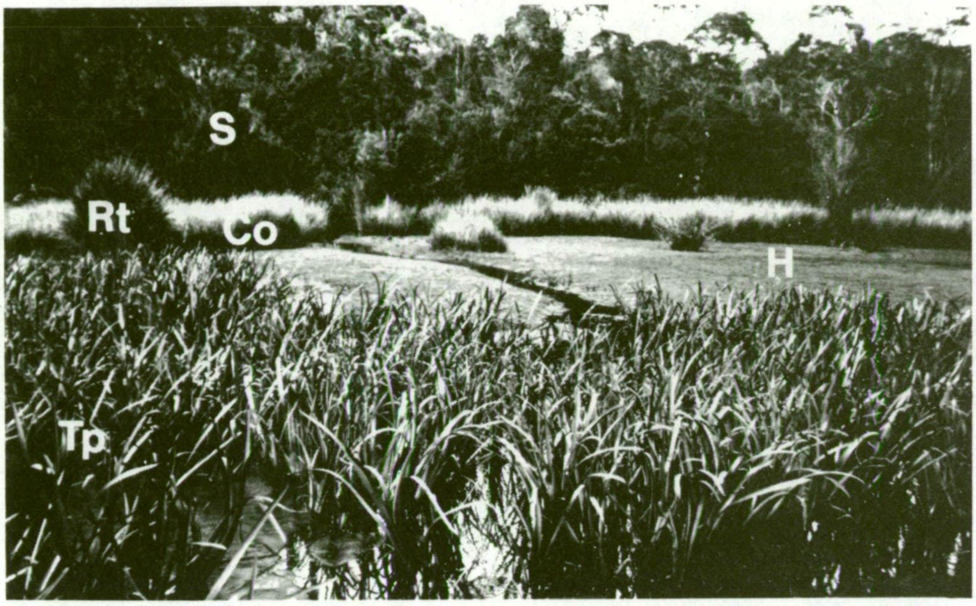

PLATE 21: LAKE FIDLER INFLOW CREEK 2, LOOKING WEST. *TRIGLOCHIN* SURROUNDS THE LAKE (TP) HERBFIELDS IN THE CENTRE (H) AND *CAREX OPPRESSA* (Co) AND *RESTIO TETRAPHYLLA* (Rt) AT THE EDGE OF THE RIVERINE SCRUB VEGETATION (S).

PLATE 22: LAKE FIDLER LEVEL ELEVATED WHEN THE GORDON RIVER FLOODED IN DECEMBER 1977. THE GAUGE BOARD IS JUST VISIBLE IN THE CENTRE. HIGHER LAKE LEVELS HAVE BEEN RECORDED ABOVE THE HEIGHT OF THE BOARD.

PLATE23: SULPHIDE POOL LOOKING WEST. POORLY DEVELOPED HERBFIELDS OCCUR AT BOTTOM RIGHT, SCATTERED STANDS OF ROOTED EMERGENT MACROPHYTES AT THE WATERS EDGE AND *MELALEUCA SQUAROSA* SCRUB IN THE BACKGROUND. THE BUOY MARKS THE DEEPEST POINT OF THE LAKE.

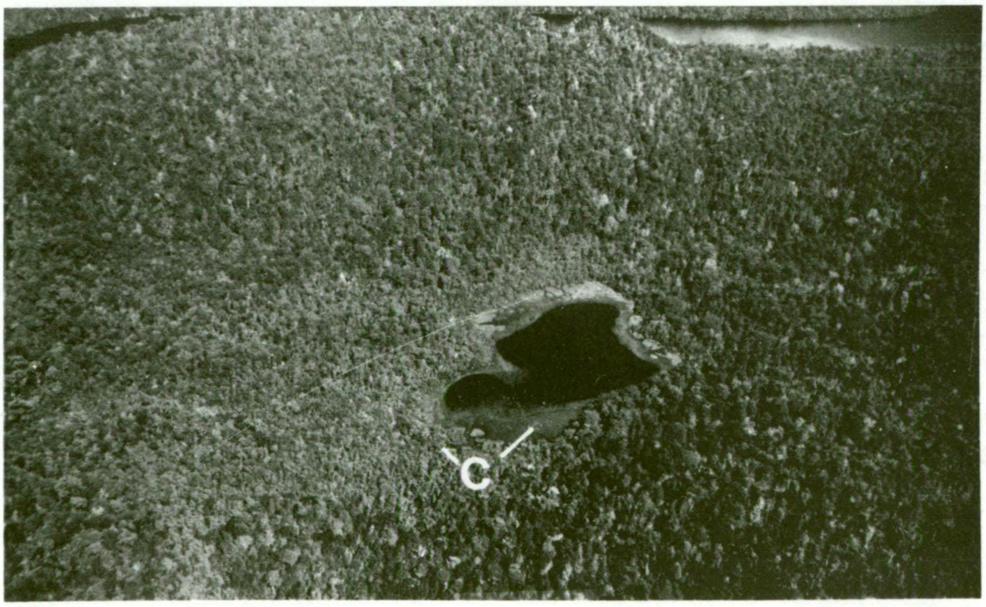

PLATE24: LAKE MORRISON FROM THE AIR, LOOKING WEST. THE GORDON RIVER IS IN THE BACKGROUND AND HORSESHOE BEND IN THE TOP RIGHT CORNER. THE CREEK JOINING THE LAKE WITH THE RIVER IS MARKED (C).

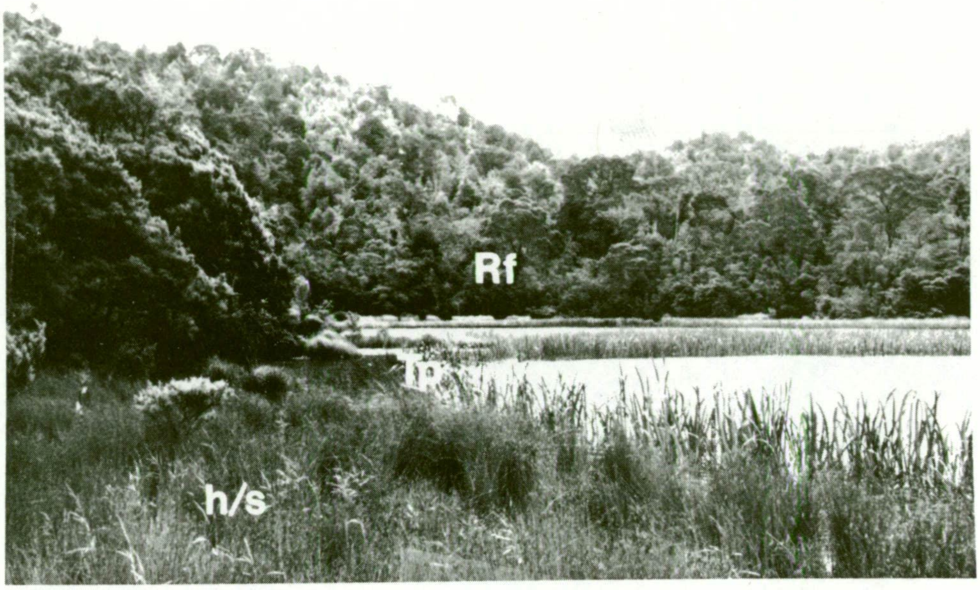

PLATE 25: LAKE MORRISON LOOKING WEST. *TRIGLOCHIN PROCERA* (Tp) DOMINATES THE EMERGENT AQUATICS AT THE EDGE OF THE LAKE, SURROUNDED BY LOW CLOSED HERBFIELD/SEDGEFIELD (h/s) WITH LOW CLOSED RAINFOREST (Rf) DOMINATED BY *MELALEUCA SQUAROSA* AND *LEPTOSPERMUM LANIGERUM* IN THE BACKGROUND.

PLATE 26: AN AERIAL VIEW OF PERCHED LAKE LOOKING WEST TOWARDS THE GORDON RIVER AND BUTLER ISLAND. KINGHORN CREEK FLATS ARE IN THE BACKGROUND.

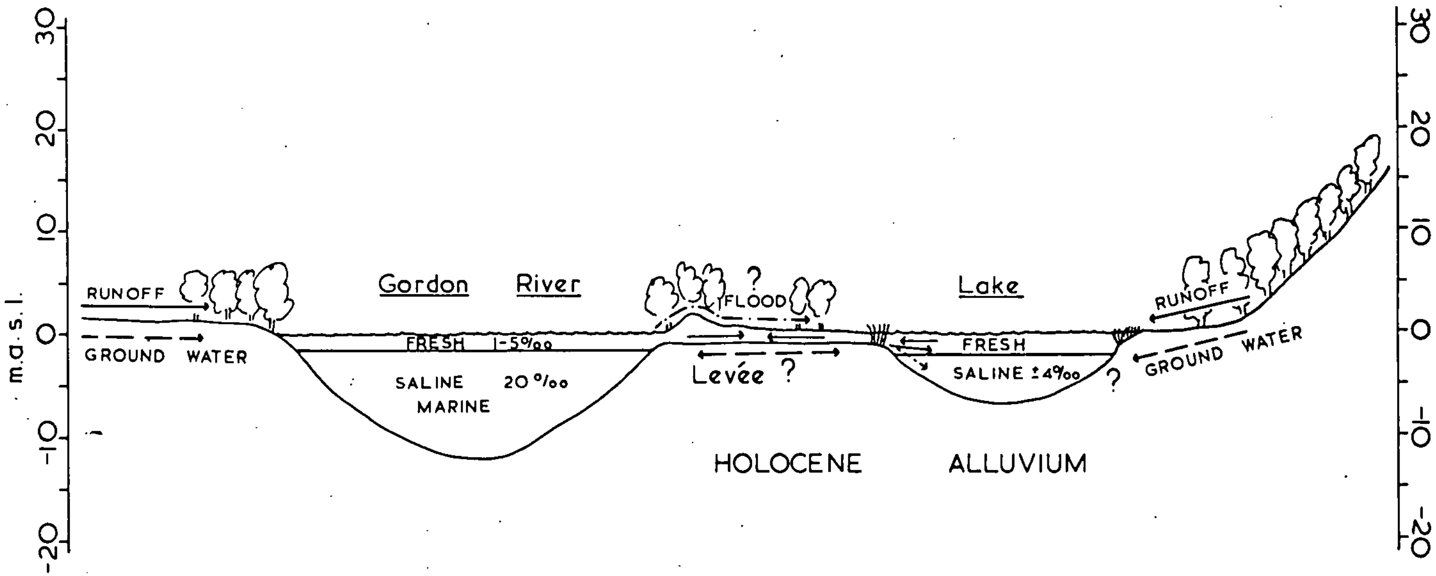

FIGURE 69: SCHEMATIC REPRESENTATION OF THE HYDROLOGY OF THE GORDON RIVER LAKES. HORIZONTAL SCALE TAKEN AT LAKE FIDLER. BROKEN ARROWS (- - →) INDICATE POSSIBLE WATER MOVEMENT NOT YET PROVEN, WHICH MAY INFLUENCE LAKE LEVELS.

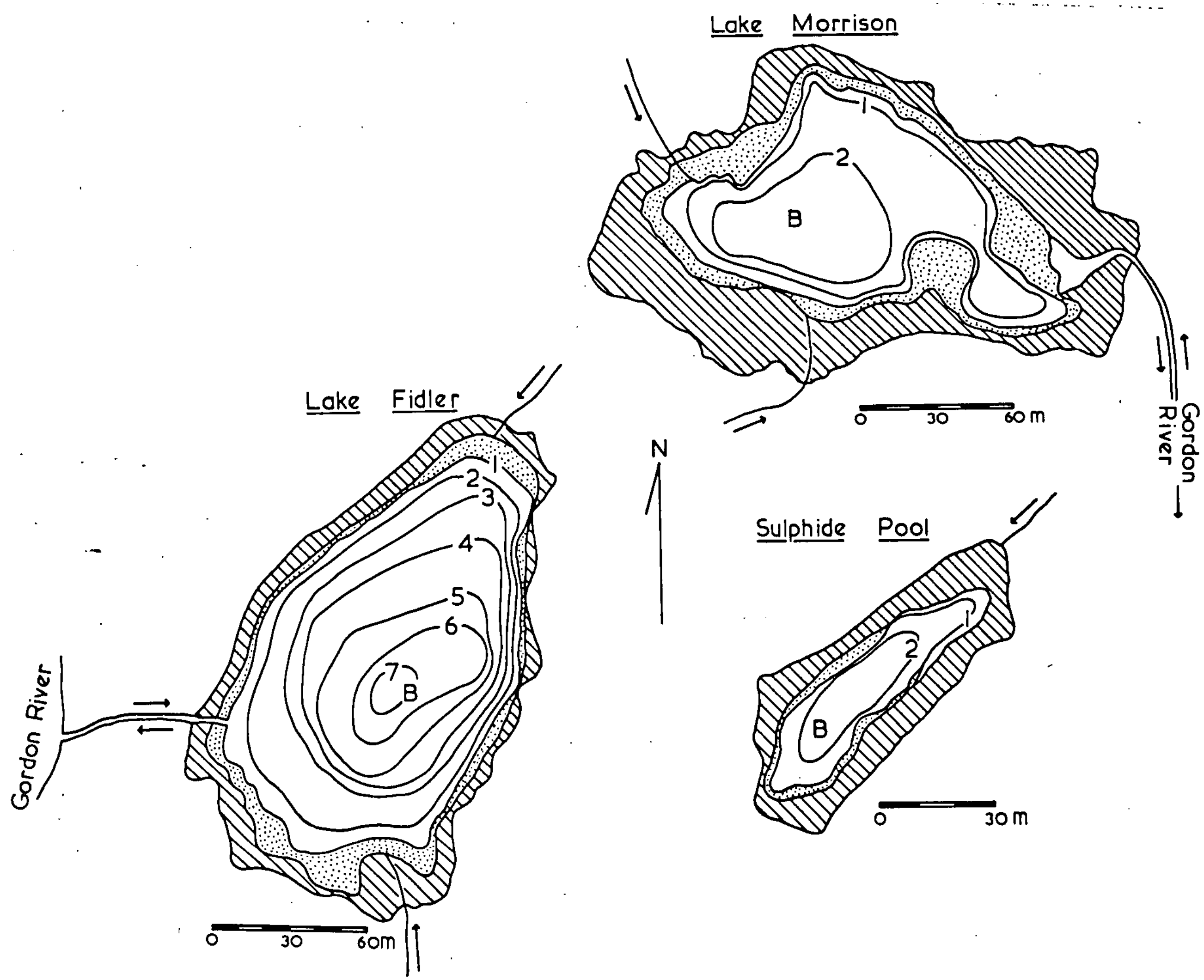

FIGURE 70: BATHYMETRIC MAPS OF THE MEROMICTIC GORDON RIVER LAKES. THE LAKES ARE SURROUNDED BY ROOTED AQUATIC MACROPHYTES [stippled] AND HERBFIELDS [hatched]. CONTOUR INTERVAL 1 m.

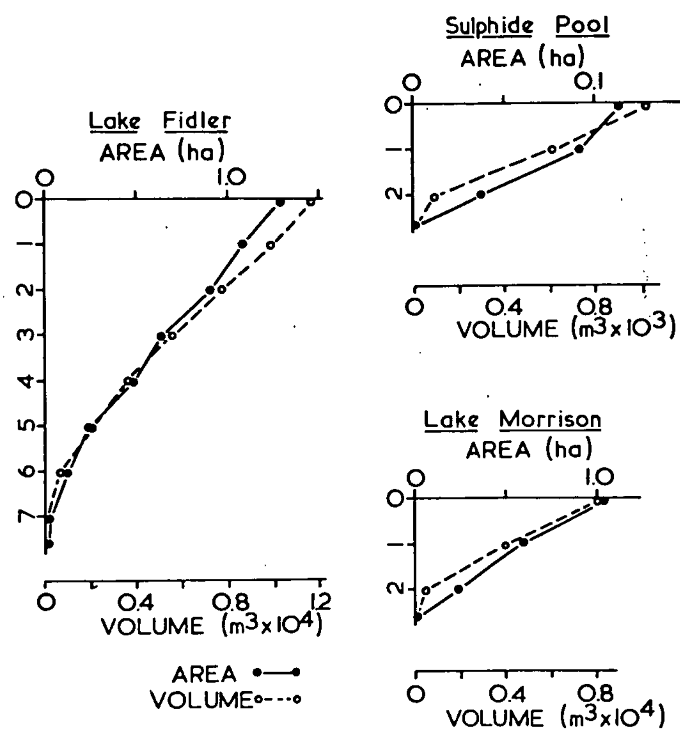

FIGURE 71: BATHYMETRIC CURVES.

these two lakes are amongst the shallowest meromictic lakes in the world, and I believe them to have the shallowest chemoclines so far reported. The bottom of Lake Fidler slopes fairly gently along the northern and western sections of the lake, and quite steeply on the eastern and southern sections. The deepest point of this lake (7.6 m) is roughly in the centre, and occurs in a small fairly flat basin. This lake is protected by a high ridge to the east.

Table 11: Morphometric parameters of the Meromictic Lakes

	Lake Fidler	Sulphide Pool	Lake Morrison
Area (A) ha	1.28	0.113	1.04
Volume (V) m^3	41317	1727	12771
Maximum depth (Z max)m	7.6	2.7	2.6
Mean depth (V/A) m	3.2	1.5	2.1
Length m	747	78	180
Width m	431	24	98
Shoreline length (S) m	1954	165	451
Shoreline development $S/2\sqrt{\pi \times A}$	1.2	1.4	4.9
Relative depth $Z_r = \frac{50Z_m\sqrt{\pi}}{\sqrt{A}}\%$	5.9	7.1	7.1

The bottoms of all three lakes are composed of fine organic sediments originating from the supply of allochthonous organic material from the surrounding rainforest, from the fringing macrophyte vegetation and dead bacterial cells sedimenting from the Plate (see section 4.3.9). The supply of autochthonous organic material will most likely be minimal in comparison to that from the rainforest even though all three lakes display extensive monimolimnitic bacterial populations. The lakes receive no noticeable inorganic silt either from their inflows or from the Gordon River as the turbidity of the influent waters was always very low.

These lakes are well protected from the prevailing winds by the surrounding hills and rainforest, so much so that strong gusty westerly winds produce only small ripples on the lake's surfaces.

2.3 Origin and maintenance of the Meromixis

As the section of the lower Gordon River along which the meromictic lakes occur is tidal, when river flow is low a saline bottom layer is present in the river (Kearsley,1978). The occurrence of and the depth below the surface of the saline water is dependent on the state of the tide and the flow of freshwater in the river (Kearsley, 1978) (Figure 72). The concentration of this salt "wedge" varies but is normally about 20‰. When river flow is low and the saline water is close to the surface, wind action on the river surface causes mixing at the chemocline, increasing the salinity of the surface water. This intrusion of saline water under the fresh river water is the salt source which produces the meromictic state in the lakes.

The origin of the chemical stratification in these lakes could have occurred in several ways. Firstly, an occasional ectogenic influx of saline water over the levee forming a density layer in a freshwater lake. This could occur during exceptionally high tides when river flow is very low.

Secondly, residual salt water could have been trapped in the bottoms of the lake basins when the levee had developed sufficiently so that river flow was unable to flush the salt out. The forming lake at Tuan Gabby is at this stage and shows weak chemical stratification (Chapter 2, page 40).

Thirdly, a regular influx of salts from the river either through the inflow - outflow creeks which have been observed for lakes Morrison and Fidler. Further investigation will probably show a similar feature for Sulphide Pool. Surface river water has been observed flowing into the lakes, and according to Kearsley (1978) surface river salinity can reach from 3.5 to 4.2‰, so the more concentrated surface river water can maintain the salt supply and thus the meromixis.

At this stage, it is only possible to speculate on the origin of meromixis, but salt supply from the river to the lakes probably maintains this state. This is dependent on low river flows which previously occurred during the low rainfall summer. Unfortunately the flow in the river has been altered by Stage 1 of the Gordon Power development, such that summer flows have been greatly increased and winter flows decreased slightly. River flows are now sufficiently high at all times of the year to flush the saline water out of the river channel (Figure 5 Chapter 2, Kearsley 1978). Salt supply has therefore been cut off from the lakes, and it is probable that

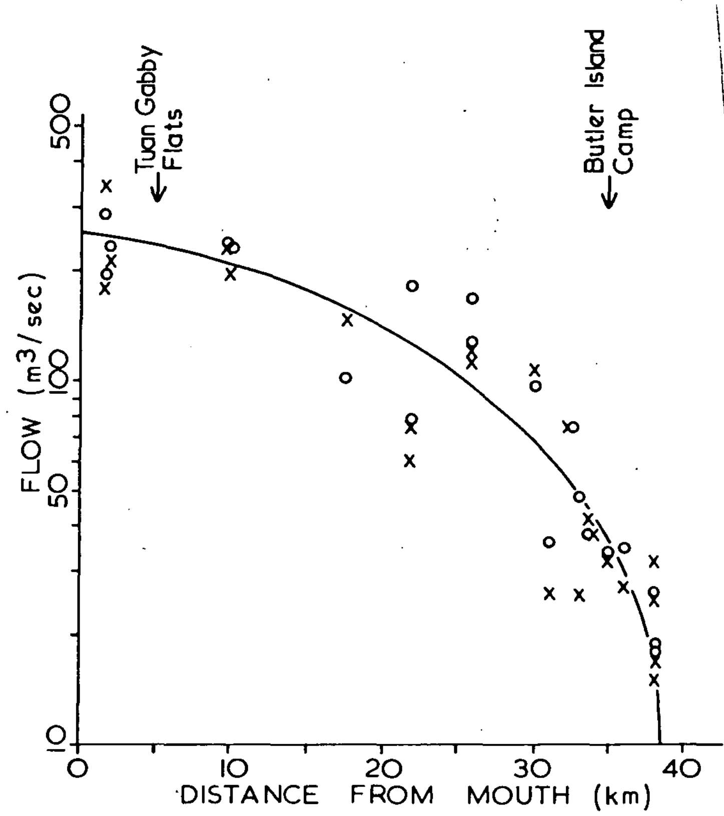

FIGURE72: UPPER LIMIT OF THE 'SALT WEDGE' IN THE GORDON RIVER IN RELATION TO AVERAGE DAILY RIVER FLOW FOR THE PREVIOUS 5 DAYS (O) AND PREVIOUS 10 DAYS (X) PRIOR TO SAMPLING. (REDRAWN FROM KEARSLEY 1978.)

the chemical stratification will slowly decline, a situation which appears to be occurring in Lake Morrison (Figure 104) and the lakes will evolve toward typical monomictic dystrophic west coast lakes such as Perched Lake (Plate 26) which is elevated above the river and receives no salt input from the river.

2.4 Climate

The climate of the lower Gordon River area is described by the Bureau of Meteorology (1977) as temperate maritime. The winters are abnormally mild and the cool summers are largely influenced by heat absorption in the seas. This west coast region lies within the belt of the prevailing westerly winds. Climatic information for Strahan and Strathgordon is presented in Figures 6A and 6B; the climate of South West Tasmania has been reviewed by Bosworth (1977) and Faircloth (1978). Watson (1978*b*) presents a detailed description of the climate of the Lower Gordon Scientific Survey area.

2.5 Vegetation

Vegetation types in the vicinity of the Gordon River meromictic lakes have been classified according to Specht (1970), and interpreted for south west Tasmania by Jarman and Crowden (1978).

Vegetation of the levee banks and valley slopes surrounding Lake Fidler consists of *Nothofagus cunninghamii* (Hook) Aerst. closed forests, with an open understorey dominated by *Richea pandanifolia* Hook.f., *Dacrydium franklinii* Hook.f. and *Eucryphia lucida* (Labill.) Baill. Fringing the lake the closed scrub vegetation is dominated by *Melaleuca squarosa* Donn. ex Sur., with *Leptospermum riparium* D.I. Morris subdominant, and scraggy plants of *Dacrydium franklinnii*, *Acacia melanoxylon* R. Br. and *A. verticillata* (L. Her.) Willd. commonly occurring. Within the scrub there is a dense tangle of *Bauera rubioides* Andr., *Gleichenia dicarpa* R. Br. and *Gahnia grandis* Labill. This scrub is bordered by *Carex appressa* R. Br. and *Restio tetraphyllus* Labill. Woody species also occurring in the scrub are *Cenarrhenes nitida* Labill., *Anopterus glandulosus* Labill., *Drymis lanceolata* (Poir.) Baill. *Lomatia polymorpha* R. Br. and *Sprengelia incarnata* Sm.

Herbfields occur almost continuously around the lake (Plates 19, 20 and 21); common species include *Eleocharis gracilis*, R. Br., *Nymphoides exigua* (F. Muell.) Kuntze, *Scirpus fluitans* L., *Lileopsis brownii* A.W. Hill and *Ranunculus rivularis* Banks and Sol. ex D.C. The edge of the lake is fringed with rooted emergent aquatic plants of *Triglochin procera* R. Br.

and *Baumea rubiginosa* (Spreng.) Boeck. Surrounding herbfields were frequently submerged by rises in lake level caused by tidal rises in river level (Plate 22), as well as by high flows in the Gordon River. The levee bank vegetation adjacent to Sulphide Pool is low closed forest dominated by *Nothofagus cunninghamii* with an open understorey of *Richea pandanifolia*, *Dacrydium franklinii* and *Eucryphia lucida*. *Anodopetalum biglandulosum* A. Cunn ex Endl. is common in the low tree layer while *Anopterus glandulosus* and *Cenarrhenes nitida* are scattered in the understorey. *Blechnum wattsii* Tindale forms a sparse ground layer. Between the levee bank and the lake, *Acradenia frankliniae* Milligan ex Kippeat, dominates the low tree and scrub layers. Shrubs and ferns are sparse and the ground surface is clear because of regular tidal inundation, and sporadic flooding from the Gordon River.

Forest height decreases and becomes more scrubby close to the lake. On the western side *Acacia melanoxylon* and *Dacrydium franklinii* dominate the low scrub woodland, accompanied by *Eucryphia lucida*, *Acacia verticillata*, *Anopterus glandulosus*, *Drymis lanceolata*, *Bauera rubioides* and *Melaleuca squarosa*. On the eastern side of the lake *Melaleuca squarosa* forms a closed scrub vegetation with *Acacia melanoxylon* and *Dacrydium franklinii* as low emergents. *Leptospermum riparium* occurs frequently at the edge of the scrub together with *Carex appressa* and *Restio tetraphyllus*.

There is no well defined herbfield surrounding this lake (Plate 23), but species such as *Myriophyllum amphibium* Labill., *M. pedunculatum*, Hook.f. *Hydrocotyle pterocarpa* F. Muell., *Scirpus inundatus* (R. Br.) Poir. and *Callitriche* sp. occur occasionally. Along the lake edge stands of *Triglochin procera* and *Eleocharis sphacelata* R. Br. occur as well as local patches of *E. gracilis*.

Between the Gordon River and Lake Morrison rainforest vegetation is highly variable, changing from low woodland through low open and closed forest to tall woodland and open forest. Dominant elements in this vegetation are *Leptospermum lanigerum* (Ait.) Sm, *Melaleuca squarrosa* and *Dacrydium franklinii*, with *Acacia verticillata* and *A. melanoxylon* also present. *Acradenia frankliniae* occurs commonly in the understorey, and *Anopterus glandulosus*, *Cenerrhenes nitida*, *Coprosma quadrifida* Hook.f., *Pomaderris apetala* Labill. and *Monotoca glauca* (Labill.) Druce are scattered throughout. The area adjacent to the inflow/outflow creek is boggy because of frequent tidal inundation and rises of the Gordon River. Species characteristic of wet conditions, namely *Gahnia grandis*, *Carex appressa*, *Restio tetraphyllus*, *Scirpus inundatus* and *Hydrocotyle* spp. are locally frequent where light conditions are suitable.

Most of the lake is surrounded by closed scrub forest (Plate 24) dominated by *Melaleuca squarrosa* and *Leptospermum lanigerum*. *Dacrydium franklinii* occurs frequently, often projecting above the canopy. Towards the northern edge of the lake the closed forest is dominated by *Acacia melanoxylon*. Other species present include *Acacia verticillata*, *Drymis lanceolata*, *Pomaderis apetala* and *Ghania grandis*. Bordering the lake are clumps of *Carex appressa* and *Restio tetraphyllus*.

Frequent around the shores of the lake are low closed herbfields and/or sedgelands, where species dominance is variable and includes *Nymphoides exigua*, *Lileopsis brownii*, *Hydrocotyle muscosa*, R. Br. *Myriophyllum pedunculatum*, *Ranunculus rivularis*, *Centella cordifolia* (Hook.f.) Nannf., *Callitriche* sp., *Carex gaudichaudiana*, Kunth, *Eleocharis acuta*, R. Br., *E. gracilis*, *Leptocarpus brownii* and *Baumea juncea* (R. Br.) Palla.

The lake is completely surrounded at its edge by emergent aquatics (Plates 25&26) of *Triglochin procera*, *Eleocharis sphacelata* and *Baumea rubiginosa*. Scattered around the edge of the lake, and occurring both in the water and on the shore, are local dense patches of *Scirpus fluitans*.

3. METHODS

The lakes were visited for the first time in October 1976. The regular sampling programme commenced in December 1976 and terminated in April 1978.

The bathymetric maps were constructed by sounding along measured transects with a weighted line. The lake outlines were traced from enlarged aerial photographs and the transects scaled on to these maps. Bathymetric data were measured from them.

All sampling was carried out at marker buoys anchored over the deepest part of each lake. Water samples were collected using a modified van Dorn sampler, and stored in black polyethylene bottles in the cool during the field trip, and then at 5^{o} C in the laboratory.

Close interval samples from the vicinity of the chemocline were collected with a microsampler (Baker 1970). The sample bottles were spaced 15 cm apart and the samples spanned a depth of 1 m. Several series of samples were collected from each lake; for Lake Morrison (Z_{max} = 2.6 m) and Sulphide Pool (Z_{max} = 2.7 m) the whole profile was sampled. For Lake Fidler (Z_{max} = 7.6 m) sampling was concentrated through the chemocline zone (from 1 m to about 5 m depth). These samples were stored in their collecting bottles and were analyzed the same night.

Temperature profiles were measured electrometrically using a Wheatstone Bridge thermistor. Littoral water and air temperatures were measured with a mercury thermometer. Dissolved oxygen was measured by the azide modification of the Winkler method (APHA 1971), and total dissolved sulphides by the "nose test" and titrimetrically by the iodine method (Golterman 1967).

Samplers were lowered to the required depth, filled and brought to the surface very slowly to minimize disturbance of the chemical stratification in the lakes. pH and redox potential were measured electrometrically in situ. The remainder of each sample was stored and returned to the field laboratory where turbidity was measured on a nephelometer and photosynthetic pigments were extracted in methanol and stored until they were scanned in the laboratory on a Perkin Elmer spectrophotometer (Golterman 1967).

On their return to the laboratory, water samples were immediately analysed for pH and alkalinity. For the latter, an end point of pH = 4.5 was used with 0.01N HCl and filtered samples (Golterman 1967). Turbidity was measured with a Hach 2100 turbidimeter, calibrated against formazin standards. Samples were filtered through 0.45 μm pore size discs. Conductivity was measured electrometrically at 18^{o}C and chloride by conductimetric titration with silver nitrate (Golterman 1967). Sulphate was determined turbidimetrically by precipitation with barium chloride, calcium by the bis-(2-hydroxyanil) method (Kerr 1960), magnesium, sodium and potassium by atomic absorption spectrophotometry, and silica as "molybdate reactive silica" by the molybdate yellow method (APHA, 1971).

Colour was measured, on filtered samples, in Hazen Units (Pt units) with a Lovibond colour comparator. The absorbance of river water (dissolved organic material or gilvin - see King and Tyler 1978 - Perched Lake) was determined at 440 nm in 40 mm cuvettes, and calculated for a 1 m path length (Kirk 1976). Salinity was calculated as the sum of the major ion concentrations in mg/l.

Lake and river levels were measured on guage boards independently fixed but, unfortunately, not surveyed in to a bench mark.

4. RESULTS AND DISCUSSION

4.1 Temperature

The seasonal variation in the surface water temperature of the lower Gordon River lakes generally lies within the range of mean monthly air temperatures measured at Strahan on the west coast (Figure 73). The sheltering of the lakes by the surrounding hills and rainforest allowed the lake waters to retain heat, for the temperatures were mostly above the monthly air temperatures throughout the year. The surface waters of Lake Fidler, the largest and deepest of these meromictic lakes, showed the smallest temperature variation, while Sulphide Pool, which has the smallest surface area and is very well sheltered from the prevailing wind, underwent more extreme temporal surface temperature variations than either lakes Fidler or Morrison. The profiles of temperature against depth for the three lakes show certain anomalies, such as inverse stratification and mesothermic bulges. Undoubtedly these are related to the salinity gradient and may be explained in a number of ways. Apart from the sheltering of these lakes from the prevailing westerly weather, the saline gradient (Figures 86 to 88, 105 and 106) which exists within these lakes is the major factor influencing temperature patterns (Anderson 1958, Duthie and Carter 1969, Mori 1976). The density layering of the waters due to dissolved salts far exceeds that caused by temperature, therefore small thermally induced density differences will be largely overridden by density attributed to dissolved salts. Because of the strong haloclines in these lakes (to a lesser extent in Lake Morrison which displayed a partial breakdown in its halocline towards the end of the study - see Section Major ions) mixing was absent, or if it did occur, would be extremely slow and hardly likely to influence temperature patterns to any great extent, and heat exchange between the mixolimnion and monimolimnion would be slight.

Bearing the chemically stratified nature of these lakes in mind, temperature patterns can be variously affected:

1. Ambient air temperature controls mixolimnetic temperature, and by wind-induced mixing heat is transferred downwards in summer, but to shallow depths only, and transferred out of the lakes in winter. Heat input from the atmosphere to the mixolimnion is most unlikely to penetrate the chemocline and heat the monimolimnion.
2. During summer the surrounding rainforest acts as a greenhouse and absorbs heat which in turn warms the peats and alluvium below. By geothermal conduction bottom waters of the lakes are possibly warmed. Similarly in winter when the peats and alluvium have cooled, heat can be conducted from the bottom waters back through the sediments, [illegible] the [illegible]ments, as water within the monimolimnion undoubtedly circulates slowly, mostly in a horizontal pattern. By this process the monimolimnion can be both warmed and cooled in these non-circulating lakes. Some heat could also be conducted upwards through the water profile, and it is believed that heat trapped at intermediate depths would originate partly from below as well as from above.

3. Heat can be produced from biological breakdown of organic matter, both allochthonous and autochthonous. Undoubtedly some heat of this type is generated in the sediments and probably permits the monimolimnion to maintain constant temperatures above ambient air temperatures, thereby buffering monimolimnetic temperatures. Heating of bottom waters can well be explained in this way, but their cooling presents a problem which discounts biological heat being principally involved in warming the monimolimnion. This is mainly due to the fact that the algal plates (Figures 109 and 110) reach their maxima towards the end of summer, then decrease through winter before building up again in spring. Therefore seasonal biological heat generation would most likely occur in winter rather than from late spring when the monimolimnion begins warming. Heat trapped at intermediate depths could possibly have been generated from biological activity at the plate (particularly Lake Fidler, Figure 86). However, on occasions when the plate was well developed no intermediate temperature "bulge" was recorded (e.g. 27.2.77 in Figure 86). Also, temperature variations with depths in all three lakes are far more significantly associated with the increase in dissolved salts with depth than with bacterial biomass (or turbidity) (Figures 86, 87 and 88).
4. Water of particular temperature and density enters the lakes from the Gordon River, could undercut lake surface waters and flow out at some intermediate depth within the lake, thereby influencing lake temperatures. Mesothermal heat as well as many temperature perculiarities could be explained in this way. After power station discharge this mechanism would not occur.

The above merely attempts to explain some of the factors influencing temperature within these meromictic lakes, and a far more thorough investigation will be required before the processes are understood.

Due to the extremely large amounts of organic colour (gilvin), heat input from solar radiation to these lakes is greatly reduced, and coupled with the protection from prevailing westerly weather, resulted in diurnal surface heating only occurring down to shallow depths. This was most noticeable in Sulphide Pool and least apparent in Lake Morrison (Figure 76). The colour strongly absorbs radiation at all wavelengths, but absorption increases exponentially toward the long wavelength end of the spectrum. A lengthly period of warm weather will permit heat to be mixed to greater depths. Attenuation of incident radiation by organic colour has been discussed in more detail in Section 4.4 below.

4.1.1 Lake Fidler

Temporal variation of temperature in Lake Fidler is illustrated in Figures 74, 75, 76 and 86. The overall thermal pattern in Lake Fidler was for both summer stratification and inverse stratification in winter to occur. The monimolimnion maintained a more constant temperature than did the mixolimnion due to the total absence of vertical mixing in the lake. The intensity of the summer stratification was different for the two successive summer periods, which can be attributed to variations in the local weather.

During the first summer of the study the surface waters warmed and reached 19.2^{o}C in late February 1977. The most intense decrease in temperature at this time occurred in the upper 1.7 m. Wind-induced vertical mixing occurred fairly deeply in the mixolimnion possibly warming the upper chemocline, and some of this heat was exchanged down into the upper monimolimnion. This partially coincided with variations in the saline layering in the lake.

In about March as the surface waters began cooling 15^{o}C temperatures were recorded at deeper layers. Simultaneously there was a noticeable disturbance of the dissolved salt layering, possibly by an introduction of coal denser water from the Gordon River into the surface of the lake, and an intensification of chemical stratification between 0.5 m and 1.0 m (Figure 105). This inflow density current could also have caused the mixing down of warm water into the upper monimolimnion.

As the surface waters in the lake continued cooling with the onset of winter the lake became isothermal by about May 1977. During this period monimolimnetic waters also cooled very slightly, losing heat by diffusion to the sediments and to overlying layers. Further heat loss from the mixolimnion produced a state of inverse stratification which became most pronounced between July and August. In late July cold surface water ($< 9^{o}$C) was mixed down into the upper chemocline. Warm calm weather at this time of the year could cause quite noticeable diurnal heating of the surface waters.

From late August the surface waters began warming rapidly and the lake was again almost isothermal towards the end of September, after which the entire lake began warming, most noticeably in the top 1 m. The warming of the bottom waters as summer stratification became established is not fully understood but perhaps attributable to warm calm weather, warmer than the previous summer. A similar phenomenon was recorded in Perched Lake (Figure 52) for the 1977 - 1978 summer.

Hot calm weather in the south west region may allow heat to be trapped in the rainforest, thus allowing subsurface geology to warm up. Monimolimnetic heating could thus occur by geothermal heat conduction through the sediments and into the lake. Similarly, heat loss from bottom waters could occur by reverse flow, as heat loss from this region of the lake to surface waters is inhibited by the salinity gradient.

This second summer monimolimnetic heating which commenced from late September 1977 onwards is unlikely to have originated from biological sources, for the bacterial plate was re-establishing itself after the winter decrease, and occurred between 2 and 3.5 m depth at that time (Figure 109) and very low turbidity water was recorded below 3.5 m depth (see Figure 86). Similar geothermal heating of the lower monimolimnion is reported from Banyoles Lake, Spain (Guerrero et al 1978).

Maximum surface temperatures were reached during December 1977 and lasted until late February 1978. This intense surface heating only occurred in the upper half of the mixolimnion. Apart from the effect of the salt gradient stabilizing this thermal pattern, water low in dissolved salts released from Lake Gordon entered the lake from the river, further intensifying the density gradient in the lake. Calm hot weather experienced throughout this early summer undoubtedly also contributed to the maintenance of this warm upper mixolimnion. The depth at which the 15°C isopleth was plotted only about 0.5 m deeper in 1978 than in 1977, when much less intense surface heating occurred, and when the lake was more windswept. Unreliability and variability of the westerly weather will almost certainly be responsible for variability in the thermal pattern in this lake from year to year.

As the surface waters began cooling in early March 1978, so also did the bottom waters start losing heat. The most likely cause of these lowering monimolimnetic temperatures was heat loss to the sediments of the lake basin, or more unlikely by very slow heat loss upwards through the chemical gradient. More detailed investigation will be required to fully understand this phenomenon. However, due to the stable chemical stratification in the lake (Figure 105), heat became trapped in the region of the chemocline at about 2 - 3 m depth as bottom waters continued cooling, producing a poikilothermic temperature profile (Figure 76). By April further surface and bottom water heat loss had occurred, resulting again in a residual heat storage layer at about 2 - 3.5 m. It is possible that some of the heat at this depth was biologically produced by the bacterial plate (Figure 109). This heat trapped in the chemocline (Figures 76 and 102) began rapidly dissipating to adjacent layers and was coincidental with the senescing of the bacterial population in April 1978. The bottom waters continued losing heat until temperatures of about 12.5^{o}C were reached, and remained at about that level when the lake was nearly isothermal, when presumably the temperature of the monimolimnion and that of the sediments reached equilibrium.

The diurnal temperature variation in the lake was measured on the 13th and 14th December 1977 (Figure 77). At this time of the year the lake was strongly thermally stratified down to 1 m depth, and the bottom waters had warmed from about 12.5^{o}C in August to about 14^{o}C in December (Figure 74).

Surface water temperatures were highest at about 1600 hours, reaching 22.7^{o}C on the 13th and 23.2^{o}C on the 14th December. Heat was lost very slowly to the atmosphere with the minimum temperature of 19.1^{o}C possibly occurring at about 0500 hours. During the early morning the temperature began increasing very slowly until the first sun rays reached the lake, thereafter surface waters heated rapidly, reaching a maximum at about 1600 hours. Heat loss from the surface waters of the lake was 0.25^{o}C/hour and heat gain was 0.71^{o}C/hour.

The temperature profile below 1.5 m depth remained unchanged during this diurnal study as a result of the intense chemical stratification prevalent in the lake and has therefore been omitted from Figure 77. Figure 86 shows that the top 1 m of the water profile on 13th December 1977 contained low concentrations of dissolved salts, which began increasing rapidly below this depth. In like manner this intense chemical stratification below 1 m depth was the major factor which contributed to the extremely warm shallow layers in Sulphide Pool (Figure 76). In Fidler, surface water temperature variations in the open lake were very conservative in comparison with either the air temperature or littoral water temperature variations (Figure 77). Air temperatures remained lower than the lake temperatures during the sunshine hours of the two days when measurements were made and were considerably colder (up to 11^{o}C) from about midnight until just before the sun reached the lake in the morning.

Littoral water temperatures were more significantly affected by the air temperature than were lake water temperatures (Figure 77). The littoral zone lost heat at a rate of about 0.9^{o}C/hour and gained heat at 1.4^{o}C/hour. From 2240 hours to 0600 hours the littoral water temperature only fell by 1.8^{o}C, exhibiting similar stable temperatures from about midnight to dawn as did air temperature. As heat input to the lake began after sunrise the littoral temperature increased rapidly above that of the open lake, and by 1500 hours on the 14th were almost 6^{o}C higher.

4.1.2 Sulphide Pool

Seasonal temperature variations in Sulphide Pool are presented in Figures 76, 78, 79 and 87. As with Lake Fidler, Sulphide Pool is strongly chemically stratified (Figures 104 and 106), which contributes significantly to the temporal temperature pattern within this lake. The shallowness of the lake would be the most important factor accounting for monimolimnetic heating and cooling. During the first summer of the study the surface water temperatures often displayed pronounced heating (January 1977), and due to weak wind action on the lake surface heat was only slowly mixed to shallow layers where it became mesothermally trapped in the chemically stratified waters in autumn (April 1977 - Figure 76). As the summer progressed, bottom waters gradually warmed probably due to geothermal heat exchange with the lake sediments. It is envisaged that this process is similar to that occurring in Lake Fidler. This heat source to the lake probably also contributed to some of the mesothermal heat storage. It is recognised that biological heat input into the lake occurs, but is expected to be minimal in comparison with geothermal exchange. This is borne out by two factors, firstly bacterial biomass in this lake was increasing as bottom waters were warming (at this stage biological decomposition would be minimal), and secondly, bottom water cooling occurs when the bacterial biomass decreases (cf. Figures 78 and 110). Biological heat generation would be highest when the bacterial biomass (measures as extracted pigments) was decreasing. Undoubtedly some biological heat is generated in this lake, both in the water phase and in the sediments, but the overriding problem is explaining cooling of bottom waters when presumably biological decomposition would be at a maximum. Heat loss from the bottom waters is therefore expected to take place via the sediments, and to a lesser extent exchanged with overlying layers of water, even though no actual mixing of the respective layers occurs. By April 1977 the surface waters had begun cooling, thus trapping heat in the lake at intermediate levels.

From April 1977 onwards the entire lake lost heat, and by about May 1977 was practically isothermal (Figure 78). This situation probably did not persist for more than a few weeks, after which time the surface waters began warming again, producing high winter and spring surface temperatures, e.g. October 1977 (Figures 78 and 79).

The thermal pattern during the winter months of June and July 1977 suggest that the surface waters had continued cooling below that of the bottom waters, reaching minimum temperatures of about 8^{o}C at 0.2 to 0.5 m depth. As temperature profiles were measured in the afternoon on these two occasions some surface heating was noted (Figure 76). Significant monimolimnetic heat loss occurred with the onset of winter when temperatures dropped from 14.9°C in April to 9.5°C in June. Thereafter the bottom waters slowly gained heat, reaching a maximum in early autumn 1978. This monimolimnetic cooling and subsequent heating must have occurred by geothermal conduction, as previously indicated. During the heating cycle at this time of the year only a small bacterial population was present in the bottom waters (Figure 108), most of which occurred in the upper monimolimnion. At this time total sulphides were also low, suggesting low respiration rates, and coupled with low bacterial biomass in an active state of growth, were unlikely to warm the bottom waters.

With the onset of spring the surface water began warming and mixed progressively with lower layers into the upper mixolimnion. As summer approached the entire profile warmed, the upper 0.5 m of the mixolimnion experiencing considerable diurnal heating and cooling as well as monimolimnetic heating. Again, geothermal heat exchange is thought to be responsible.

An unusual phenomenon resulted during this second summer when, due to depressed ambient air temperatures and increased cloud cover and rainfall the lake surface cooled to a point where the lake became almost isothermal (early February 1978). Some heat remained in the upper 1 m and at about 2 m depth producing a slightly poikilothermic profile (Cole 1975). Extreme surface temperatures were again recorded in early autumn 1978 (Figure 76). Though no data are available, the lake is thought to have become isothermal by mid April 1978.

Autumnal cooling of the mixolimnion (down to about 0.6 m depth) occurred while the monimolimnion lost heat far more slowly, resulting in a dichothermal profile in March 1978. Considerable heat loss to the surface waters occurred in the vicinity of the chemocline while monimolimnion heat was lost to the lake basin (see above). An intensification of the westerly winds in late April (Section 2.5, Chapter 2) produced increased wind-induced vertical mixing, further monimolimnion heat loss to the sediments occurred, and the lake again approached isothermy.

4.1.3 Lake Morrison

Temporal distribution of temperature in Lake Morrison is illustrated in Figures 76 and 88. Owing to the inaccessability of Lake Morrison in comparison with the other two lakes temperature profiles were only measured occasionally (Figure 76). The temporal thermal pattern in Lake Morrison is unclear but thought to be typical of meromictic lakes.

Summer stratification occurred down to about 1 m depth with inverse stratification occurring in winter. Even though the maximum depth of Lake Morrison if similar to Sulphide Pool, the temperature pattern more closely resembled that in Lake Fidler, Because of the shallow depth and large surface area of Lake Morrison, the lake underwent regular seasonal heating and cooling as a result of heat exchange with the atmosphere (mixolimnion) and lake sediments (monimolimnion). Extreme surface heating recorded from Lake Fidler and Sulphide Pool was not apparent in Lake Morrison, which was generally well mixed down to about 1 m depth.

Autumnal cooling began in March and the lake probably became isothermal in early May. Continued loss of heat to the atmosphere caused inverse stratification which was most intense during July (Figures 76 and 88). During the cooling periods the lower monimolimnion lost heat to the sediments, although more slowly than the mixolimnion, equilibrating between 11.0 and 11.8°C while the surface temperatures were at 7.2°C. The slight warming which occurred in the monimolimnion in July possibly resulted from an influx of warmer Gordon River water which undercut the lake water, causing the unusual winter monimolimnetic warming (Figure 76).

Heating and/or an influx of warmer more dilute water into the lake surface from the Gordon River and influent creeks, and wind-induced mixing together with intense chemical stratification resulted in a dichothermic profile in August 1977.

As spring approached the entire lake began warming, probably reaching isothermy about late September, and thereafter the mixolimnion heated far more rapidly than did the monimolimnion. Maximum surface temperatures recorded during this second summer ranged from 17.8°C to 18.6°C. Monimolimnetic heating began in the spring and by mid summer had equilibrated between 14.2 and 14.7°C. Mild weather at this time of year permitted further surface warming to occur, thereby causing minimal vertical mixing, but in early March an intensification of the prevailing westerly winds circulated the mixolimnion, and as a result of decreased chemical stratification, circulated to depths previously part of the monimolimnion. Complete overturn of this lake may have occurred due to persistent wind action and reduced chemical stratification, but was not recorded. Strangely, slight surface and bottom heating still occurred in April 1978, again producing a typical dichothermic profile. The cooler intermediate layer could not have originated from Gordon River inflow for the salinity in the river was about 26 times lower than in the surface waters of the lake (Gordon Power Station operating, conductivity measured at Butler Island camp 48 µS/cm, while Lake Morrison was 1285 µS/cm).

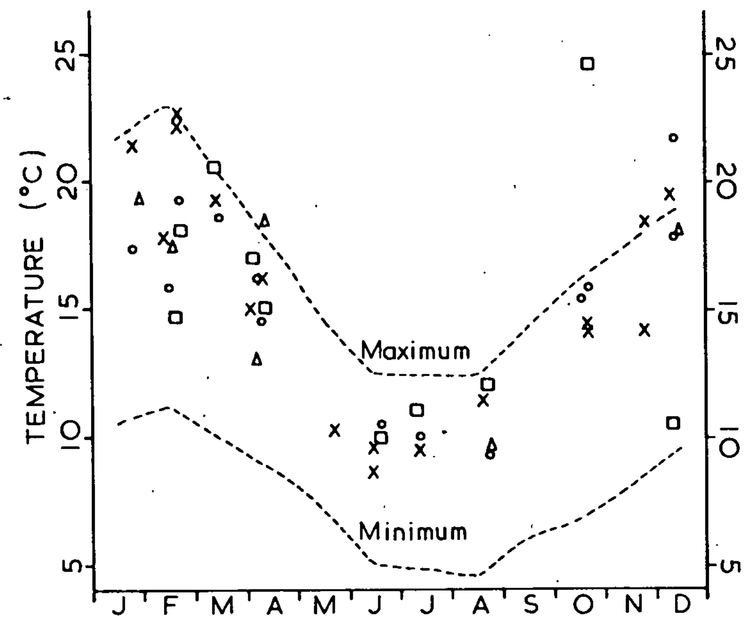

FIGURE 73: MEAN MONTHLY MAXIMUM AND MINIMUM AIR TEMPERATURES AT STRAHAN (— — —) ON THE WEST COAST, AND SURFACE WATER TEMPERATURES FROM LAKES FIDLER (O) AND MORRISON (Δ), AND SULPHIDE POOL (□). PERCHED LAKE (X) IS INCLUDED FOR COMPARISON. (STRAHAN TEMPERATURES FROM BUREAU OF METEOROLOGY 1977.)

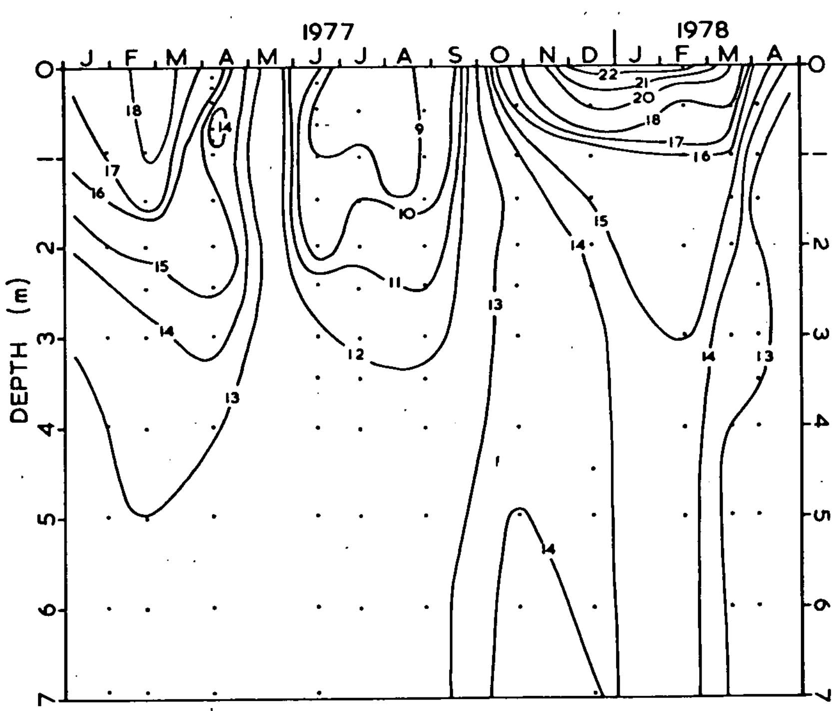

FIGURE 74: ISOTHERMS (°C) FOR LAKE FIDLER.

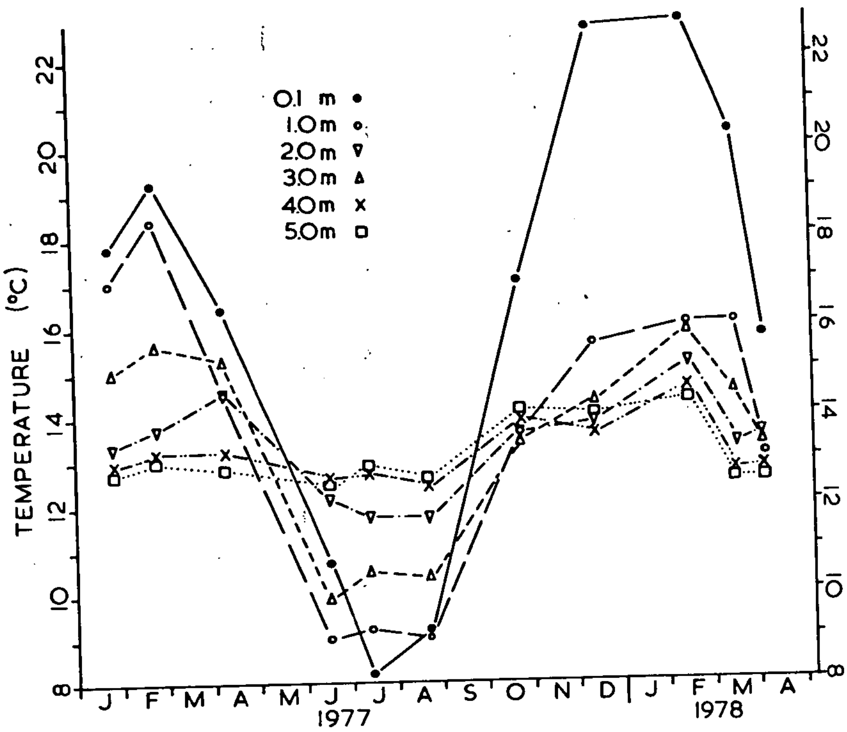

FIGURE 75: SEASONAL VARIATION IN TEMPERATURE (°C) AT SPECIFIC DEPTHS IN LAKE FIDLER.

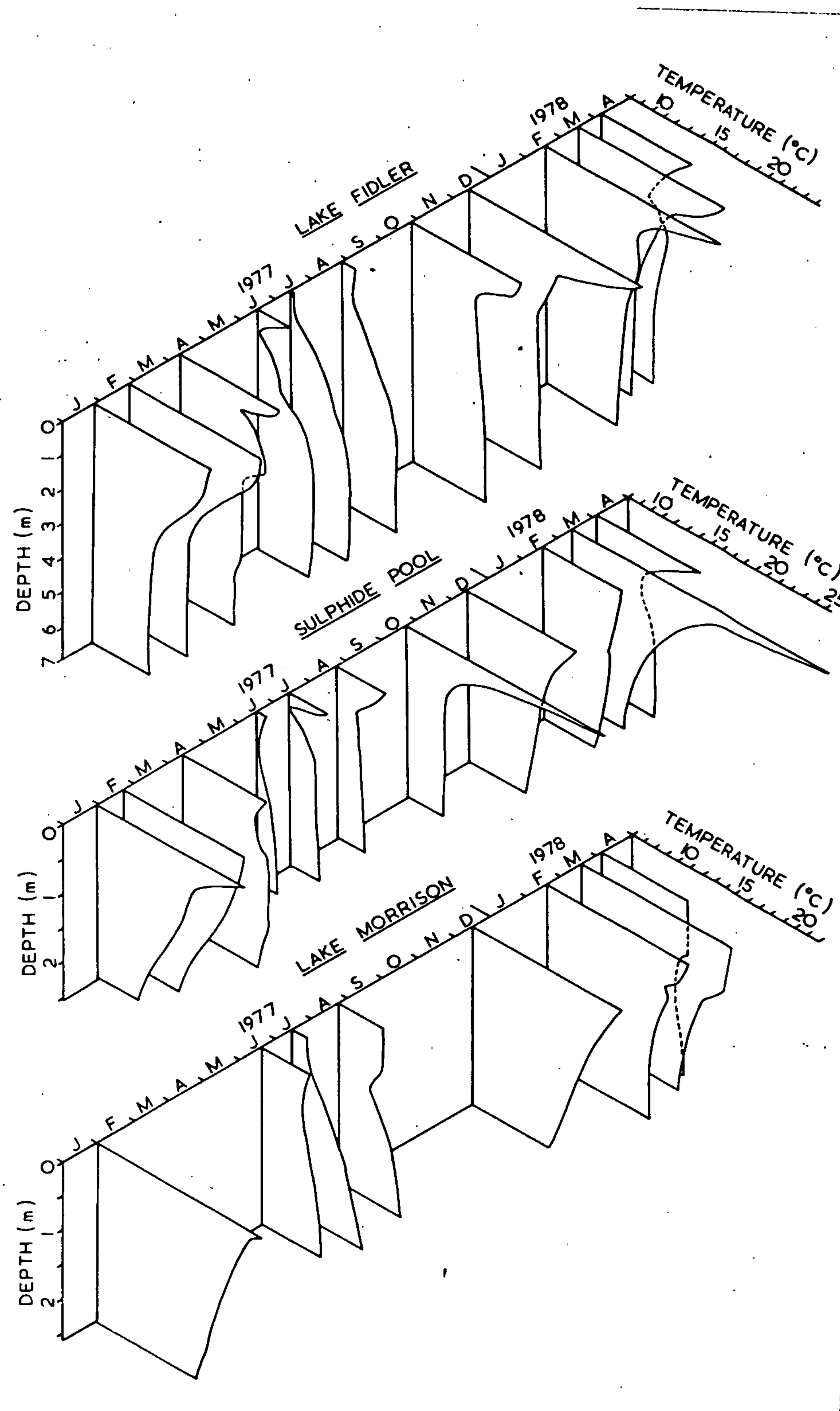

FIGURE 76: TEMPERATURE (°C) PROFILES FOR THE MEROMICTIC LAKES.

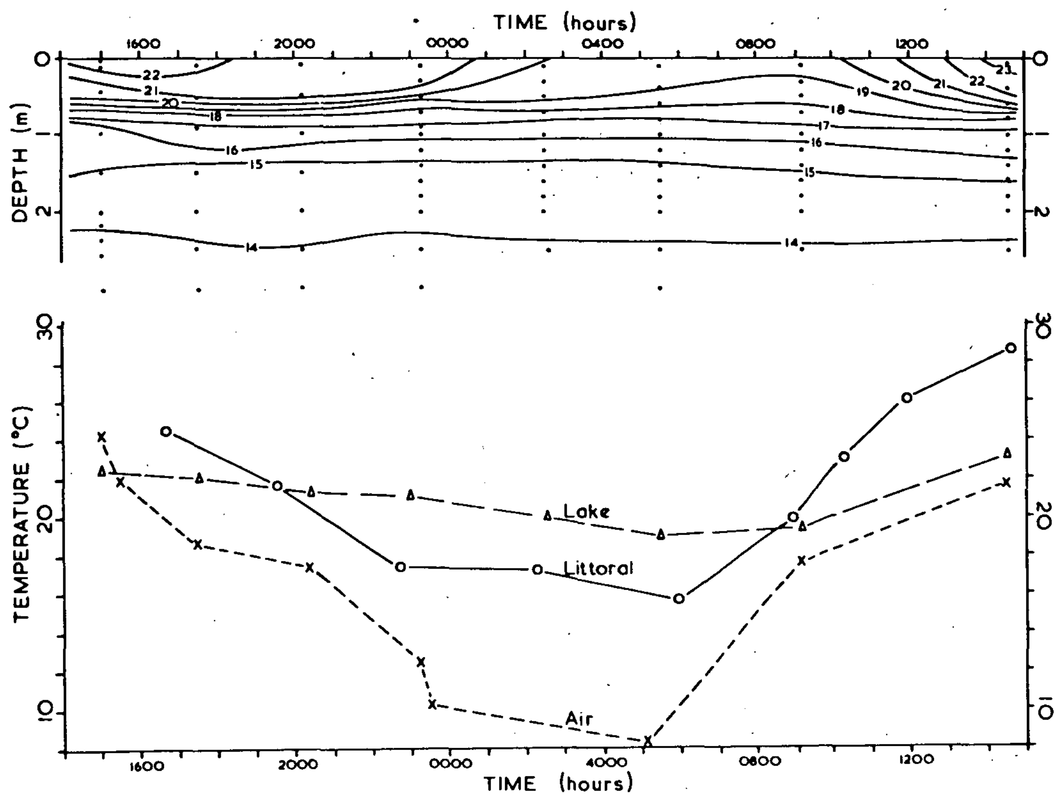

FIGURE 77. DIURNAL TEMPERATURE VARIATION IN THE UPPER 2.5m in LAKE FIDLER (ABOVE) RECORDED ON THE 13TH AND 14TH DECEMBER 1977, AND A COMPARISON OF DIURNAL TEMPERATURES OF THE LAKE SURFACE WATER, LITTORAL WATER TEMPERATURE AT THE LAKE'S EDGE OF THE HERBFIELD, AND AIR TEMPERATURE (BELOW).

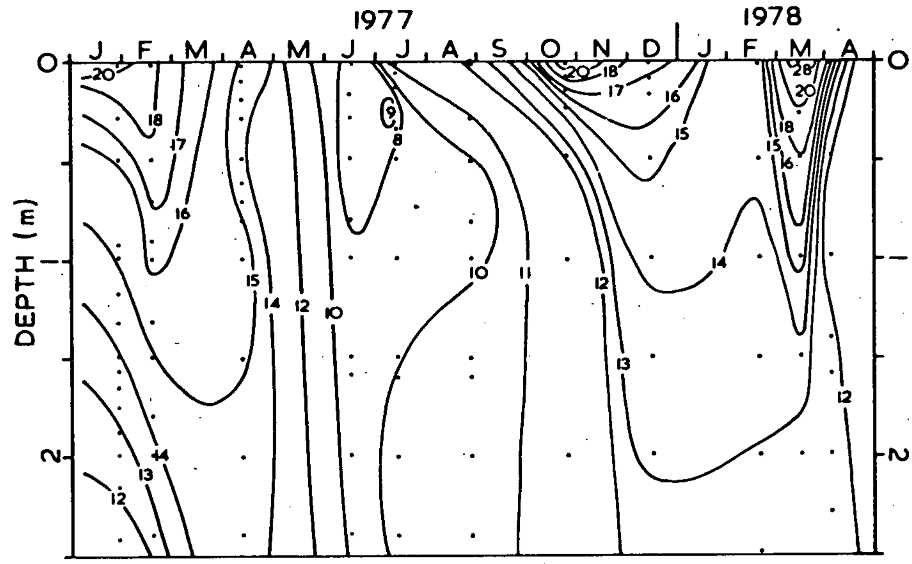

FIGURE 78: ISOTHERMS (°C) FOR SULPHIDE POOL.

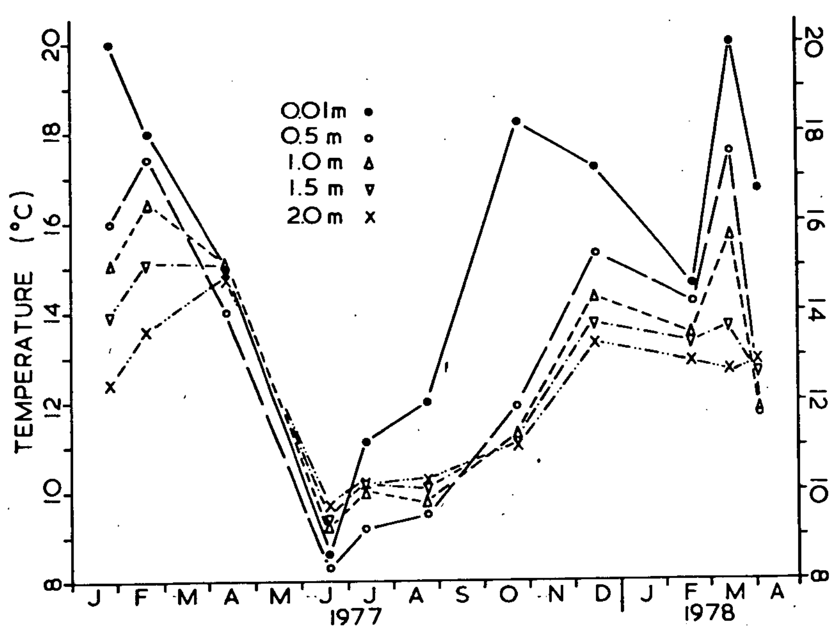

FIGURE 79: TEMPORAL TEMPERATURE (°C) VARIATION AT SPECIFIC DEPTHS IN SULPHIDE POOL.

4.2 Dissolved Oxygen and Total Sulphides

The temporal distribution of dissolved oxygen (D.O.) and total dissolved sulphides in Lake Fidler are presented in Figure 80, in Sulphide Pool in Figure 82, and Lake Morrison in Figure 84. Diurnal variations in Lake Fidler are shown in Figure 81, and Figure 83 illustrates the temporal variation of temperature, total dissolved sulphides and silica in the bottom waters of Sulphide Pool. In this report sulphides and S^{2-} will refer to the three forms of soluble sulphide, namely H_2S, HS^- and S^{2-}.

There was always a sharp discontinuity between the oxic mixolimnion and the anoxic monimolimnion. We never recorded oxygen and sulphides in the same sample, but Sorokin and Denoto (1975) claim that D.O. and S^{2-} exist together in small amounts at the oxycline. Disturbance by sampling apparatus at intense oxyclines could well account for both components occurring together. Occasionally we recorded neither of the two dissolved gases in the samples collected at the oxic-anoxic zone, probably because of the lack of sensitivity of the methods when these two gases occur in very low concentrations. The distribution of D.O. and total dissolved sulphides is intimately related to the chemically stratified nature of these lakes, and both are biologically extremely important and closely related to the distribution of microorganisms. The positions of both the chemocline and bacterial plates coincide fairly well with the transition zone between D.O. and total sulphides, and at this level redox values indicate the transition from the oxic mixolimnion to the anoxic monimolimnion (Figures 86, 87 and 88).

4.2.1 Lake Fidler

There was no apparent seasonal variation of dissolved oxygen in Lake Fidler except that the top 1 m of the mixolimnion remained fairly well ventilated during the summer months, and below 1 m depth dissolved oxygen decreased rapidly to the oxycline, which coincided with the temperature, salinity and redox discontinuities (see Figure 86).

Surface waters of Lake Fidler were mostly under unsaturated with respect to oxygen, sometimes as low as 63%. The depth distribution of oxygen in the lake was typically clinograde throughout the study period, except for one positive heterograde profile recorded on the 15th March 1978. The oxygen originated principally from photosynthetic evolution and from oxygen dissolved in influent Gordon River water, creek inflows and rainfall. Diffusion from the atmosphere into the surface waters is considered negligible due to the lake's sheltered situation.

Total dissolved sulphides did, on the other hand, vary seasonally in relation to the summer stratification. For a depth of about 1 m below the oxycline the concentration of sulphides increased rapidly down to the bottom. This was very significant from mid-summer to mid-autumn in both 1977 and 1978. These sulphides were released either from the sediments and mixed slowly into the overlying monimolimnion, or produced in the water body by biological activity. The sulphide maxima are correlated with monimolimnetic heating in summer (Figure 74).

By the time the lake became isothermal in May, sulphide concentrations had decreased and stabilized between 30 to 45 mg/l from about 3.5 m depth to the bottom. Concentrations of sulphides began slowly increasing in July, reaching a summer peak of 179 mg/l at 4.5 m depth by the 15th January 1978. Sulphides were not measured below this depth, so it is possible that sulphide concentrations at this time could well have been higher.

During the gradual build-up of sulphides culminating in the February 1978 maximum, a decrease in bicarbonate and sulphate occurred in the monimolimnion (Figures 90 and 92). As the lake water lost heat and became isothermal in April 1978, so the concentration of sulphides decreased and sulphate and bicarbonate increased. The oxidation of sulphide to sulphate was probably caused by increased bacterial activity throughout the monimolimnion. In addition, the increase in monimolimnetic bicarbonate could have resulted from the formation of calcium sulphate by sulphur oxidizing bacteria, with the release of bicarbonate.

The diurnal variation in dissolved oxygen in Lake Fidler was measured on the 13th and 14th December 1977 (Figure 81).

The oxygen profile was typically clinograde with the surface waters below saturation (ranging between 83 - 90%), as a result of high bacterial action in the presence of large amounts of dissolved organic material (see Section 4.3.1), and the stable cnd consistent diurnal oxygen pattern reflected the depauperate nature of the phytoplankton. However, during the dirunal period an oxygen maximum was recorded at about 17.50 hours at a depth of 0.5 m, probably produced by a small subsurface population of *Prorocentrum* sp. (a dinoflagellate which occurs in these south west Tasmanian lakes and some coastal lagoons - see Chapter 3, page 169).

Below 1 m depth down to the oxycline at 2.2 m the decrease in oxygen saturation remained relatively constant. Dissolved sulphide just below the oxic layer at 2.5 m depth remained constant between 16 - 18 mg/l.

4.2.2 Sulphide Pool

The distribution of oxygen was typically clinograde throughout the study period, except for a single positive heterograde profile recorded on the 12th July 1977. Surface waters were always undersaturated, ranging between 36.7 - 79.6% of saturation and containing 60% dissolved oxygen during the summer stratification period (January to April, Figure 82). During the isothermal period between April and June 1977, surface oxygen was below 50% saturation and decreased reasonably quickly with depth in the first 0.5 m depth of the water column, then less dramatically down to the deepening oxycline, which resulted from shallow vertical mixing in the absence of a thermal gradient in the mixolimnion (see Figure 78). At this time respiratory processes reduced oxygen concentration significantly, rendering the surface waters on the 16th June 1977 down to 36.7% of saturation.

As the surface waters continued cooling and inverse stratification established (Figure 78), surface oxygen increased rapidly in the top 0.5 m. A plankton net haul collected on the 17th July 1977 revealed a discrete algal population (principally *Euglena acus*) at a depth somewhere in the top 0.5 m of the water column which could account for this pronounced increase in oxygen. This net sample merely indicated the presence of algal biomass and would eliminate nannoplankters as well as photosynthetic-pigmented bacteria. Near-surface turbidities at this time were also low in the top 0.5 m but the top 0.1 m contained slightly higher values (3.6 - 4.4 FTU at 0.01 m and 2.4 - 2.6 FTU at 0.2 m).

The upper 0.5 m of the water column maintained oxygen saturation values above 50% from late June 1977 through to mid-February 1978. Below this depth, during this period oxygen decreased rapidly with depth down to the oxycline, which was situated at about 1 m depth.

The maximum dissolved oxygen value of 79% was recorded on the 25th October 1977 at a depth of 0.1 m. This oxygen peak coincided with abnormally high surface water temperatures (see Figure 78).

During the late summer and autumn stratification period (Figure 78), surface oxygen concentration decreased below 50% saturation, reaching 43.7% on the 14th March 1978 when surface temperatures were 28.5^{o}C. Below 0.5 m depth to the oxycline at 1.0 m the oxygen decreased rapidly through the thermal profile.

Surface oxygen started increasing slowly as the surface waters began cooling rapidly in early April 1978. Oxygen decreased gradually from the surface (59%) down to 0.5 m depth (41%) and then decreased rapidly to the oxycline at about 1.0 m depth.

The pattern of dissolved sulphides in the anoxic zone of Sulphide Pool is closely related to monimolimnetic temperatures (Figure 83). In February 1977 the highest dissolved sulphide value recorded from Sulphide Pool was 96.3 mg/l at 2.0 m depth. This occurred as monimolimnetic temperatures were steadily increasing. In March 1977 when bottom temperatures had increased to just above 14°C, approaching isothermy, sulphide concentration had begun to decrease rapidly. During June and July 1977 monimolimnetic dissolved sulphide concentration remained below 5.0 mg/l.

Gradual increase of sulphides in the monimolimnion began in August as these waters warmed. A steady build-up of sulphide continued through the spring reaching a maximum in February and April 1978. This basically coincided with maximum summer monimolimnion temperatures.

The obvious relationship between sulphide concentration and temperature (Fig. 83) together with the distribution pattern of sulphides (Fig. 82) suggests strongly a convective rise of sulphide from the sediments as monimolimnetic heating takes place. Alternatively dissolved sulphides could have been produced in the monimolimnion as a result of decomposition of organic material. However, this suggests that sulphide maxima should be recorded some time after the bacterial biomass has reached a maximum, i.e. during winter. Unfortunately sulphide maxima coincide with bacterial maxima. Even if bacterial turnover rates are extremely high, an uncommon feature for dystrophic meromictic lakes, sulphide maxima should still be displaced later than bacterial maxima. A complicating factor is that Sulphide Pool bacterial biomass is much higher and dissolved sulphides much lower than those in Lake Fidler (Figure 80, 82, 109 and 110). This is the converse of what should occur. Perhaps it could be explained either by the physiographic differences of these lakes, or by differing biochemical processes operative in them.

4.2.3 Lake Morrison

Dissolved oxygen and total dissolved sulphide information for Lake Morrison is limited. This inaccessible lake was not sampled as frequently as either Lake Fidler or Sulphide Pool.

Temporal depth distribution of oxygen in Lake Morrison was mostly clinograde, except for a positive heterograde profile recorded on the 16th June 1977, when a maximum value of 77% of saturation was recorded at 0.6 m depth (Figure 88). On this date oxygen concentration increased gradually from 68% at the surface to 77% at 0.6 m depth, but then decreased very rapidly, being no longer detectable at the oxycline at about 1.4 m depth. This oxygen maximum at 0.6 m probably resulted from subsurface photosynthetic oxygen production, but unfortunately no evidence of the algal plate was recorded either from the net haul or from turbidity measurements. From June 1977 to the termination of the study in April 1978 oxygen decreased steadily with depth on all occasions. Surface waters were always undersaturated (a maximum of 76% of saturation recorded on the 26th August and 15th December 1977).

The depth of the oxycline varied, and tended to become deeper towards the end of the study, with oxygen being recorded down to the sediments on the 6th April 1978, and only a trace on the 16th February 1978. Recent studies by Baker and Tyler (personal communication) have shown that oxygen is now present down to the sediments, and no sulphides are present. The mechanism permitting the oxygenation of the bottom waters of this lake is intimately related to the breakdown of chemical stratification because, due to man's alteration of the Gordon River flow pattern, saline water no longer replenishes the lake. Either wind action on this relatively large shallow lake has eroded the chemocline (Figure 104), thereby permitting oxygenation of bottom waters either by wind-induced mixing or intrusion of oxygenated Gordon River water has achieved the same effect. From Figure 84 the latter event seems highly likely. The monimolimnion received a supply of oxygen on three occasions when Gordon River water entered the lake. On the 12th July 1977 Gordon River water entered the lake and caused a depression in the oxycline and sulphide isopleths, and a slight warming of the bottom waters. By the time the lake was sampled the bottom waters were anoxic, so the inflow of water must have occurred prior to the July sampling. On the two other occasions, namely the 16th February and 6th April 1978, samples were collected soon after the lake had received an influx of oxygenated Gordon River water. On the 17th February the influent river waters must have been at temperatures very similar to that of the monimolimnion (Figure 80). On this occasion the percentage oxygen was $<$10% from 1.5 m to the bottom, but oxygen was absent just above the sediments with no trace of sulphides. Due to fairly intense chemical stratification of the lake on the first two occasions, wind-induced mixing is most unlikely to have oxygenated the monimolimnion, however, on the third occasion (5th April 1978) chemical stratification had weakened considerably and wind-induced mixing could well account for oxygenation of the bottom waters in this case (Figure 105). The electrical conductivity data further suggests that fairly extensive mixing occurred in the lake at this time, for surface conductivities

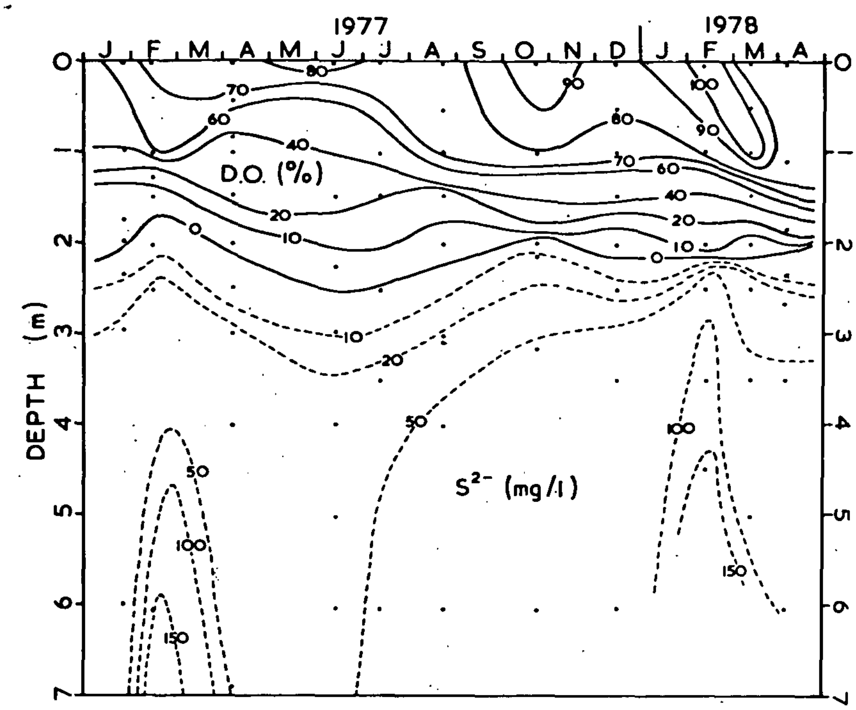

FIGURE 80: ISOPLETHS OF DISSOLVED OXYGEN AND TOTAL DISSOLVED SULPHIDES IN LAKE FIDLER.

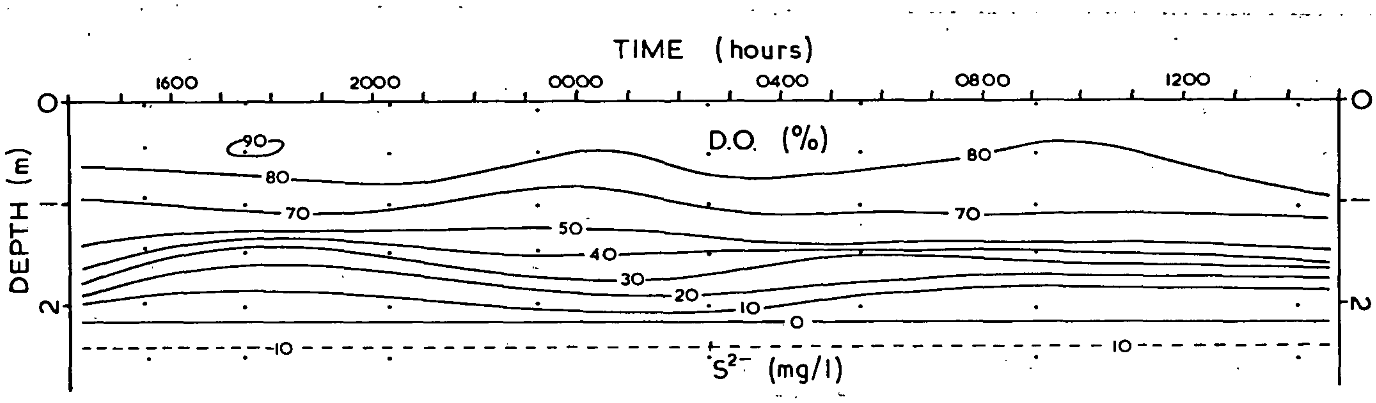

FIGURE 81: DIURNAL VARIATION OF DISSOLVED OXYGEN AND TOTAL DISSOLVED SULPHIDES IN THE MIXOLIMNION OF LAKE FIDLER MEASURED ON THE 13TH AND 14TH DECEMBER 1977. (EASTERN STANDARD AUSTRALIAN TIME.)

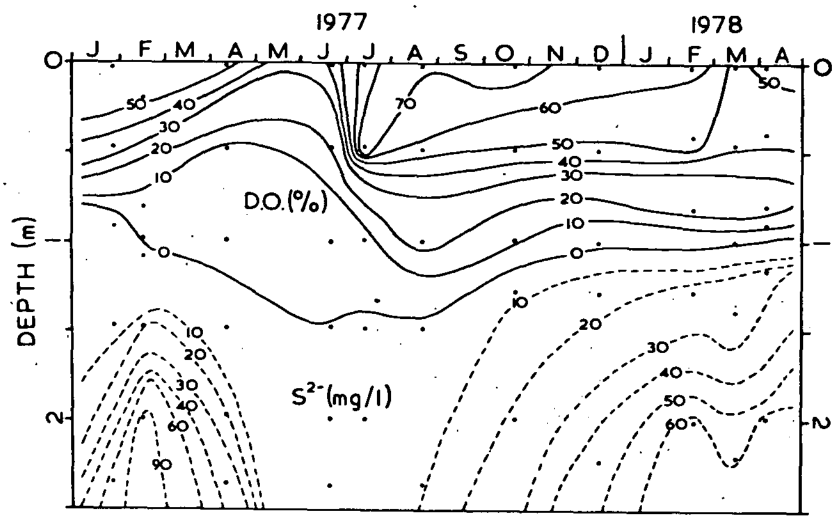

FIGURE 82: ISOPLETHS OF DISSOLVED OXYGEN AND TOTAL DISSOLVED SULPHIDES IN SULPHIDE POOL.

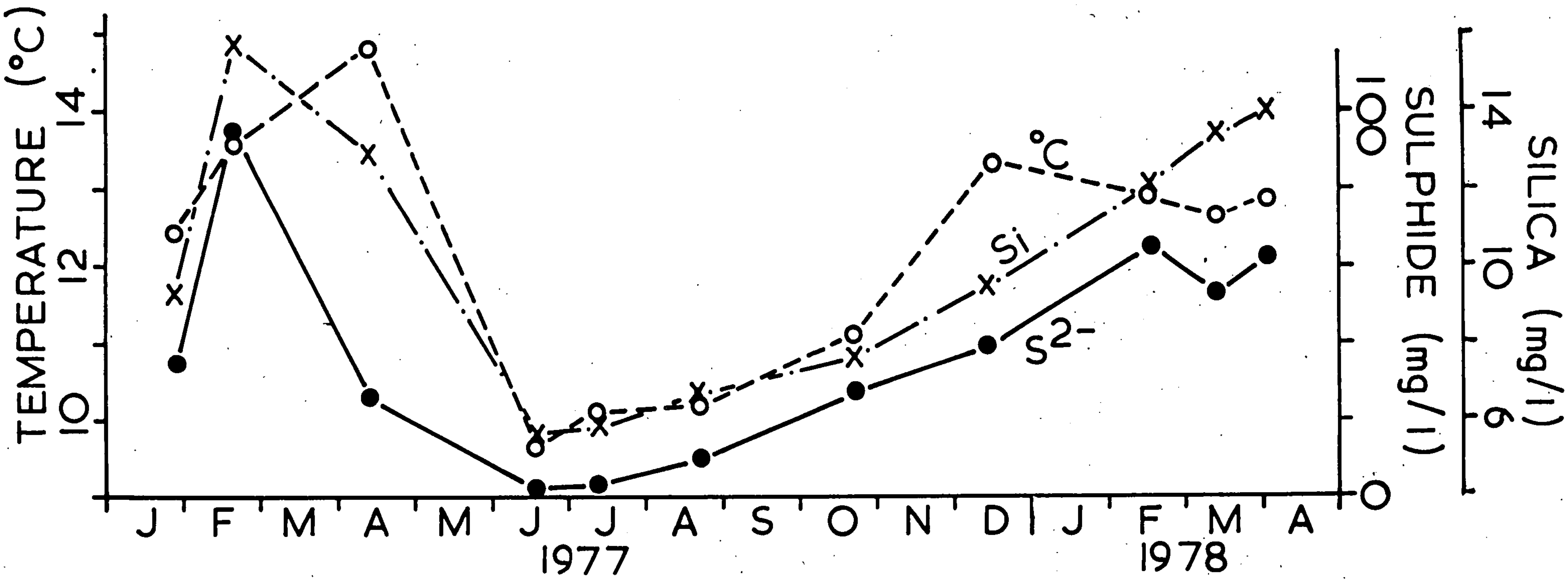

FIGURE 83. TEMPORAL VARIATION OF TEMPERATURE AND TOTAL DISSOLVED SULPHIDES AT 2.0m (EXTRAPOLATED FROM FIGURE 17.), AND SILICA AT 2.2m, IN SULPHIDE POOL.

were only slightly lower than those at 2.5 m (0.1 m, K_{18} = 1.285 mS/cm and 2.5 m, K_{18} = 1.86 mS/cm).

Due to the high dissolved organic content of these south west waters, the influxed monimolimnetic oxygen would be rapidly consumed if not regularly replenished. This is evidenced by the reappearance of sulphides in the monimolimnion between February 1978 and April when oxygenation again occureed. Due to the apparent destruction of chemical stratification in this lake contemporaneous with discharge from Lake Gordon the bottom waters of Lake Morrison will probably now remain permanently oxygenated as the lake assumes a holomictic character.

4.3 Water Chemistry

4.3.1 Dissolved Organic Colour

Dissolved organic colour was measured spectrophotometrically at 440 nm and the absorbance expressed for a 1 m pathlength and designated as gilvin (G440) (Kirk 1976). The results for Lake Fidler, Sulphide Pool and Lake Morrison are presented in Tables 12, 13 and 14 respectively. The relationship between gilvin and colour measured in platinum units is given in King and H.E.C. (1978). Temporal variation of gilvin in Lake Fidler is presented in Figure 85. The sources of gilvin input to the Gordon River lakes are discussed in Section 4.4.1b of this report and in King and Tyler (1978b).

In Lake Fidler the seasonal depth distribution of dissolved organic matter showed no apparent stratification considering the meromictic nature of this lake (Figure 85) but in Sulphide Pool and Lake Morrison the surface waters were generally much darker than the bottom waters (Tables 13 and 14). Of the three lakes, Sulphide Pool contained the highest concentration of mixolimnetic colour ranging from G440 = 6.30 to 12.15 m^{-1}, Lake Morrison ranged from G440 = 4.58 to 8.88 m^{-1}, while Lake Fidler was the least coloured, G440 = 4.38 to 8.50 m^{-1}.

Colour input to the mixolimnion of Lake Fidler was largely influenced by the local weather pattern, with maxima occurring as a result of rainfall flushing humates from adjacent forest peats e.g. December 1976, and to a lesser extent January 1977 were wet summer months - see Figure 6, Chapter 2). Minima were recorded towards the end of the first summer (February and March 1977) and during late winter and early spring of 1977 as a result of low gilvin waters entering the lake after sustained rainfall.

Table 12: Water Chemistry of Lake Fidler

Date	Z m	G_{440} m^{-1}	pH	HCO_3	Cl	SO_4	Ca	Mg	K	Na	Si mg/l	K_{18} μScm	Salinity mg/l
				←		μeq / l				→			
27.1.77	0.1	8.50	6.48	143	2200	60	170	460	43	1957	2.3	176	145
	1.0	7.73	6.97	245	9599	212	599	2056	286	8004	2.6	730	598
	2.0	7.23	6.62	197	24100	3727	1238	4276	563	22620	4.5	2240	1664
	3.0	8.33	7.48	1759	34697	4102	3004	6497	752	34365	7.0	2540	2493
	4.0	7.90	7.12	2009	44595	4914	3373	8717	957	39933	10.0	3360	3069
	5.0	8.03	7.00	1819	43597	4455	2914	8059	977	36975	10.0	3360	2916
	6.0	8.13	6.98	2094	49192	4414	3144	8882	985	42195	11.0	3580	3264
22.2.77	0.1	6.28	7.22	183	3807	541	331	839	109	3349	8.9	470	270
	1.0	6.50	7.19	188	4794	1410	489	1053	166	4263	9.0	555	377
	2.0	7.05	7.80	1193	34799	3664	2563	6579	755	32277	14.4	3600	2385
	3.0	6.98	8.18	2263	47996	4872	3992	9704	1018	42847	25.9	5150	3297
	4.0	7.00	7.80	2067	54003	4789	3812	9869	1115	44718	30.3	5550	3539
	5.0	7.48	8.02	1918	52001	5080	3273	9869	1059	47763	31.8	5450	3530
	6.0	7.45	7.92	1968	52988	4789	3493	10196	1108	45153	32.6	5420	3504
	7.0	7.05	8.00	2294	54003	5496	3393	10198	1100	49068	32.8	5600	3682
8.4.77	0.1	8.25	6.20	147	3119	200	176	658	66	2914	2.4	334	210
	1.0	5.50	6.78	563	24399	700	1168	6415	575	16008	3.5	2350	1425
	2.0	6.05	6.94	741	33499	3789	2026	6168	742	27492	5.5	3320	2192
	3.0	6.60	7.52	3468	49677	3623	3693	10855	1044	42934	11.0	4990	3381
	4.0	7.08	–	3401	55063	4705	3992	9702	1023	46980	9.5	4650	3704
	5.0	6.93	7.00	3925	53977	4580	3693	10856	1118	48720	13.0	5150	3744
	6.0	6.93	–	4081	53997	4185	3792	10198	1105	48589	13.5	5150	3725
	7.0	6.53	7.93	3598	53997	4164	3593	10362	1113	46545	14.0	5150	3646

Table 12: Water Chemistry of Lake Fidler (Continued)

Date	Z m	G_{440} m^{-1}	pH	HCO_3	Cl	SO_4	Ca	Mg	K	Na	Si mg/l	K_{18} µS/cm	Salinity mg/l
				← µeq / l →									
16.6.77	0.1	8.00	6.12	115	1599	29	127	329	33	1435	1.8	184	106
	1.5	8.08	6.96	380	27498	625	1183	5181	588	25099	4.0	2010	1715
	3.0	7.18	7.76	2588	46000	4331	4142	8553	972	47850	8.5	3930	3422
	4.0	6.83	7.75	2686	53498	4455	4221	10527	1108	45675	11.5	4380	3581
	5.0	6.55	7.49	2765	55498	4497	3812	10527	1100	46327	13.0	4660	3665
	6.0	6.13	7.53	3440	54998	4268	3742	10856	1108	44805	13.5	4520	3646
13.7.77	0.1	7.28	6.43	202	2600	73	174	617	23	2262	2.3	281	172
	1.5	5.85	6.75	328	27636	866	978	5839	562	24142	3.5	2460	1709
	3.0	7.10	7.74	2334	41000	5080	3293	9211	865	35452	6.5	3980	2867
	4.0	7.05	7.76	3537	51998	4914	3473	10938	1059	46327	12.0	5000	3605
	5.0	7.15	7.75	3462	51998	4455	3353	11349	1087	45457	12.5	5000	3562
25.8.77	0.1	7.20	6.05	108	1399	139	147	395	37	1218	1.7	175	100
	1.0	6.75	6.76	554	17399	1614	706	4605	363	13615	1.7	1365	1126
	2.0	5.63	7.28	816	31499	3040	2146	7073	639	27100	4.5	3130	2090
	3.0	6.98	7.80	3275	46000	3498	4241	10362	822	35670	9.5	4470	3065
	4.0	6.75	7.80	3680	51499	3768	4072	10856	998	42630	12.0	4850	3464
	5.0	9.40	7.70	3658	51000	3768	3862	11020	985	44370	12.5	4850	3483
	6.0	7.00	7.59	3532	52999	4164	3834	11349	1010	43282	13.5	4940	3544
26.10.77	0.1	7.65	6.05	113	1201	119	98	345	36	1044	2.1	151	87
	1.0	7.38	6.38	146	3201	408	244	748	74	2914	2.3	356	226
	2.0	6.30	7.77	1467	32399	3177	2705	6135	737	26970	6.0	3260	2168
	3.0	7.88	7.10	3278	43998	2707	3812	8388	829	36540	10.5	3180	2941
	4.0	6.68	7.64	2345	47999	4372	3713	8800	972	41325	12.5	3430	3280
	5.0	6.84	7.82	3930	51000	3893	3643	9375	3125	41760	9.5	3750	3420
	6.0	6.73	7.69	3640	50498	4268	3703	11691	957	42412	9.5	3770	3434

Table 12: Water Chemistry of Lake Fidler (Continued)

Date	Z m	G_{440} m^{-1}	pH	HCO_3	Cl	SO_4	Ca	Mg	K	Na	Si mg/l	K_{18} µS/cm	Salinity mg/l
				← µeq / l →									
14.12.77	0.1	7.13	6.44	199	840	75	130	255	26	757	2.3	117	70
	1.0	7.48	6.32	126	1400	150	299	362	37	1144	2.3	164	103
	2.0	6.53	7.55	836	26749	2873	1697	6086	522	23055	5.0	2650	1796
	3.0	6.75	7.55	2440	38499	3456	3295	8388	729	36540	9.0	3670	2717
	4.0	7.05	7.74	3203	48999	3706	3493	10033	908	41760	12.5	4640	3298
	5.0	7.53	7.72	2968	50999	4206	4193	11020	1028	42847	14.0	4810	3435
	6.0	7.25	7.58	2606	47999	3956	3293	10856	998	42630	13.5	4600	3268
15.2.78	0.1	5.70	6.40	181	3700	233	309	757	77	3001	2.0	461	241
	1.0	5.30	6.53	221	5600	271	459	1143	118	4459	2.5	597	355
	2.0	6.13	6.70	590	20999	2353	1567	4441	381	15660	5.0	1580	1553
	3.0	7.75	7.78	3680	46499	333	3593	10567	857	35670	11.0	3440	3087
	4.0	8.10	6.94	3009	44038	3414	3493	11514	1010	37845	14.0	3850	3029
	5.0	8.48	6.86	3153	44539	3789	3693	11843	1010	37410	14.5	3940	3071
15.3.78	0.1	5.18	6.65	157	3570	223	189	641	68	2892	3.6	353	128
	1.5	5.05	6.97	251	8201	654	699	1727	166	6782	5.5	810	535
	3.0	7.08	7.72	3258	47497	3560	2196	10856	882	40890	11.0	4470	3205
	4.0	7.70	7.72	3470	51998	3519	2096	11349	1049	46110	13.0	4810	3506
	5.0	7.08	7.68	3765	52497	3768	2295	12171	998	45240	14.0	4860	3545
	6.0	7.38	7.53	3542	52999	3560	1996	11842	1042	47850	14.0	4950	3592
5.4.78	0.1	4.53	6.88	239	5299	595	349	995	102	4637	1.7	584	368
	1.5	4.38	6.96	298	8801	1066	579	1398	169	8700	2.6	840	617
	3.0	-	8.15	3812	46499	3061	3094	9860	870	39150	10.5	4400	3145
	4.0	7.00	7.30	3344	51998	4372	3194	11349	998	43500	12.5	4780	3499
	5.0	6.83	7.28	3335	52497	4081	3383	11514	985	44370	14.5	4850	3528
	6.0	6.98	7.51	4107	52999	3852	3393	11349	1010	45240	15.0	4860	3601

Table 13: Water Chemistry of Sulphide Pool

Date	Z m	G_{440} m^{-1}	pH	HCO_3	Cl	SO_4	Ca	Mg	K	Na	Si mg/l	K_{18} μS/cm	Salinity mg/l
				μeq / l									
28.1.77	0.1	11.90	5.00	39	1100	10	65	239	20	896	2.0	124	68
	0.9	10.48	6.48	211	12101	2186	599	2533	317	11875	4.5	975	875
	1.3	7.53	6.65	427	19898	3081	1098	3618	468	17095	6.0	1570	1357
	2.2	8.33	6.91	883	30597	3206	1237	5510	660	30885	9.5	2158	2121
23.2.77	0.1	11.63	6.28	167	3900	98	172	691	97	3280	7.1	438	244
	1.0	8.95	6.98	321	13700	2436	1048	3203	345	11440	14.8	1470	948
11.4.77	0.1	12.08	4.84	33	1320	40	62	304	23	1035	2.9	143	80
	1.0	5.40	6.43	513	16001	2457	1078	2632	378	14790	6.5	1660	1125
	2.2	6.80	6.73	1664	26500	2769	1487	3618	599	24012	13.0	2680	1823
16.6.77	0.1	10.50	4.62	18	468	4	41	90	8	405	2.0	51	29
	1.0	5.18	6.67	488	26000	2811	1077	4605	576	25230	6.0	2160	1767
	2.2	5.13	6.81	415	26500	3123	1387	4970	583	23403	5.5	2160	1717
12.7.77	0.1	12.15	5.12	65	1085	17	52	247	18	935	2.4	122	70
	2.2	6.85	6.43	488	24999	3789	5559	5757	563	21097	6.0	2570	1787

Table 13: Water Chemistry of Sulphide Pool (Continued)

Date	Z m	G_{440} m^{-1}	pH	HCO_3	Cl	SO_4	Ca	Mg	K	Na	Si mg/l	K_{18} µS/cm	Salinity mg/l
				← µeq / l →									
25.8.77	0.1	11.48	4.59	12	801	237	71	230	23	661	1.9	104	61
	1.0	7.15	6.08	120	3201	593	379	724	71	2793	2.5	345	233
	2.2	6.73	6.82	701	25498	2436	1417	5592	499	22185	6.5	2480	1690
25.10.77	0.1	11.58	4.76	31	491	21	37	115	16	418	1.5	58	33
	1.0	6.88	6.75	331	16001	2165	753	2549	384	14311	6.0	1658	1082
	1.5	6.84	6.96	829	23200	2228	733	2796	420	23272	7.5	1720	1581
13.12.77	0.1	6.30	6.72	180	1340	158	150	214	37	979	2.6	147	96
	1.0	9.23	6.77	326	10800	1062	459	2303	215	8526	6.0	1000	696
	2.2	6.98	7.11	741	25499	2644	1397	5757	499	21663	9.5	2470	1692
17.2.78	0.1	10.43	5.34	62	1553	81	189	312	23	1305	2.6	157	102
	2.2	7.63	7.07	1503	24499	150	1397	4193	430	22141	12.0	1980	1724
14.3.78	0.1	10.85	6.11	93	1999	94	110	378	36	1740	2.4	187	129
	2.2	7.20	7.10	1532	24841	1603	1397	5017	448	22968	13.5	2400	1686
5.4.78	0.1	9.58	5.58	75	1085	87	80	247	20	1000	2.7	132	76
	2.2	7.03	7.02	1416	24198	162	1697	4811	445	20662	14.0	2560	1529

Table 14: Water Chemistry of Lake Morrison

Date	Z m	G_{440} m^{-1}	pH	HCO_3	Cl	SO_4	Ca	Mg	K	Na	Si mg/l	K_{18} μScm	Salinity mg/l
				← μeq / l →									
29.1.77	0.1	8.68	6.67	168	3201	102	230	650	69	2740	2.5	261	207
	2.5	8.48	7.48	1504	20704	3123	1996	3948	499	20663	7.5	1650	1554
10.4.77	0.1	8.23	6.33	450	3999	146	340	790	77	3697	2.8	430	298
17.6.77	0.1	8.88	4.40	0	1399	208	44	99	15	1522	5.7	175	97
	2.3	6.50	7.41	1655	34500	3477	2884	6415	755	29797	6.8	2440	2342
14.7.77	0.1	8.38	6.58	190	4501	123	326	1028	90	3262	2.6	492	274
	2.3	6.63	7.50	1862	35498	3602	1609	8142	780	31320	10.5	3550	2432
26.8.77	0.1	7.93	5.88	85	801	21	109	230	32	566	1.9	96	54
	2.5	6.33	7.72	2721	35498	2811	1766	8060	691	28710	10.5	3540	2380
15.12.77	0.1	8.20	6.50	149	1560	83	170	411	40	1392	3.5	188	106
	2.2	7.25	7.76	2286	21499	83	898	4934	435	18485	10.0	2160	1426
16.2.78	0.1	7.28	6.83	289	5800	73	479	1135	118	4350	2.8	610	355
	1.8	5.38	7.08	380	14780	210	1008	3207	348	12397	5.0	1620	915
16.3.78	0.1	5.53	6.83	202	5200	458	299	1053	90	4654	2.8	600	348
	2.0	5.40	7.53	912	19500	1957	459	3701	376	17313	11.0	1940	1308
6.4.78	0.1	4.58	6.86	281	11700	1551	319	2344	223	9788	2.6	1285	776
	2.2	3.90	7.20	456	19799	4331	1397	4030	371	17400	3.0	1860	1429

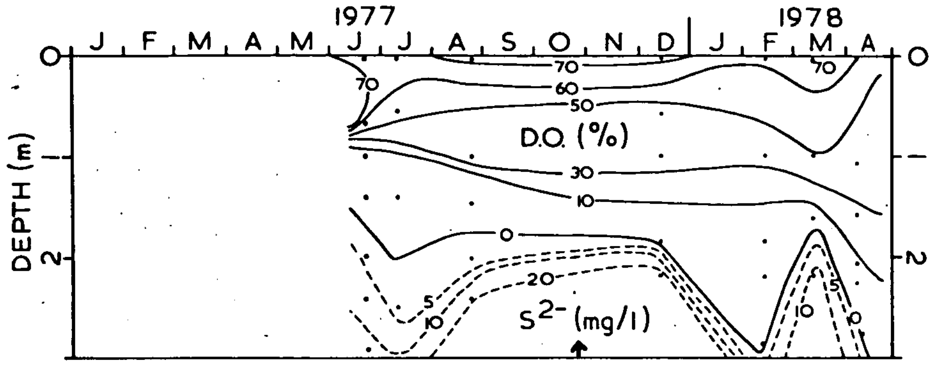

FIGURE 84. ISOPLETHS OF DISSOLVED OXYGEN AND TOTAL DISSOLVED SULPHIDES IN LAKE MORRISON.

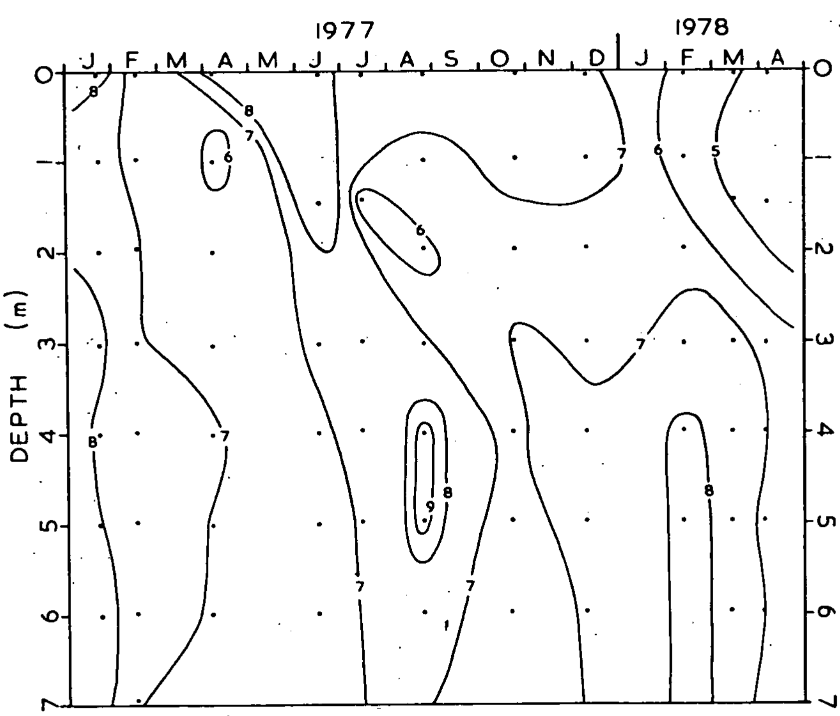

FIGURE 85. ISOPLETHS OF DISSOLVED ORGANIC COLOUR (GILVIN G440m-1) IN LAKE FIDLER.

After November 1977 surface organic colour was further decreased when relatively uncoloured waters released from Lake Gordon (Steane & Tyler 1978) entered the lake and progressively lowered the colour of the mixolimnion. The effect of lower gilvin, measured in the Gordon River at Butler Island camp after December 1977, on the surface Lake Fidler water is clearly shown in Figures 85 and 113. In March 1978 the two inflow creeks also partly contributed to the reduced colour levels in the lake (King and H.E.C. 1978). Reduced gilvin levels in the Gordon River caused a lowering of gilvin values in Lake Fidler surface waters, and as the salt content of this influent was significantly lower than for previous summers, it was unable to penetrate the halocline, so that the bottom waters maintained previous levels.

Minima recorded in April 1977 at about 1 m, and July and August 1977 between 1.5 m and 2.5 m in Lake Fidler are difficult to explain but could possibly have been due to light-independent aerobic decomposition processes (Kuznetsov 1968), or relatively clear inflows from the Gordon River of a specific density that would not mix with lake water but would flow out as a density layer producing less coloured intermediate layers.

Surface dissolved colour was significantly increased on the 15th December 1977 when the combined effect of rainfall and power station discharge caused the Gordon River to flood over the lake inundating much of the surrounding rainforest floor, from which additional quantities of organic matter were dissolved. This was a short-lived flood effect and surface colour soon decreased to more normal levels. These highly coloured flood waters contained an appreciable particulate organic fraction, so the gilvin value probably increased during storage of the sample; therefore the data for this single sample is not reliable and not included in Figure 85.

Gilvin in the monimolimnion of Lake Fidler remained fairly constant with time (Figure 85), ranging between 6.13 and 8.48 m^{-1}, excluding the high colour between about 4 m and 5 m depth in late August 1977. No explanation for this high gilvin stratum is obvious but it could have resulted from bacterial decomposition, at some intermediate depth in the monimolimnion, of cells which originated from the declining bacterial plate (see Figure 109).

A further possible explanation could be an influx of dense coloured water from the Gordon River into the lake, undercutting the mixolimnion and forming a highly coloured monimolimnetic layer. Slow circulation in the monimolimnion would permit mixing of this gilvin layer with adjacent layers. However, as gilvin values for the Gordon River during the winter of 1977 only reached a maximum of 7.75 m^{-1} and salinities ≃ 33 mg/l (King and Tyler 1978b), Gordon River inflows would only mix with the lake surface waters and could not penetrate below the chemocline (Figure 86). Therefore, in situ production of gilvin is the most likely explanation.

Monimolimnetic increases in gilvin during the early part of the study (January 1977) and more particularly in the summer of 1977 - 1978, were probably released from the sediments and became mixed throughout the monimolimnion, could occur when waters adjacent to the sediments were geothermally heated in summer (see Figure 74). From 3 m depth to the sediments electrolytes remained remarkably constant (see Figure 102) and would permit warm, less dense water to rise producing monimolimnetic water circulation. When the monimolimnion began cooling in late February 1978, circulation would be retarded and the input of gilvin from the sediments correspondingly reduced, then light-independent bacterial consumption of organic material (Kuznetsov 1968) would cause the observed lowering of gilvin values.

Variations in monimolimnetic colour could well be due to decomposition of cells raining down from the bacterial plate. The quantity of dead cells entering the monimolimnion would depend on state of growth of the bacteria in the plate, and the rate at which these cells were able to sink through the saline gradient. Close interval information from these lakes suggests that there is often a discrepancy between bacterial biomass (measured as chlorophyll) and turbidity (Figures 86 to 88), but on most occasions these two parameters were closely related in the plate region, and below this level both were extremely low, suggesting that particles would descend at rapid rates and not remain in the monimolimnion for long periods. This is best illustrated in Lake Fidler (Figure 86) which is sufficiently deep to permit the plate to occur at an intermediate depth in the water profile. Sulphide Pool and Lake Morrison (Figures 87 and 88) do not always display the close relation between bacterial biomass and turbidity, for both their plates occurred close to the sediment surface.

Monimolimnetic organic concentrations in Sulphide Pool were inclined to be slightly higher during the summer than in winter (Figure 99), which correlates fairly well with sulphide migration from the sediments when monimolimnetic waters warmed in summer (Figure 83).

In both Sulphide Pool and Lake Morrison there was a significant diminution of gilvin with depth (Tables 13 and 14). Whereas allochthonous organic inputs created high gilvin values within the mixolimnion, as vertical circulation in these lakes is chemically restricted, increased storage time would permit aerobic decomposition processes to reduce organic colour with depth (Kusnetsov 1968, Steane & Tyler 1978), a feature common

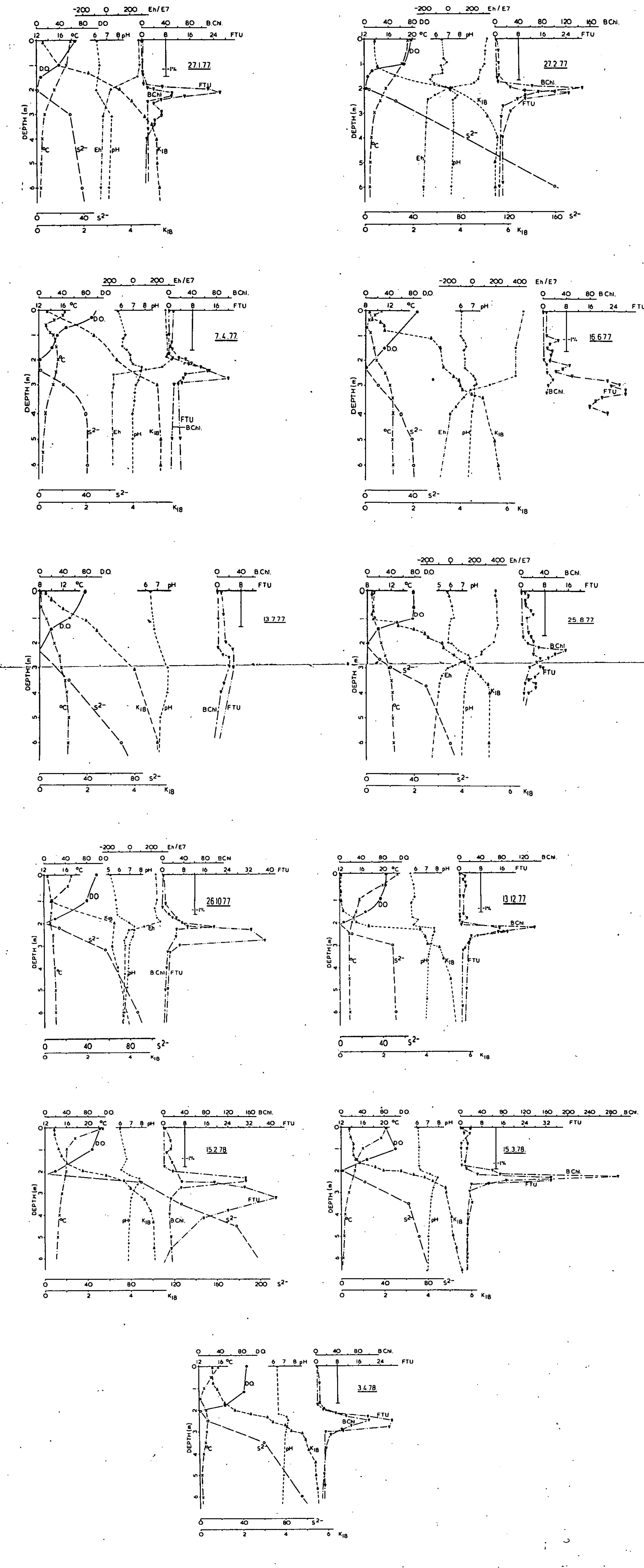

FIGURE 86: DEPTH PROFILES OF VARIOUS PARAMETERS IN LAKE FIDLER. UNITS OF REDOX POTENTIAL ARE (mV Eh/E7)m, DISSOLVED OXYGEN (% SATURATION), TOTAL DISSOLVED SULPHIDES (mg/1), TEMPERATURE (°C), CONDUCTIVITY (mS/cm), pH UNITS, BACTERIAL CHLOROPHYLL ((B.Chl)µg/1), TURBIDITY IN FORMAZIN TURBIDITY UNITS (FTU), SECCHI DISC (m) (|), AND LOWER LIMIT OF THE PHOTIC ZONE (m) (—| —/%).

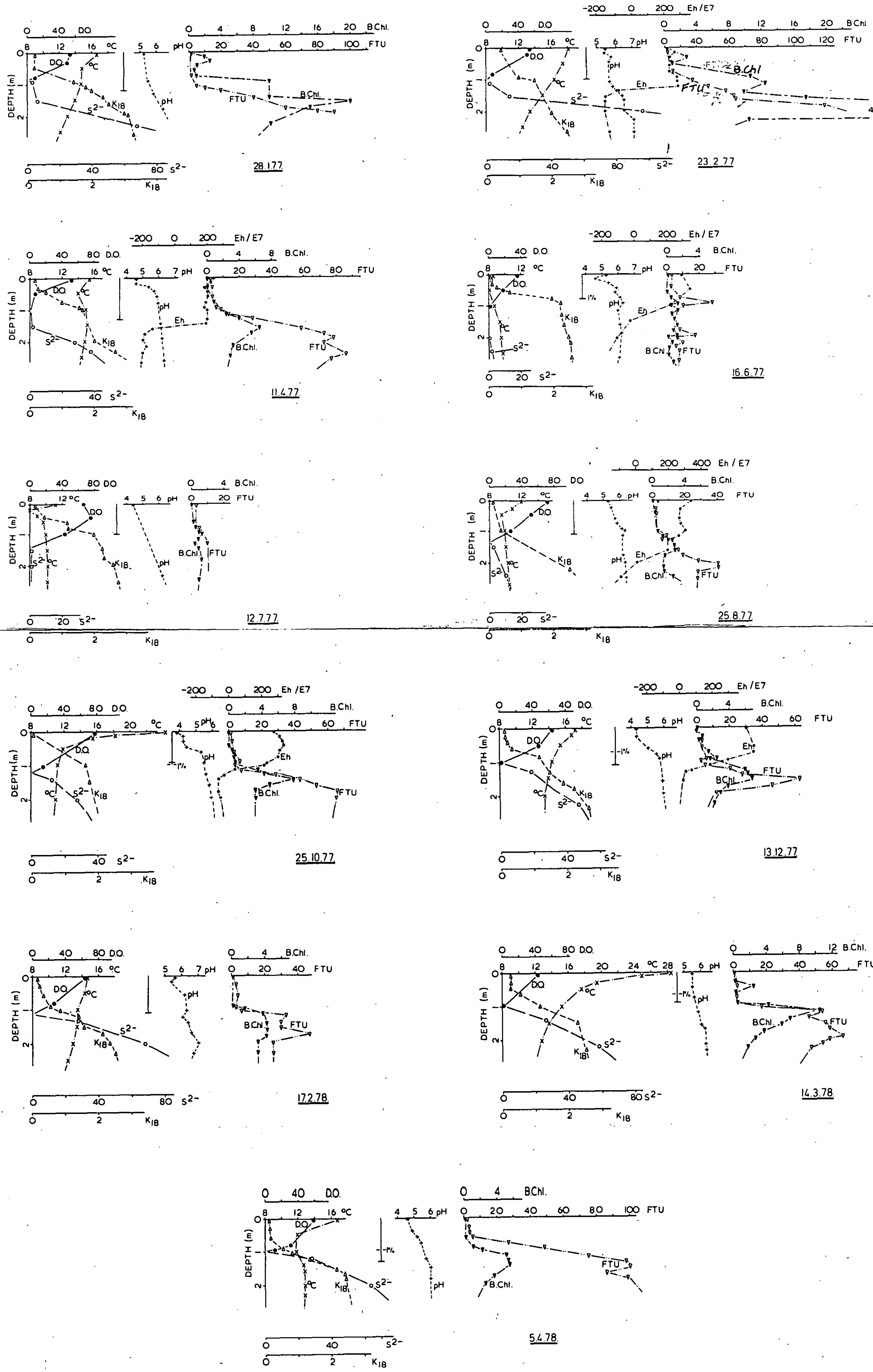

FIGURE 87. DEPTH PROFILES OF VARIOUS PARAMETERS IN SULPHIDE POOL. UNITS AS IN FIGURE 86.

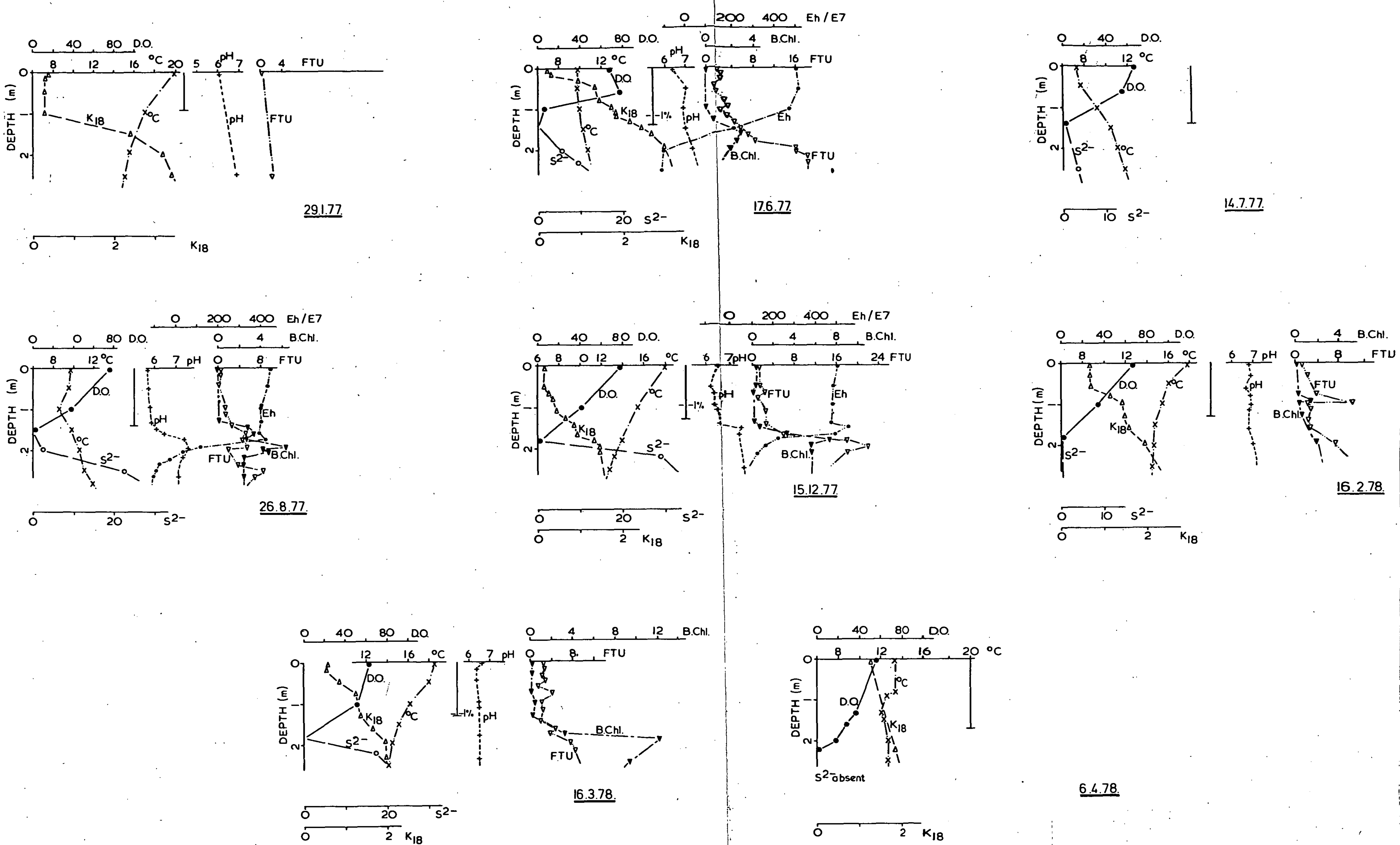

FIGURE 88: DEPTH PROFILES OF VARIOUS PARAMETERS IN LAKE MORRISON. UNITS AS IN FIGURE 86.

when water rich in dissolved organics is stored for long periods (Baxter 1977).

Due to the strong light absorbing properties of humic substances, in the Gordon lakes light penetration only occurs to very shallow depths (Brezonik 1977; King and Tyler 1978 a & b and Section 4.4) therefore organic decomposition must occur in very low light or total darkness, both aerobically and anaerobically. In addition, when dissolved humic substances come into contact with saline water a selective precipitation of the high molecular weight fraction would occur leaving only the low molecular weight fraction behind thus lowering the colour (Prakash 1971).

Seasonal variation of dissolved organics in Sulphide Pool was minimal except for a significant decrease in surface gilvin on the 13th December 1977, probably due to localized rainfall diluting the lake surface waters. Even though this lake has no known channelized connection with the Gordon River, fluctuations in river level also affected the lake level, so it is possible for low gilvin water to enter the lake surface from the river. Creek and seepage inflows entering the lake contained much lower gilvin than the lake surface prior to December 1977, thus diluting the lake water gilvin (see King and Tyler 1978b).

Decreases in gilvin in the Gordon River due to power station discharge (Figure 113) also influenced concentration of organics in Sulphide Pool, but to a smaller degree than in Lakes Fidler and Morrison. Lower gilvin values were recorded in the second summer of the study after power station discharge had commenced, and not before.

4.3.2 pH

Close interval pH-depth profiles (measured in situ) for the three Gordon River lakes are presented in Figures 86, 87 and 88, and seasonal variation of laboratory measured pH in Lake Fidler in Figure 89. Certain discrepancies are evident in pH values between those in Figure 86 and those in Figure 89 which can be attributed to biochemical processes operative within the stored samples, particularly those from the region of the bacterial plate.

Mixolimnetic waters of all three lakes were mostly acidic due to the influent waters containing high concentrations of dissolved organic acids which entered the lakes as seepage from surrounding rainforest and from the Gordon River.

This strong hydrogen ion activity would be partly due to cations dissolved in rainfall being exchanged for hydrogen ions in the rainforest peats, as well as the dissolution of organic acids leached from the peats (Wetzel

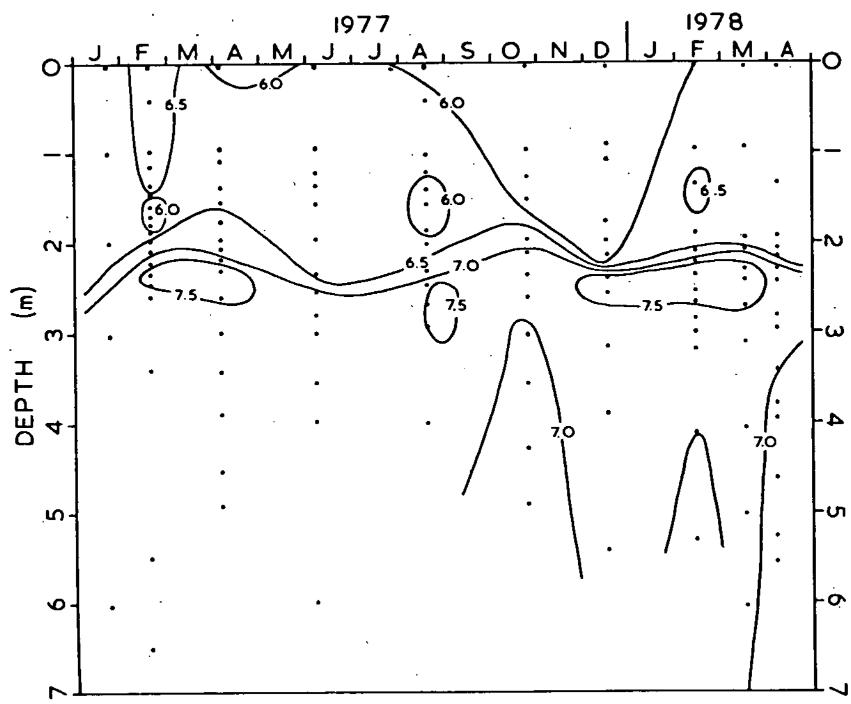

FIGURE 89: pH ISOPLETHS FOR LAKE FIDLER.

1975). Mixolimnetic pH values varied widely, ranging from 5.2 - 6.9 in Lake Fidler, to 3.8 - 6.0 in Sulphide Pool, and 5.7 - 7.0 in Lake Morrison. Occasionally within the mixolimnion pH rises were recorded which are correlated with increased algal biomass and therefore photosynthetic activity (see for example Sulphide Pool on 23rd February 1977 - pH increase of 5.3 at 0.15 m to 5.7 at 0.3 m, which then dropped to 5.6 at 0.44 m, correlated with an increase in algal biomass of 0.4 mg chl. /l at 0.01 m to 2.8 mg chl. /l at 0.3 m, decreasing to 1.0 mg chl. /l at 0.44 m).

There was often a marked pH increase at the oxycline where conditions became anaerobic and where dissolved sulphides began increasing rapidly with depth. The most dramatic increase in pH was measured in Lake Fidler on the 27th February 1977 (Figure 86) when the pH increased from 5.5 to 7.8 between 1.65 m and 2.3 m depth.

pH rises at or below the oxycline in all three lakes were usually associated with the occurrence of a bacterial plate in the upper monimolimnion, where conditions were mildly anaerobic. Below this level for a short distance only there was a general tendency for small pH decreases, then for pH to remain fairly constant to the bottom.

These positive heterograde pH profiles resulted primarily from a constant increase in bicarbonate with depth (Table 12, 13 and 14, figure 90) which accounts for the mixolimnion being more acid than the monimolimnion. In the presence of bi-carbonate the utilization of CO_2 for photosynthesis by the bacterial plates would cause the pH to increase in the upper monimolimnion (Wetzel 1975).

Lowering of pH in the lower monimolimnion occured periodically, presumably when organic matter became decomposed (Baxter 1977) and CO_2 released (Wetzel 1975), a common feature of meromictic lakes (Kjensmo 1962, 1967a and 1968b, Timms 1972).

4.3.3 Major ions

The seasonal depth distribution of various chemical parameters of the Gordon River lakes is presented in Table 12, 13 and 14, and illustrated in figures 90 to 103.

In North America ectogenic meromictic lakes have either marine characteristics or an alkaline-evaporite affinity (Likens 1967) where sodium, magnesium, chloride and sulphate are the dominant ions. In contrast, biogenic (endogenic - Walker and Likens 1975) meromictic lakes are dominated by calcium and magnesium sulphate and bicarbonate (Likens 1967, Tyler and Buckney 1974). Certain exceptions to this basic rule exist, for example the major ions in

Hot Lake, Washington are dominated by magnesium and sulphate because the lake occupies an old epsom salt mine (Anderson 1958). Most ectogenic meromictic lakes are situated in coastal areas and have received marine salts at some time during their histories (Northcote, Wilson and Hurn 1964, Boyum and Kjensmo 1970, Bremmeng 1974, Mori 1976, and Robarts and Allanson 1977). All three meromictic lakes of the Gordon River have ionic proportions very close, at all depths, to these of seawater (Figures 99 to 101).

All three Gordon River lakes displayed a significant increase in sea salts with depth (Figures 98, 93 and 104), which is typical of ectogenic meromixis (Hutchinson 1957, Walker and Likens 1975).

Mixolimnetic water chemistry of these riverine meromictic lakes was mainly controlled by the dilution of sea water in the estuarine region, of the Gordon River (Kearsley 1978) and to a lesser extent by atmospheric precipitation. Slight influence was exerted on lake waters by geochemically modified waters from the Gordon Basin entering from the Gordon River and from creek inflows (Figure 981). Chemistry of the monimolimnia was entirely controlled by the input of sea salts to the lakes via the channelized connection of Lakes Fidler and Morrison with the Gordon River. Unfortunately Sulphide Pool has no such obvious link but it is influenced by tidal variations. Whether the lake contains old relictual—trapped sea water in the monimolimnion or whether there has been recent renewal of salts from the river is not known. In any case, sodium and chloride dominated the chemistry of all three lakes and monimolimnial salinity values lie within the range of 1 - 5‰ reported by Kearsley (1978) for the Gordon River below Butler Island when the salt wedge was well developed in the river. The increase in salinity from the surface to the bottom represents a dilution series of sea water (Figure 103), which would occur widely throughout the world where sea water and fresh water come into contact e.g. coastal lagoons and estuaries.

Monimolimnetic waters of all three lakes, if plotted on the "boomerang" diagram, which Gibbs (1970) used to explain controls on water chemistry, would in composition and concentration plot at the "evaporation-crystallization end type" part of the graph. However, their position there clearly results from interchange of mixing with estuarine water and not from evaporation-crystallisation processes.

As an example, lakes waters from Macquarie Island which occur within 2 km of the west coast of the island and receive sea spray are displaced to lie outside the Gibbs boomerang (Tyler 1972). Migration from the evaporation - precipitation end member down a concentration gradient to an atmospheric precipitation type, or vice versa, therefore occurs without the mandatory alteration of composition by land based salts (Figure 103).

Similarly an influx of saline water into or evaporation from a water surface will result in increased concentration without any variation in composition, therefore Gibbs' notion that variation in concentration necessarily implies a change in composition from land based salts is invalid in the lower Gordon River region, as well as for all estuaries in general. Gordon River Basin water chemistry can vary in composition without the large variation in concentration suggested by Gibbs (discussed in Chapter 2, horizontal arrow GR in Figure 103, The intrusion of the saline "wedge" then permits increases in concentration but not composition to occur. This pattern is well illustrated in the meromictic lakes. Therefore, if Gibbs' boomerang is converted into a triangle, his mechanisms become more applicable, covering a wider range of water types.

Discharge from Lake Gordon has reduced the supply of sea salts to the lakes as a result of significantly increased summer flows in the river (Figure 5), flushing the salt "wedge" permanently from the river bed (Kearsley 1978) with very low salinity Lake Gordon water (27 - 37 mg/l). Water of similar ionic composition to sea water but of much lower salinity (Steane and Tyler 1978) will still enter the mixolimnia of the lakes but due to the removal of the salt "wedge", saline inflows from the river will no longer replenish monimolimnial salts. Monimolimnial salts are now relictual in this respect and the meromictic state of the lakes will rely on these salts remaining in the lake basin without any further replenishment.

All major ions in the mixolimnion of Lake Fidler displayed a small increase in concentration (Figure 102), In accordance with the winter rainfall pattern (Bureau of Meteorology 1977, Bosworth 1977 and Watson 1978*b*), minimum concentrations of all major ions in the mixolimnia occurred towards the end of winter and into spring, and maximum concentrations towards the end of summer and into autumn (Figures 97 and 98).

In Lake Fidler the chemocline occurred between a depth of 1 m and 3 m where the concentration of all ions increased rapidly, particularly sodium and chloride (Figure 102). Concentrations of ions at various depths in the monimolimnion varied only slightly with time, and the chemocline remained intense throughout the study period (Figure 105), thus reflecting the conservative nature of the major ions (Wetzel 1975; Cole 1975), possibly with the exception of bicarbonate. Relatively minor variations in concentration occurred from 3 m to the bottom, though some features are worthy of note.

In early February 1977, when Gordon River flows were moderately low, an influx of saline water from the river entered the lake slightly elevating the concentration of all major ions, except bicarbonate, in the minimolimnion. There also occurred an increased intensification and upward shift of the chemocline at this time (Figures 91, 93 to 96).

Both sulphate and bicarbonate were present in low concentrations in the monimolimnion in comparison with chloride, and varied surprisingly little throughout the study period, for in ectogenic meromictic lakes elsewhere they are both biologically active anions (Anderson 1958, Weimer and Lee 1973, Bremming 1974, Cole 1975 and Wetzel 1975); being more specifically affected by metabolic processes of the plankton (principally sulphur bacteria) than by hydrological events. Sulphate was always present in the monimolimnion and maximum concentrations coincided with maximum sulphide levels particularly in the first summer of the study (Figures 80 and 92). This further suggests that sulphides were produced in the lake sediments and released to the overlying waters (Figure 80), rather than from the biological reduction of sulphate in the water itself. However, more recent studies have indicated that sulphide levels vary considerably through the monimolimnion (A.L. Baker, pers. comm.) and indicate bacterial involvement in the distribution of sulphides (and hence sulphates) in the monimolimnion.

Bicarbonate displayed an apparent relationship with the bacterial plate biomass (Figures 80 and 90) and with pH (Figures 89 and 90), but varied minimally within the monimolimnion. The increase in bicarbonate between 2 m and 3 m was probably a result of bicarbonate produced biologically in the plate which could then be mixed to deeper layers in the monimolimnion.

From April 1977 onwards, both sodium and chloride (and sulphate to a lesser extent) displayed a gradual decrease in concentration (Figures 96, 91 and 26) until early March 1978, when their concentration increased back to levels recorded towards the end of the previous summer. The sharp drop in calcium in late February 1978 is unexpected, however a similar though less marked decrease occurred at the beginning of the study period suggesting some seasonal pattern. Wetzel (1975) indicates that though no metabolic requirement for calcium has been demonstrated for algae, it is considered a basic requirement as a micronutrient. On the other hand, fresh and brackish water fauna display a more specific requirement for calcium, and taxa may be separated into hard or soft-water species (Wetzel, 1975). Throughout the present study only small populations of *Chaoborus* sp were noted from the monimolimnion. Probably the most plausible explanation for the minor variation in major ion concentrations could have been due to slow monimolimnial circulation. Bicarbonate, sulphate, and to a lesser extent magnesium, potassium and sodium displayed increased variability (see Buckney 1976a) just above the lake sediments (Figure 102). Therefore, under certain conditions, specific ions may be released or incorporated into the sediments, thereby permitting small monimolimnial variations to occur.

The chemistry of Sulphide Pool was completely dominated by sodium and chloride (similar to Lake Fidler and Lake Morrison) in similar proportions to that of sea water (Figures 98 and 100) and maximum concentrations of these ions occurred during the summer months when rainfall and seepage inflows to the lake were low. In contrast minimum concentrations occurred during the rainy winter months. Differences in magnitude of the two respective summer maxima were attributed at least in part to increased Gordon River flows during the second summer period causing elevated lake levels after power station discharge commenced. The absence of the salt wedge in the river eliminated saline water replenishment to Sulphide Pool

In the monimolimnion of Sulphide Pool both sodium and chloride gradually decreased in concentration from January 1977 to July 1977, thereafter remaining virtually constant to March 1978 and then decreased slightly to April 1978. Sulphate concentrations remained very constant but from February 1978 onwards decreased slightly. Slight reductions in ionic concentration cannot be directly attributed to power station discharge because Lake Gordon water was considerably more dilute than that of the Sulphide Pool monimolimnion (Steane & Tyler 1978) and would not undercut the mixolimnion. The decrease in concentration of sodium, magnesium and chloride also occurred in the mixlimnion and was most likely caused by the peculiar hydrological pattern of the lake when very dilute river water was probably mixed with surface waters.

Ionic proportions in Sulphide Pool closely resembled that of world average sea water at all depths and were similar to other waters of south west Tasmania which are not geochemically modified (Figure 98 and 100, Buckney and Tyler 1973a and b, Steane and Tyler 1978, King and Tyler 1978). In Sulphide Pool, calcium, potassium, bicarbonate and sulphate characteristically occurred in relatively small amounts and contributed minimally to the ionic composition. In July 1977 calcium in the bottom waters increased and equalled magnesium, but soon decreased to previous concentrations (Figure 99). There was no apparent reason for this fluctuation and was most probably due to sample contamination or analytical error.

The ionic composition in Lake Morrison was always completely dominated by sodium and chloride with the order of ionic dominance mostly that of sea water. Occasionally magnesium was only slightly more plentiful than calcium, and bicarbonate exceeded sulphate by up to 10%. These minor departures from sea water composition were probably due to Gordon River inflows (at low flows Gordon River water displays geochemical modification in the absence of admixture with the salt wedge). and to a lesser extent to creek and seepage inflows (King & Tyler 1978b).

Table 14 presents chemical information for Lake Morrison from the mixolimnion (0.1 m depth) and from the monimolimnion (1.8 m to 2.5 m depth - samples were always collected just above the sediments) and the range of sampling depths is due to fluctuations in lake level caused by variations in the Gordon River level (See Kearsley 1978).

The limited data from Lake Morrison suggests a seasonal variation in major ion concentrations in the monimolimnion, and no apparent seasonal pattern in the mixolimnion, prior to Lake Gordon discharge. Sodium and chloride maxima in the maximolimnion may be attributed to salt water entering the lake during short rain free periods in winter. Since Lake Morrison is only 14 km upstream from Macquarie Harbour the salt wedge would only penetrate for this distance under reduced flow conditions. Equally sustained high river flows would flush saline water from the river, and in a similar way fresh low salinity water would flow from the river to the lake, reducing mixolimnetic ionic concentration. Mixolimnetic sodium and chloride maxima in July 1977 probably resulted from wind-induced mixing of saline inflow waters within the lake (see Figure 88). The remaining major ions displayed almost identical fluctuations to those of sodium and chloride (Table 14).

Discharge from Lake Gordon was intermittent between late October 1977 and mid-February 1978. Increased flow rates in the lower Gordon River completely flushed all saline water intrusions from the river bed, except perhaps for a few kilometers upstream from Macquarie Harbour (Kearsley 1978). Therefore only very dilute water, essentially Lake Gordon water, entered Lake Morrison in response to river level fluctuations from October 1977 onwards. In order to maintain the meromictic state in this lake, which has a large surface area to mean depth ratio, constant input of sea salts would probably be required, which would not necessarily be the case in other ectogenic meromictic lakes which receive sea salts (Carter 1963, Northcoat and Johnson 1964, Matsuyama 1973, Bremmeng 1974). However, meromixis became established in the expanded lake-like upper reaches in Swartvlei estuary, South Africa only when the estuary was open to the intrusion of sea (Robarts and Allanson 1977). When this estuary was closed to the sea stratification weakened and persisted under mild weather conditions, whereas, strong wind action destroyed stratification. Similarly, chemical stratification in Lake Morrison was apparently weakened due to the reduction of sea salts entering the lake because of the flushing out of saline water from the riverbed after commencement of power station discharge.

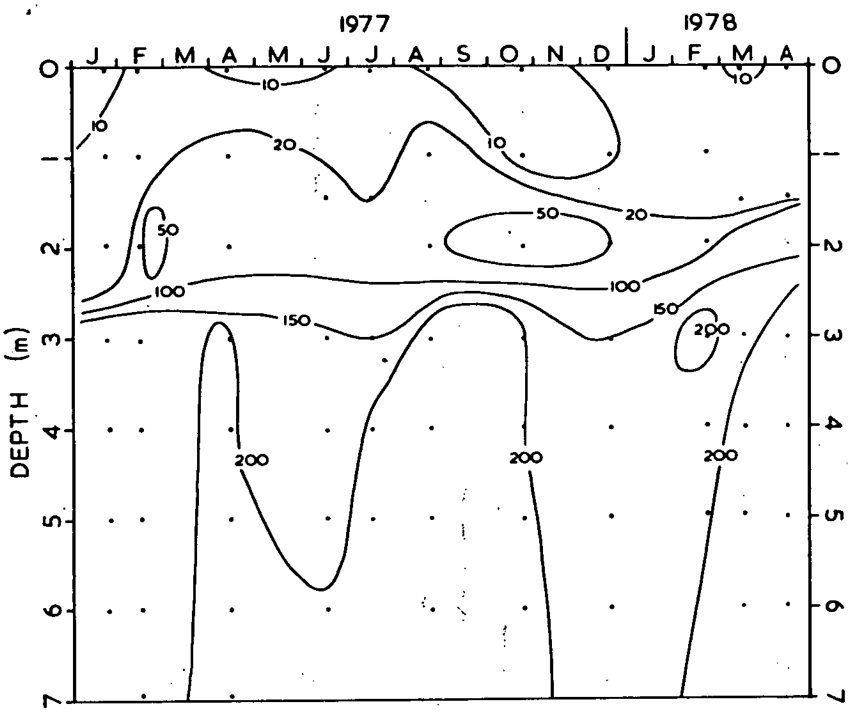

FIGURE 90: BICARBONATE (mg/1) ISOPLETHS FOR LAKE FIDLER.

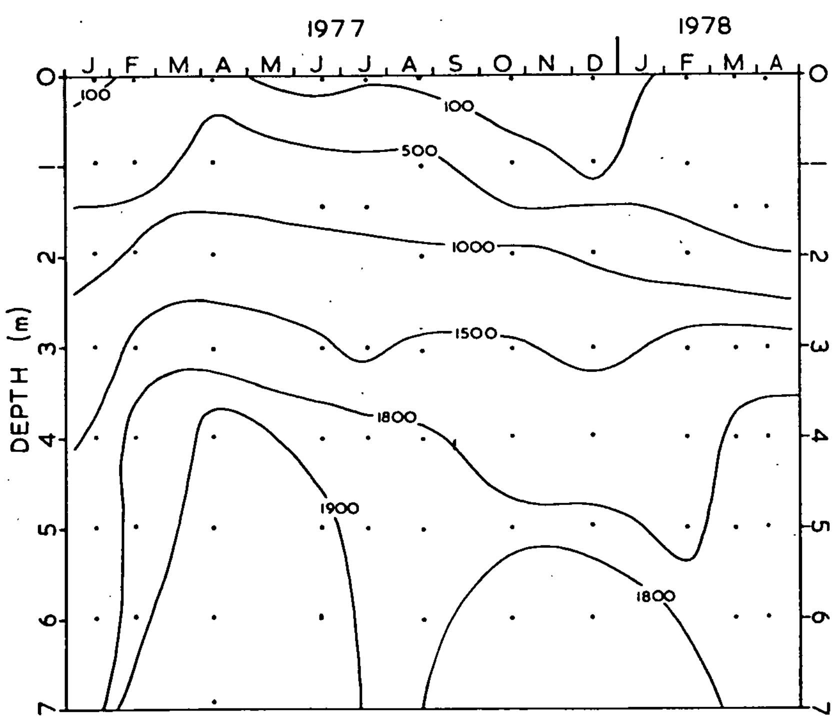

FIGURE 91: CHLORIDE (mg/1) ISOPLETHS FOR LAKE FIDLER.

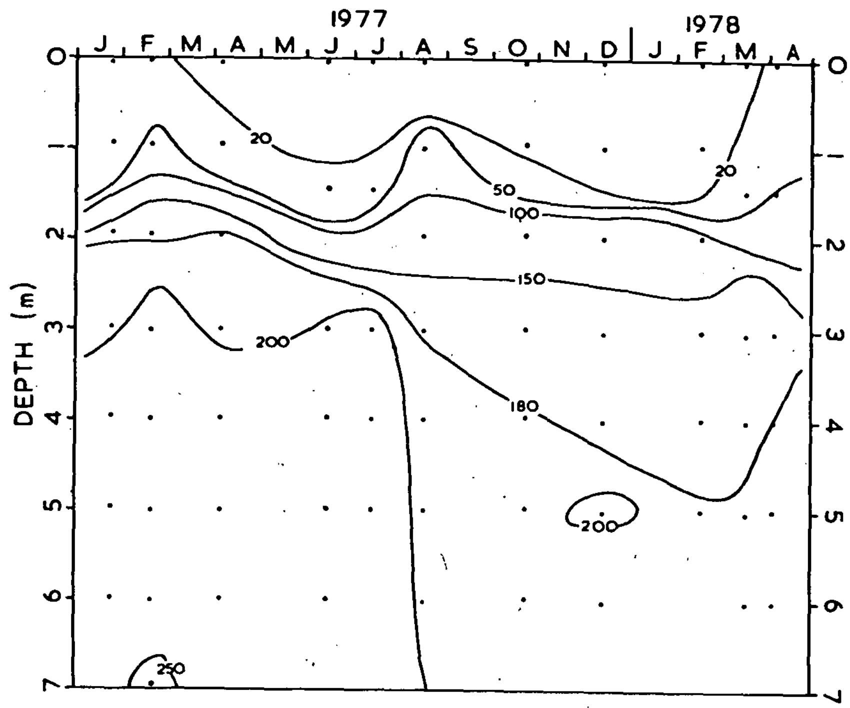

FIGURE 92: SULPHATE (mg/1) ISOPLETHS FOR LAKE FIDLER.

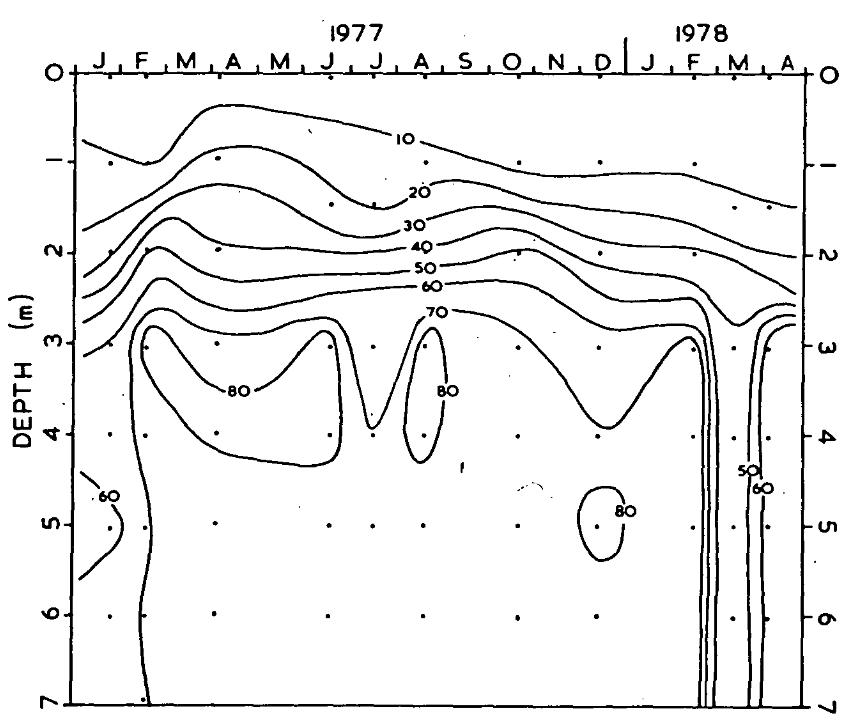

FIGURE 93: CALCIUM (mg/1) ISOPLETHS FOR LAKE FIDLER.

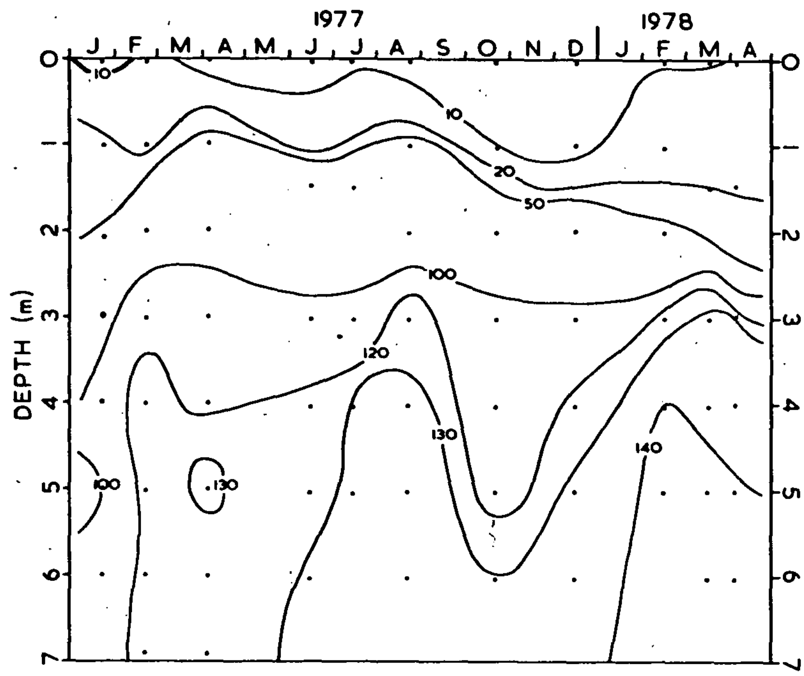

FIGURE 94: MAGNESIUM (mg/1) ISOPLETHS FOR LAKE FIDLER.

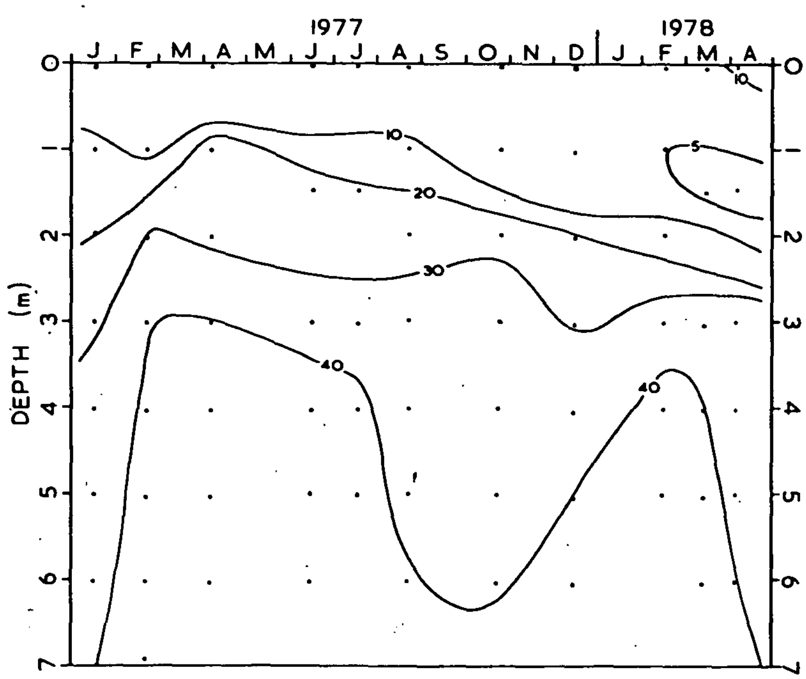

FIGURE 95: POTASSIUM (mg/1) ISOPLETHS FOR LAKE FIDLER.

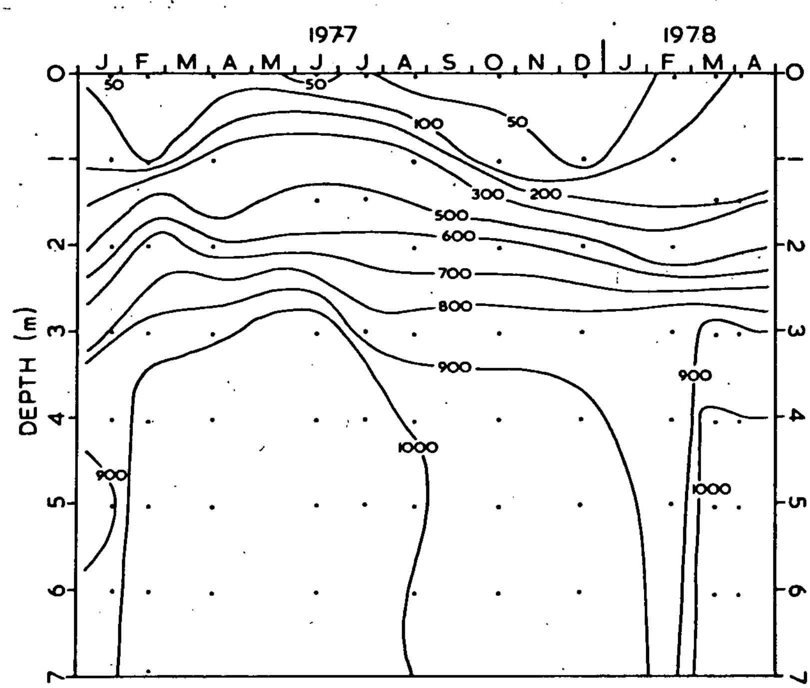

FIGURE 96: SODIUM (mg/1) ISOPLETHS FOR LAKE FIDLER.

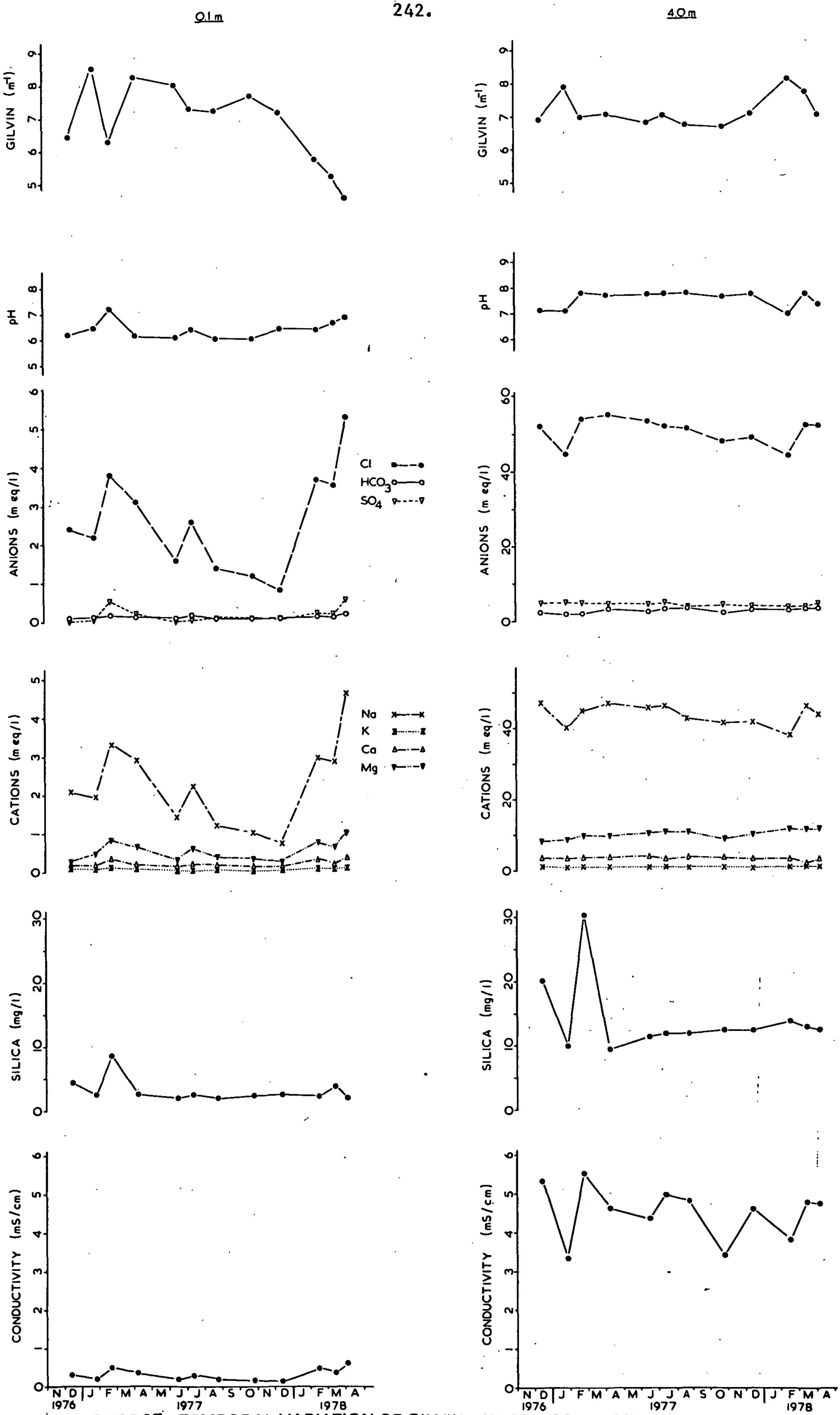

FIGURE 97: TEMPORAL VARIATION OF GILVIN AND MAJOR CHEMICAL PARAMETERS IN LAKE FIDLER AT 0.1m AND AT 4.0m DEPTHS.

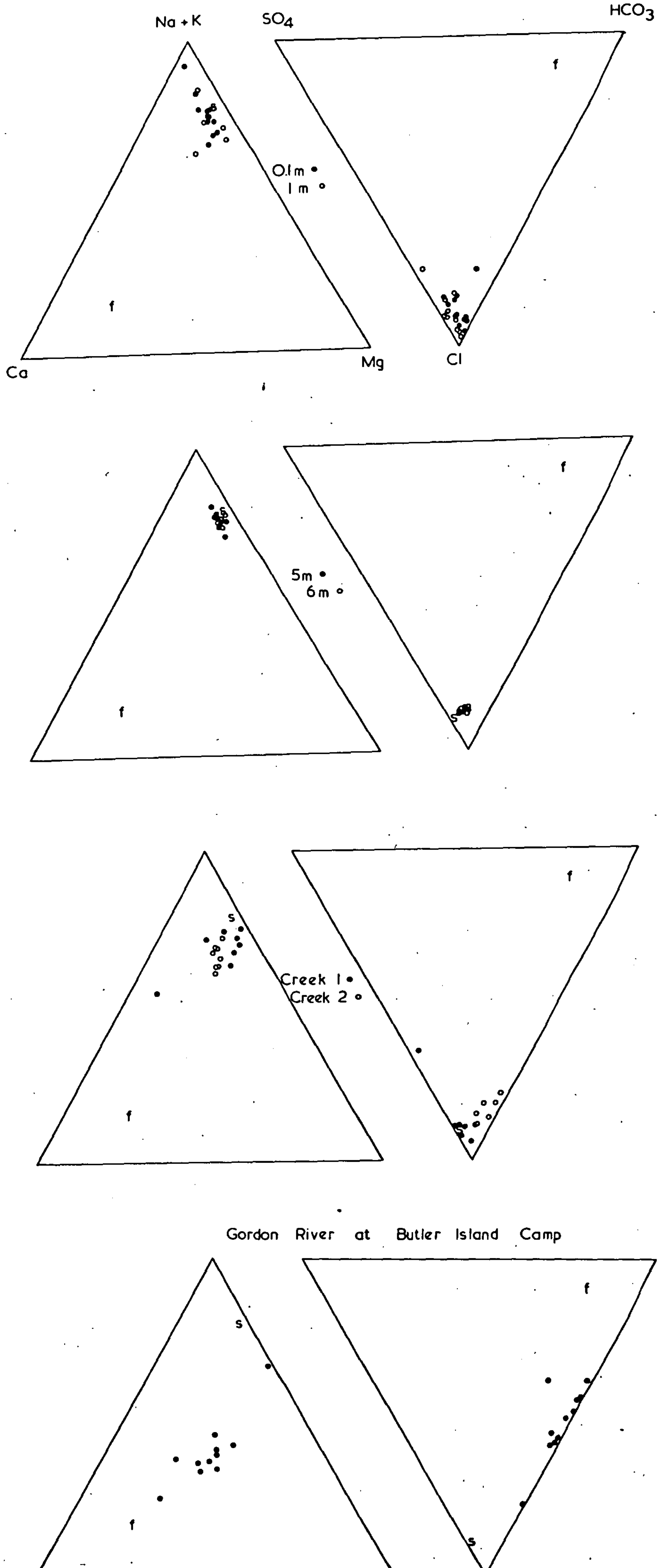

FIGURE 98: IONIC PROPORTIONS IN LAKE FIDLER, AS WELL AS THE TWO INFLOW CREEKS, AND THE GORDON RIVER AT BUTLER ISLAND. WORLD AVERAGE FRESHWATER (f) AND SEAWATER (s) ARE INDICATED.

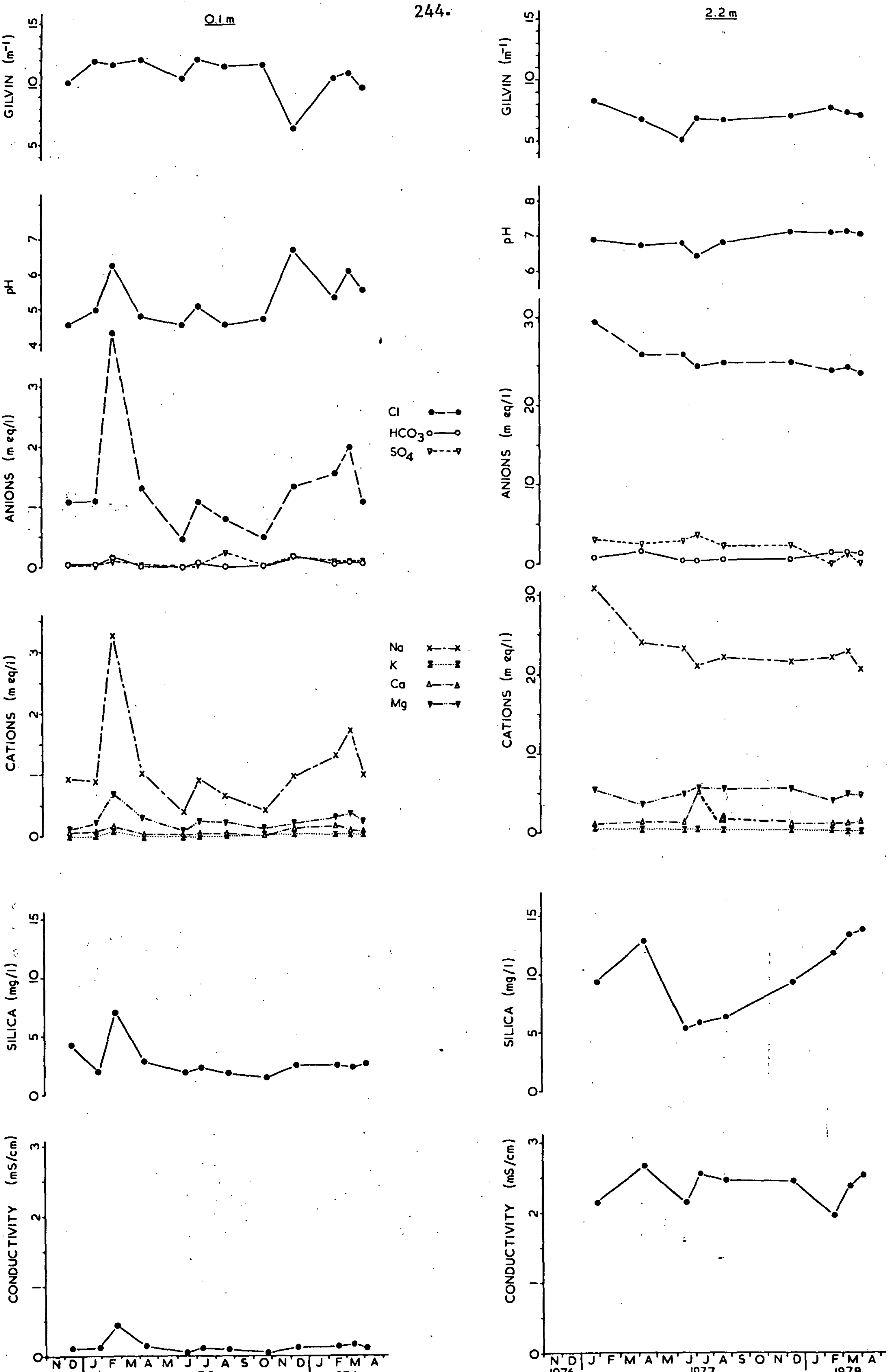

FIGURE 99: TEMPORAL VARIATION OF GILVIN AND MAJOR WATER CHEMISTRY IN SULPHIDE POOL AT 0.1m AND 2.2m DEPTHS

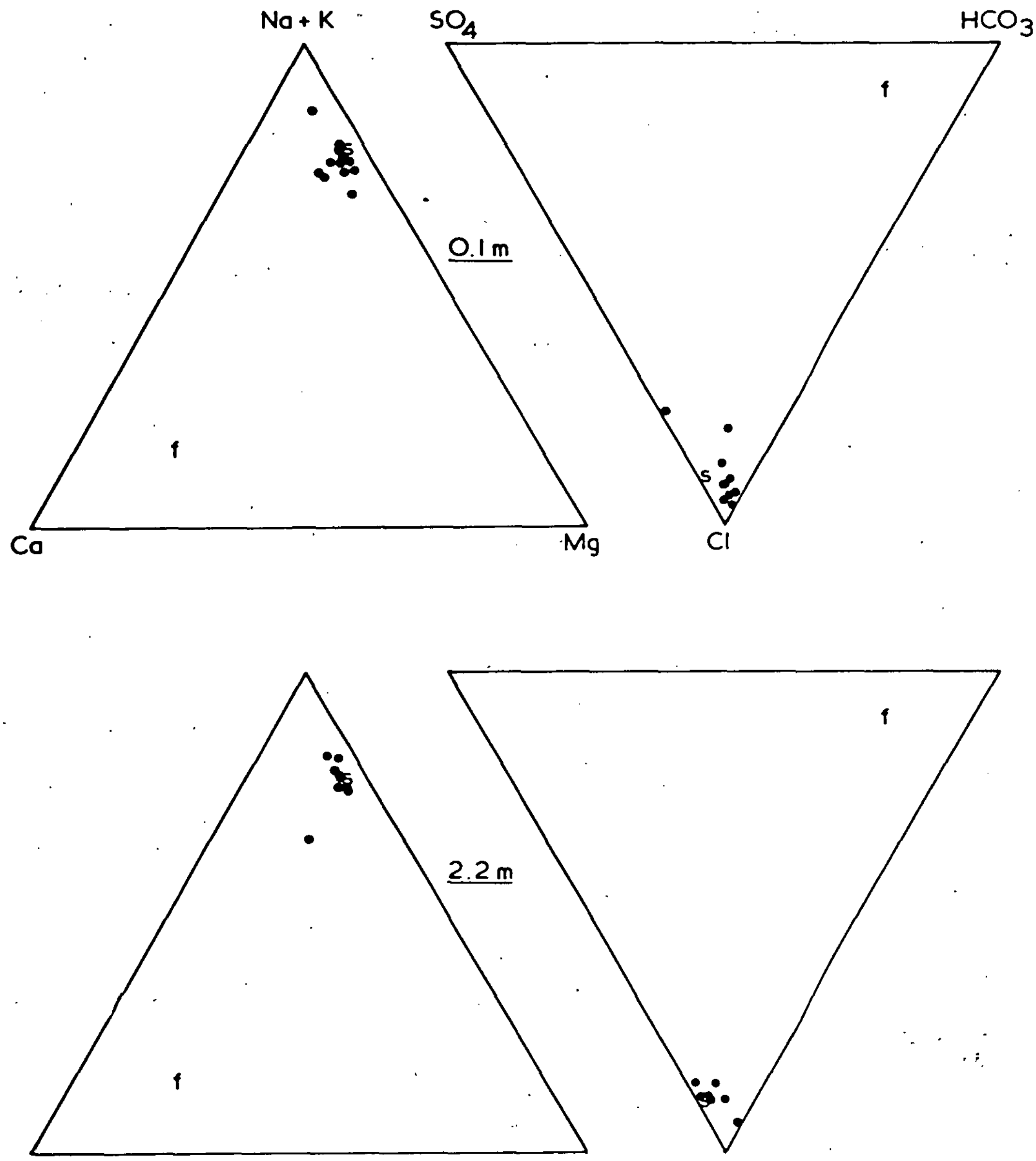

FIGURE 100: IONIC PROPORTIONS IN SULPHIDE POOL. WORLD AVERAGE FRESHWATER (f) AND SEAWATER (s) ARE INCLUDED.

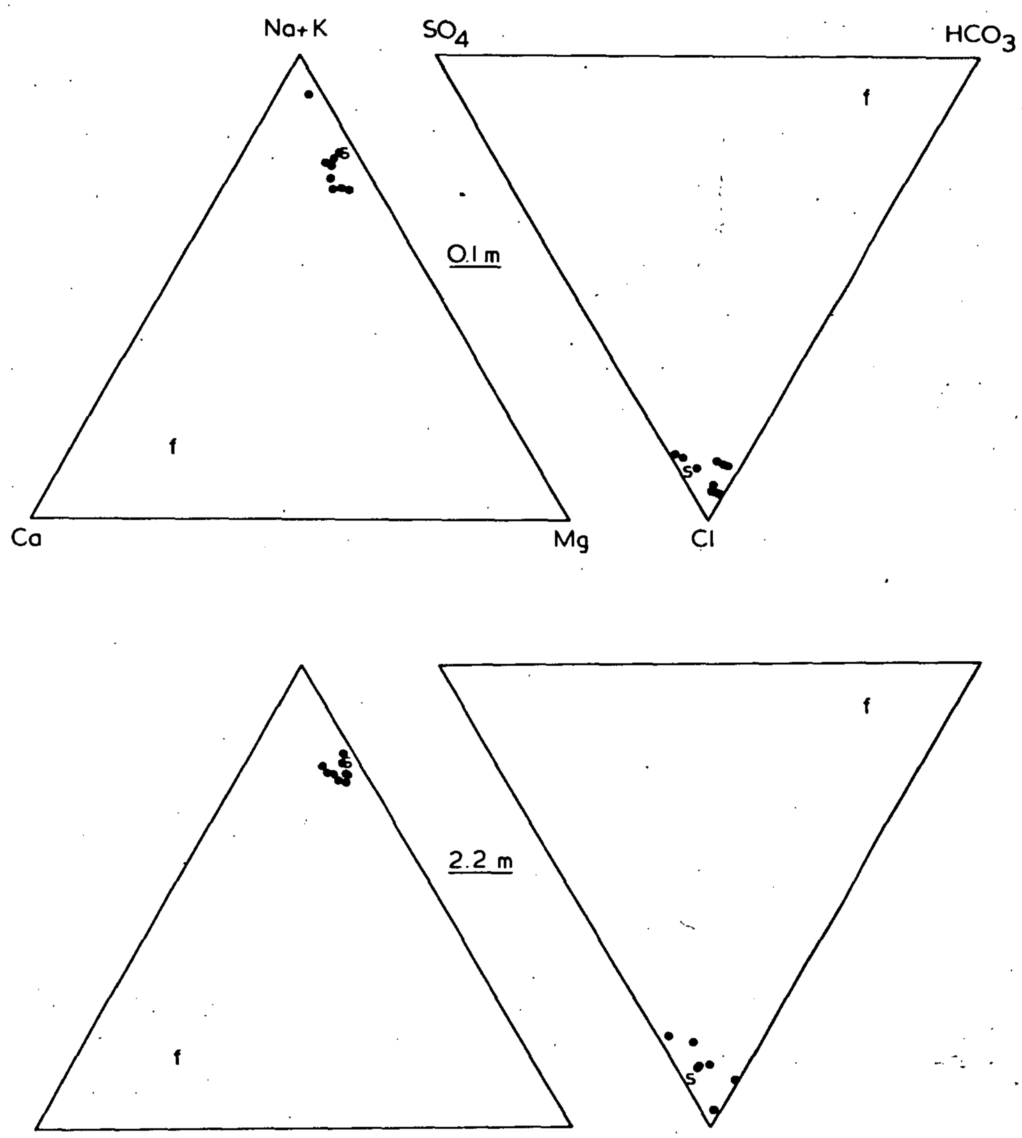

FIGURE 101: IONIC PROPORTIONS IN LAKE MORRISON. WORLD AVERAGE FRESHWATER (f) AND SEAWATER (s) ARE INCLUDED.

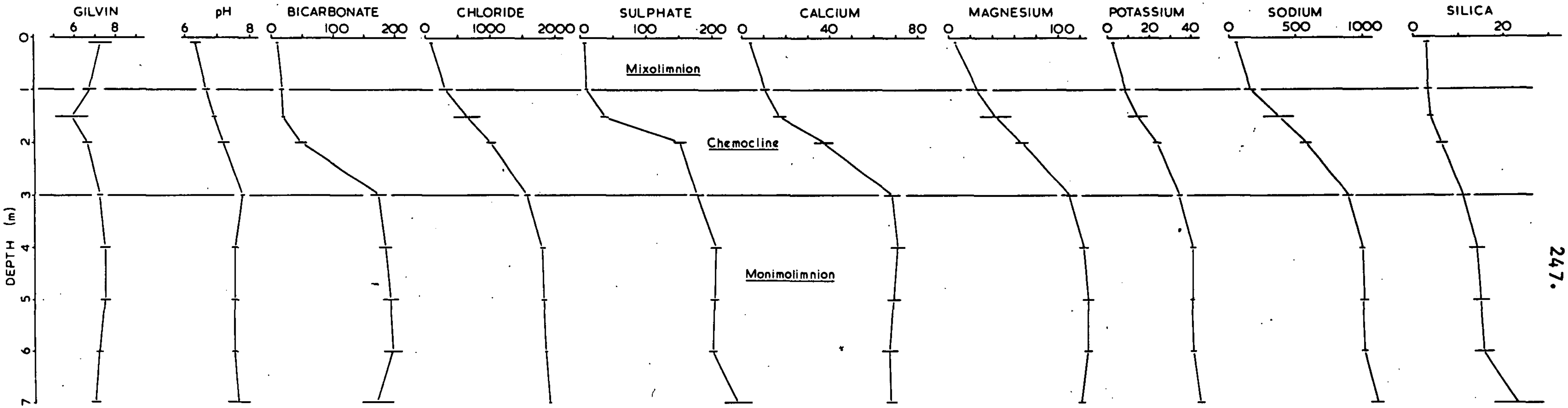

FIGURE 102: DEPTH PROFILES OF GILVIN AND MAJOR CHEMICAL COMPONENTS IN LAKE FIDLER. MEAN VALUES FOR ALL DATA ARE PLOTTED WITH STANDARD DEVIATIONS (HORIZONTAL LINES). (UNITS:— GILVIN M^{-1}, MAJOR IONS AND SILICA MG/1).

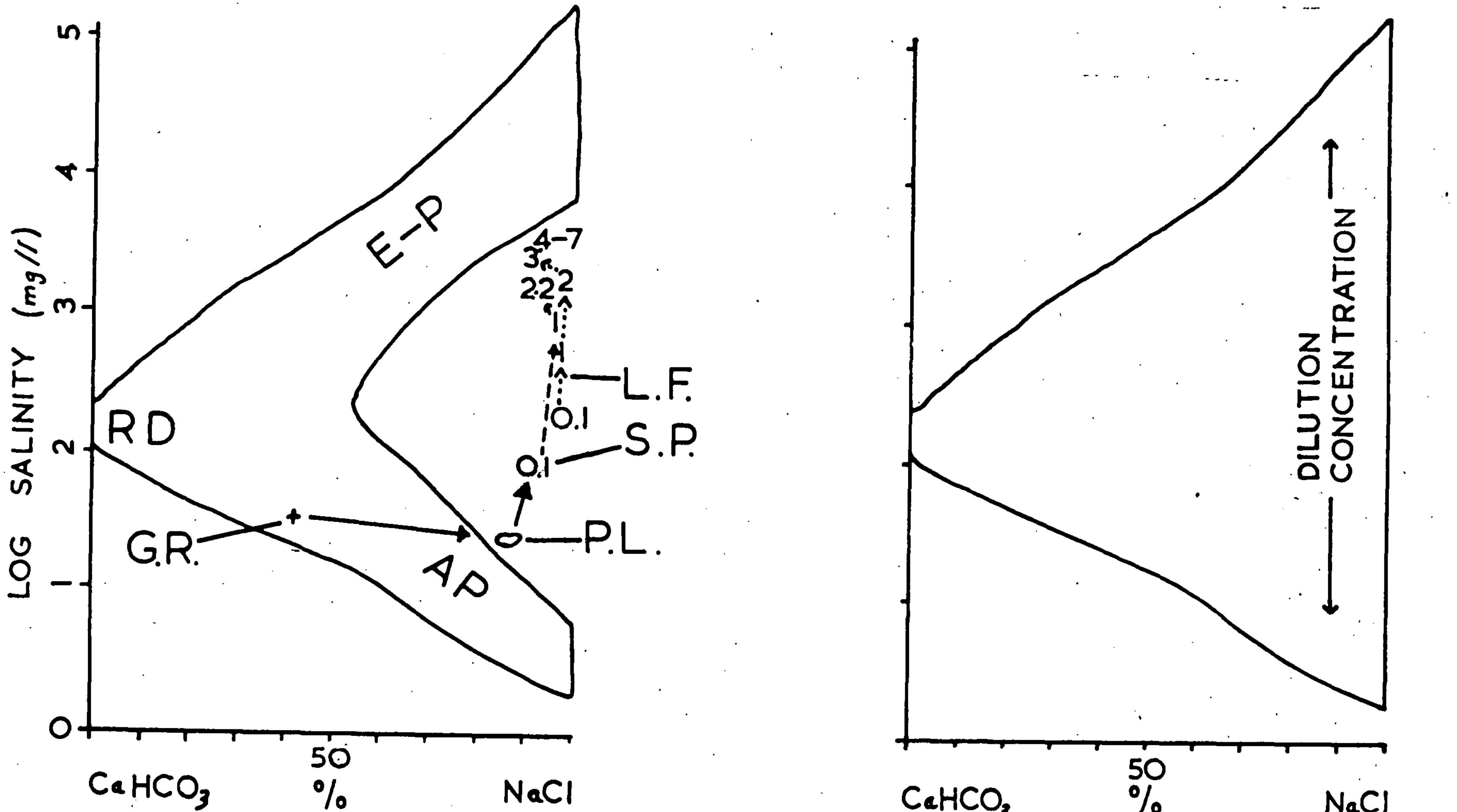

FIGURE 103: PROCESSES CONTROLLING SALINITIES IN THE GORDON RIVER LAKES ACCORDING TO THE MECHANISMS PROPOSED BY GIBBS (1970).

A - Gibbs' 1970 scheme; B - proposed modification; E-P - evaporation-precipitation; RD - rock dominance; AP - atmospheric precipitation; G.R. - Gordon River; P.L. - Perched Lake; S.P. - Sulphide Pool; L.F. - Lake Fidler; figures (e.g. 2.2) are depths in metres below water surface.

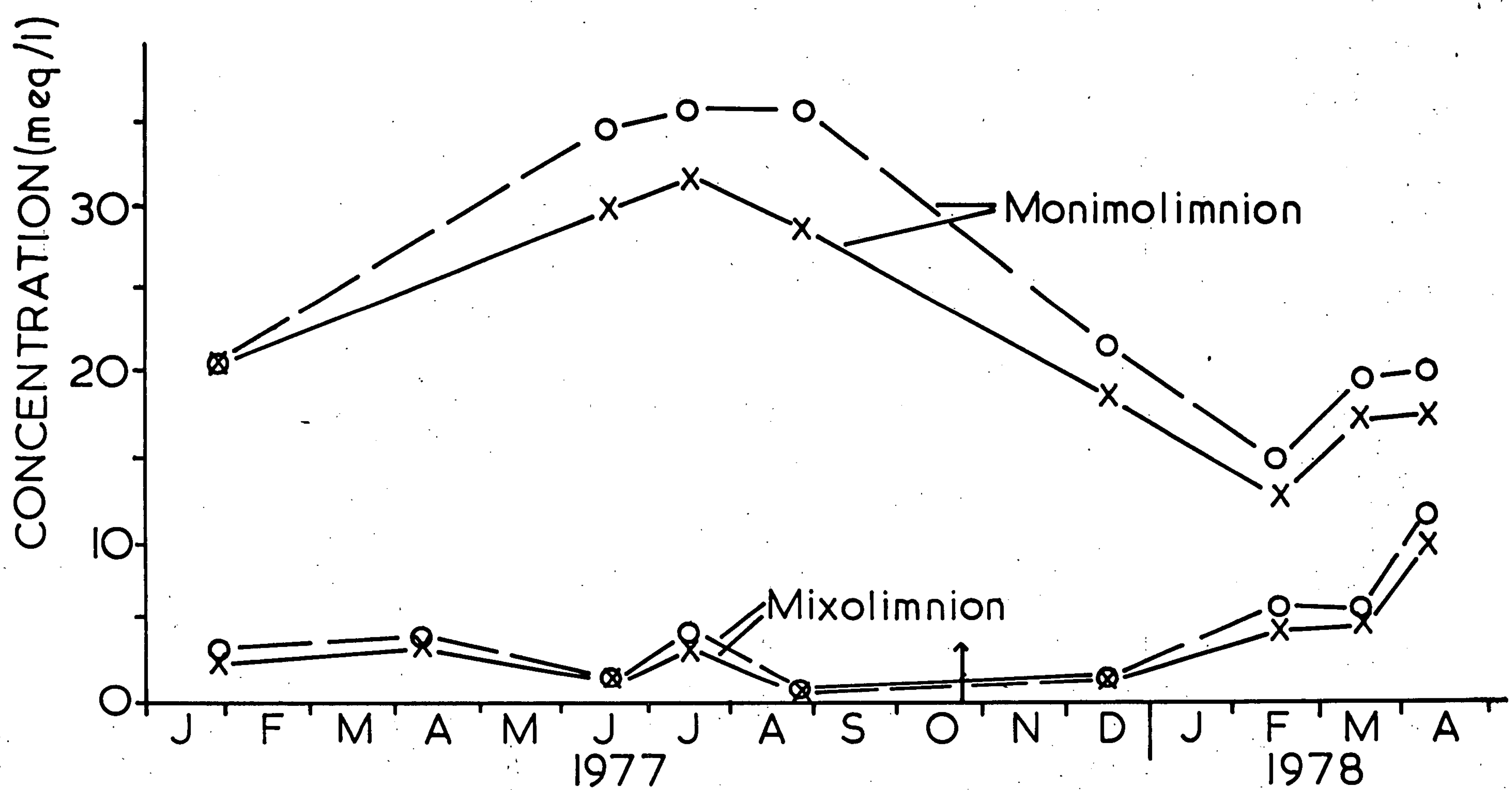

FIGURE 104. SEASONAL VARIATION OF SODIUM (x———x) AND CHLORIDE (o— —o) IN THE MIXOLIMNION (A) AND MONIMOLIMNION (B) IN LAKE MORRISON. MONIMOLIMNETIC SAMPLES WERE COLLECTED JUST ABOVE THE SEDIMENTS. LAKE GORDON BEGAN DISCHARGING IN LATE OCTOBER 1977 (↑).

Concentrations of major ions in the mixolimnion of Lake Morrison after February 1978 have increased significantly above levels recorded during the previous summer (Figure 104) as well as exceeding concentrations recorded in either Lake Fidler or Sulphide Pool (Tables 12, 13 and 14). At the same time chloride and more particularly sodium became considerably less abundant in the monimolimnion than for the same period in 1977. This is strong evidence for the breakdown of the chemocline and consequent mixing of mixolimnetic and monimolimnetic waters. Lake Morrison was last visited on the 6th April, 1978 and was almost isothermal at about 13°C. Dissolved oxygen was recorded down to 2.0 m, and a platypus (*Ornithorhynchus anatinus*) diving in the middle of the lake, was observed for the first time on any of the Gordon River lakes. A sure sign of sweet waters. This, and the increase in sodium chloride in the mixolimnion, indicated a weakening of the meromixis in this lake and the imminence of holomixis.

4.3.4 Conductivity

The meromictic lakes all showed a marked increase in electrolytes with depth, as a result of the accumulation of saline waters in the bottom of the lakes (see also Roberts and Allanson 1977, Bremmeng 1977). The depth from the surface of the upper limit of the monimolimnion varied from lake to lake, in response to Gordon River height fluctuations. In Lake Fidler the lower limit of the mixolimnion occurred between 1 and 2 m depth (Figure 102), while in Sulphide Pool and Lake Morrison the lower limit of the mixolimnion was very much shallower. In Sulphide Pool it occurred between 0.3 m and 1 m (Figure 87) and in Lake Morrison between 0.15 and 1 m depth (Figure 88), and the latter can therefore be considered to maintain a shallower meromictic condition than Vee Pond Alaska which was considered to be the shallowest meromictic lake in the world, with the lower limit of that mixolimnion occurring at 0.5 m to 1.0 m depth (Likens 1962).

Seasonal variation of conductivity with depth in Lake Fidler showed the chemocline lying between 1 and 3 m depth (Figure 102 and 105). Mixolimnetic conductivities were controlled by the admixture of lake water with dilute Gordon River water entering the lake via the inflow/outflow channels, seep inflows (Plates 20 and 21) (see chapter 2 section 6.3) The low surface conductivity during the summer and autumn probably results from minimal inflow of comparatively dilute Gordon River water (King and Tyler 1978a). Prior to October 1977 (when Lake Gordon discharge commenced) and when Gordon River flows were low the "salt wedge" became well established in the river (Kearsley 1978), electrolytes in the surface river waters increased due to wind-induced mixing at the chemocline.

This moderately saline river water would then enter the lake at its particular density level by undercutting surface waters, thereby replenishing monimolimnion salts, and not necessary mixing with surface waters. Slight lowering of mixolimnetic conductivities from July 1977 to December 1977 can be explained by inflow of very dilute river water (Steane and Tyler 1978). But increased mixolimnetic conductivities from late February 1978 onwards are perplexing and no satisfactory explanation can be offered, except to suggest some slight wind induced vertical mixing within the lake. From February onwards when thermal stratification began breaking down, slight vertical mixing into the upper monimolimnion probably accounts for the rise in mixolimnetic conductivity.

Low conductivity in the monimolimnion in January 1977 of Lake Fidler and the return to higher values were perplexing (Figure 105). They could have been due to the inflow of cold, slightly less saline river water than that of the monimolimnion, which undercut the mixolimnion and mixed into the monimolimnion from the lake basin, or flow of dilute water into the basin via groundwater may explain the anomally. Sodium and chloride concentration showed concomitant declines. Dilution is therefore the most likely explanation.

If this were the case one would have to hypothesize a further inflow of more saline water. Similar lowering of monimolimnion conductivities occurred in October 1977, and to a lesser extent in February 1978, and is thought to have been similar to the event in January 1977.

In early February 1977 the average conductivity of the monimolimnion (below 4 m depth) increased rapidly from 3430 mS/cm on the 27th January 1977 to 5470 mS/cm on the 22nd February 1977. This was undoubtedly due to the inflow and mixing of saline river water into the monimolimnion (Figures 99 and 106).

Conductivities in the mixolimnion of Sulphide Pool displayed a regular seasonal pattern (Figure 106) being most concentrated in late summer to early autumn and least concentrated during the winter. This lake has no known connection with the Gordon River, but lake levels rose and fell in response to fluctuations in river level, (personal observation). When the river rose, low lying areas behind the levee bank, including the lake, became inundated, and conductivities of the flood waters were similar to that of dilute river water (Steane and Tyler 1978). Flooding behind the levee banks mostly occurred during the winter months before power station release and occasionally during summer flash floods (Watson 1978). Rainfall would further enhance this seasonal fluctuation. However, after power station discharge commenced areas behind the levee banks were likely to be blooded more frequently, thereby maintaining lower surface conductivities (King and Tyler 1978b). Conductivity increase in the surface waters of

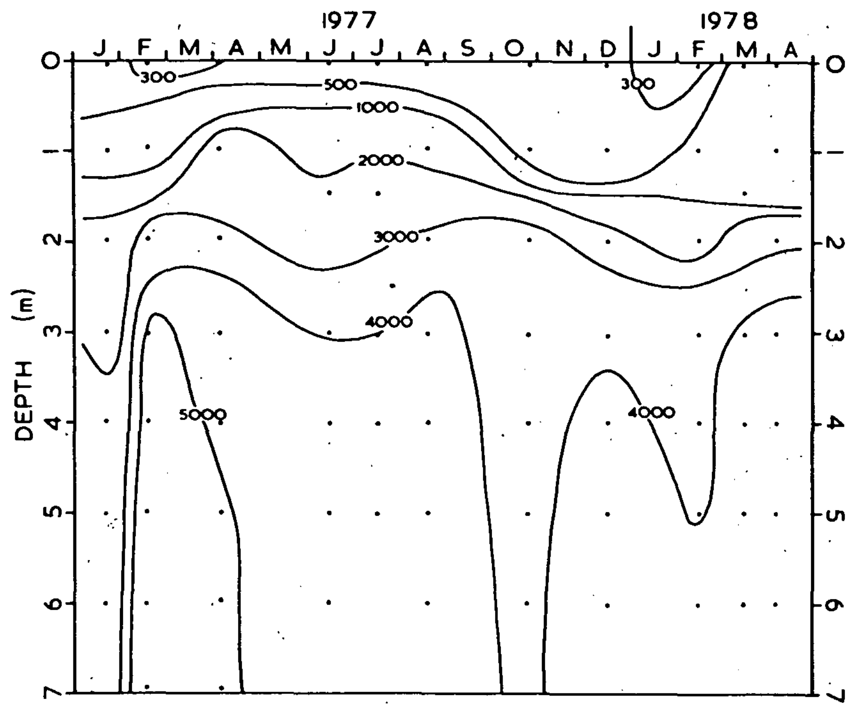

FIGURE 105: CONDUCTIVITY (AT 18°C, μS/cm) ISOPLETHS IN LAKE FIDLER.

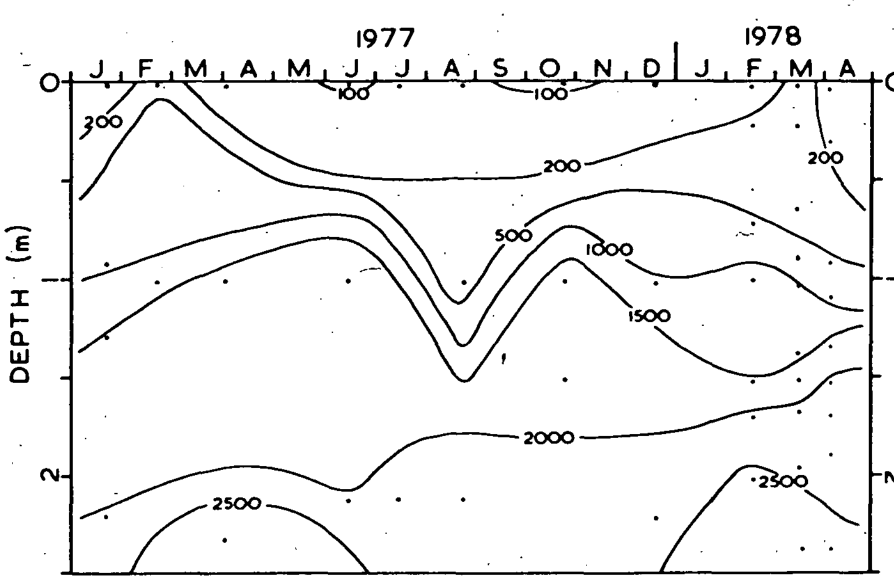

FIGURE 106: CONDUCTIVITY (AT 18°C, μS/cm) ISOPLETHS FOR SULPHIDE POOL.

Sulphide Pool during the summer and autumn would be principally due to evaporation processes when surface temperatures reach their maximum (Figure 75), and when seepage and rainfall were at a minimum (Watson 1978*b*). At this time the mixolimnion was virtually absent, except for the top 20 cm or less, containing low levels of electrolytes (Figure 87). The major conductivity discontinuity in Sulphide Pool occurred at about 1 m depth.

Conductivities in the monimolimnion of Sulphide Pool remained remarkably constant, except for increases just above the sediments during summer and autumn, which coincided with conductivity maxima in surface waters as well as periods of thermal stratification (Figure 76) and sulphide release from the sediments.

The limited data for Lake Morrison (Table 14) suggests that considerable seasonal variation in conductivity occurred. A marked increase with depth in electrolytes was observed prior to October 1977 (Figure 88), but after commencement of discharge from Lake Gordon (November 1977) the chemocline became less pronounced as electrolytes in the mixolimnion increased and those of the monimolimnion decreased (See Figure 104). Due to the reduced salt input from the river, the intense chemical stratification was eroded by wind action, and the lake began evolving towards holomixis. Meromixis could well become re-established in Lake Morrison should the power station discharge policy of the H.E.C. change and the salt wedge from Macquarie Harbour again be permitted to penetrate up the river, and thus replenished salts to this lake.

4.3.5 Silica

The silica cycle has been discussed by Hutchinson (1957) and Wetzel (1975), and information on the occurrence of silica in south west Tasmania presented by Buckney and Tyler (1973 a & b) and King and Tyler (1978 a & b). Seasonal depth distribution of silica in Lake Fidler is presented in Table 12, for Sulphide Pool in Table 13, and for Lake Morrison in Table 14.

In all three meromictic lakes silica increases markedly with depth (see also Culver 1975), in a similar manner to the major ions (Figure 107).

Silica enters Lakes Fidler and Morrison from the Gordon River, but the major contribution is from seepage and creek inflows (Table 15).

Table 15: Mean and Ranges of silica in the Gordon River in Lake Fidler inflows and in the surface waters of the meromictic lakes.

	Silica (mg/l)
Gordon River at Butler Island camp	3.0 (8.7 - 2.1)
Gordon River at Tuan Gabby Flats	2.2 (2.6 - 1.9)
Lake Fidler Inflow 1	4.9 (12.5 - 2.1)
Lake Fidler Inflow 2	4.6 (14.5 - 1.7)
Lake Fidler (0.1 m)	3.1 (8.9 - 1.2)
Lake Morrison (0.1 m)	3.7 (9.5 - 1.9)
Sulphide Pool (0.1 m)	2.9 (7.1 - 1.5)

Seasonal variation of silica in Lake Fidler was slight except for the large, unexplained increase at all depths in February 1977. One possibility is the release of silica from the sediments (Hutchinson 1957), which Mortimer (1941-1942 cited in Hutchinson 1957) suggests is at least partly controlled by redox potential, because silica becomes highly soluble under strongly reducing conditions. This is probably not so in this case (February 1977) in Lake Fidler because at other times of the year when redox potentials were just as low, similar monimolimnetic silica increases were not observed and could be due to analytical error.

Silica increases in the bottom waters of Sulphide Pool, and below 4 m depth in Lake Fidler after February 1977, are almost certainly derived from the sediments. Yoshimura (cited in Hutchinson 1957) recorded silica increases in the hypolimnion of Takasuka-numa, Japan, during summer stratification and attributed this silica increase to slow diffusion from the sediments. Silica increased in the bottom of the Gordon River lakes when monimolimnetic temperatures increased (Figure 84, Hutchinson 1957). According to Tessenow (1966, 1970 cited in Wetzel 1975), silica concentrations in the interstitial waters of sediments increase with rising temperatures and when pH values fall below 7, resulting in increased silica input to a lake. In Sulphide Pool the temperature of the bottom water, and hence the sediments, fluctuated from 9.7°C in the winter to 14.8°C in the summer. When the sediments warmed, sulphide concentration increased silica solubility (Figure 82). Apparently sulphide gas was released from the sediments to the lake (Figure 82).

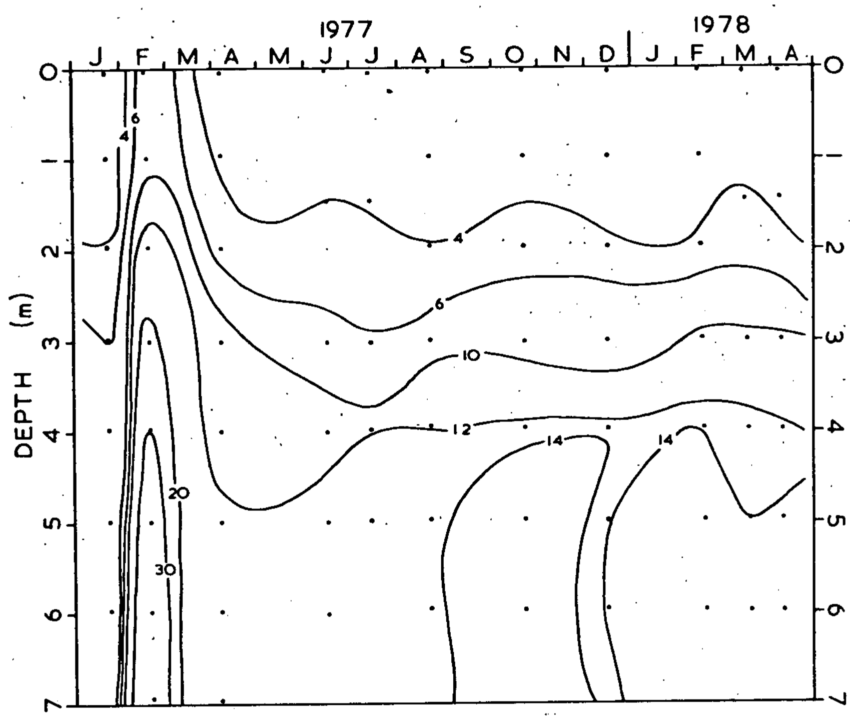

FIGURE 107. DISSOLVED SILICA (mg/1) ISOPLETHS IN LAKE FIDLER.

When lake waters and presumably the sediments of Sulphide Pool began to cool in the winter, both silica and sulphides decreased in the bottom waters. As temperature and sulphide decreased so did photosynthetic pigments (compare Figures 84 and 110). It is tempting to suppose that as temperatures decline so does the population of sulphate reducing bacteria and consequently so does the hydrogen donor of photosynthetic bacteria with consequent decline in their populations. However, light levels are so low (see Section 4.4) that one must doubt whether photosynthesis can even occur at these depths. Though the seasonal pattern of silica was very similar to that of total dissolved sulphides, silica-consuming organisms have not been recorded from the monimolimnion (Figure 84). However, the reduction of silica levels in winter below the euphotic zone could be due to absorption of silica on to dead cells from above the sediments (Tessenow 1970 cited in Wetzel 1975).

Limited data from Lake Morrison indicates that in that lake some other mechanism controlled monimolimnetic silica concentration, for silica maxima occurred during the winter when temperatures were low. The erratic nature of this data may be due to oxygen being recorded down to the bottom on occasions even when chemical stratification would normally resist complete mixing (see Section 4.2 and 4.3).

4.3.6 Iron and Manganese

Iron and particularly manganese concentrations were low in the oxygenated mixolimnetic waters of all three lakes (Table 16) (a feature noted by Einsele (1940) for oxygenated mixolimnia of other meromictic lakes), partly because of its lithological scarcity in the area (e.g. Rao and Naqvi 1977, Buckney and Tyler 1973 a and b), and partly because of the insolubility of ferric salts in oxygenated waters. What iron was present was mostly in the particulate or colloidal form, or complexed with organic matter (Wetzel 1975).

Though manganese is considerably more soluble than iron, its chemical reactions are similar, according with the pH and the oxygenation of the water (Wetzel 1975). Concentrations of both iron and manganese were also low in the monimolimnia of the Gordon lakes (Table 16) and have to be compared with levels in meromictic lakes elsewhere (Table 17).

This lack of accumulation of iron or manganese in the monimolimnia of the Gordon River lakes is in contrast to many other meromictic lakes (Table 17), and suggests that these lakes are not of the biogenic type, but rather of the crenogenic type. A very sharp drop in redox

TABLE 16: Ranges of Fe and Mn in mg/1 in South-West Tasmania.

	Fe		Mn	
	Mixo-limnion	Monimo-limnion	Mixo-limnion	Monimo-limnion
Lake Fidler	0.29	- 0.04	0.22	- trace
Lake Morrison	0.54	- 0.26	trace	
Sulphide Pool	0.56	- 0.33	trace	
Lake Gordon (1)	0.2	- 0.5	0.02	- 0.05
Lake Pedder area (2)	0.6	- 0.05	trace	
Gordon River (3)	1.5	- 0.13	0.11	- <0.01

(1) Steane and Tyler 1978
(2) Buckney and Tyler 1973
(3) King and H.E.C. 1978

TABLE 17: Range of concentrations of iron and manganese in the mixolimnion and monimolimnion of the Gordon River Lakes and various other meromictic lakes.

	Fe		Mn	
	A	B	A	B
Sunfish Lake (Duthie & Carter 1970)	trace	0.03	0.01	2.54
Lake Strandvatn (Bremming 1974)	0	0.7	0	0.3
Lake Mary (Weimer & Lee 1973)	0.44	0.80	-	
Store Tryvatn (Kjensmo 1967)	0.06	0.65	0.01	0.88
Lake Vingersjöen (Kjensmo 1965)	<0.01	10.08	<0.01	3.4
Lake Svinsjøen (Kjensmo 1968)	0.15	18.8	0.03	4.9
Lake Skjennungen (Kjensmo 1962)	0.49	33.0	0.40	3.4
Lake Barrington (Tyler & Buckney 1974)	<1.0	58.0	<1.0	11.5
Lake Store Aaklungen (Kjensmo 1962)	0.02	291.0	0.01	4.8
Gordon River Lakes	0.56	0.33	0.22	trace

A: mixolimnion

B: monimolimnion

TABLE 18: Soluble Iron and manganese in Lake Fidler, measured on 7th April, 1977 (mg/1).

Depth (m)	Fe	Mn
2.0	0.19	0.22
2.5	0.19	0.13
6.5	0.05	0.04

potential and an associated increase in pH between the oxygenated surface waters and anoxic bottom waters containing high dissolved sulphides is likely to have caused iron to precipitate as monovalent sulphides, and remain fixed in the sediments.

Metal sulphides are exceedingly insoluble at neutral to alkaline pH values (Wetzel 1975), and Fe^{2+} reacts vigorously with H_2S to form FeS which is precipitated. According to Wetzel (1975) anaerobic monimolimnia must be acidic before appreciable H_2S can accumulate, but if the water is alkaline then H_2S will only accumulate after most of the Fe^{2+} has precipitated as FeS. This was probably the process operating in the Gordon River lakes where the monimolimnion was neutral to basic.

Manganese is more soluble in oxygenated waters than iron, and exists in the divalent form as stable complexes with bicarbonate, sulphate and organic molecules (Wetzel 1975). On a world average manganese is 50 x less abundant than iron and the low levels in the surface waters of the Gordon River basin reflect its geological scarcity (Wetzel 1975).

In comparison with the insolubility of ferrous sulphide formed in the presence of high concentrations of H_2S, the sulphide of manganese is relatively soluble (Wetzel 1975). Hydrogen sulphide production thus does not affect the manganese concentration under normal lake conditions. However, the solubility of manganese is limited in alkaline waters by the formation of the insoluble carbonate.

Thus particulate allochthonous manganese, sedimenting from acidic oxygenated mixolimnia to anoxic monimolimnia where the pH increases, precipitates, and becomes locked in the sediments. This probably explains the decrease in manganese with depth which was apparent in Lake Fidler (Table 18). However, the occurrence of manganese and iron was largely governed by the limited supply of these two metals to the lakes.

4.3.7 Redox potentials

Redox potentials were measured in situ using a platinum electrode on close interval samples, from January to December 1977, after which readings were considered to be unreliable and are therefore not presented in Figures 86, 87 and 88. This uncertainty of field redox measurements has therefore not permitted me to place great emphasis on actual values, but rather to use these measurements to indicate the dramatic change in the oxic state of the lake waters with depth. The activity of hydroxyl ions influenced the activity of the hydrogen ion, which in turn significantly changed the redox potentials (Wetzel 1975). In Figures 86, 87 and 88, redox potentials have been expressed as their activities at pH = 7, which allows for the change in redox at the sample pH to that at pH = 7, E_7. (See Wetzel 1975 and Golterman 1967).

Many meromictic lakes display a significant fall in redox potential in the region of the upper monimolimnion (Allgeier et al 1941, Hutchinson 1957), as do all three Gordon River lakes (Figures 86, 87 and 88). Inflows of dissolved organic matter into lakes introduces large amounts of reducing material which lowers pH, oxygen and redox potential in the surface waters (Visser 1964), e.g. Gordon River lakes and some meromictic lakes of eastern Norway (Kjensmo 1970).

Associated with the rapid drop in redox in the Gordon River meromictic lakes (Figures 86, 87 and 88) was a marked increase in pH, probably due to the rapid increase of biologically produced bi-carbonate from the "plate" at this depth (Figures 109 and 110). Weimer and Lee (1973) noted a similar bicarbonate increase with depth in Lake Mary, which they attributed to anaerobic decomposition of organic material. In Sulphide Pool this positive heterograde distribution of pH was less apparent even though a substantial "plate" was recorded in the monimolimnion (Figure 110), rather, pH increased gradually with depth from the acidic surface waters (pH = 3.8 to 5.6) to about the depth when redox decreased sharply, thereafter varying minimally in these more buffered bottom waters (pH = 6.0 to 7.1). However, in this lake there was not always an increase in pH when redox decreased, and when these two events were recorded they did not always occur at the same depth. No explanation is obvious except to suggest disturbances of the water column by the sampling apparatus. Sometimes in Lake Morrison the positive heterograde pH "bulge" occurred with the rapid fall in redox in the upper monimolimnion, and sometimes pH showed little variation from top to bottom even when the plate was well developed (e.g. 16th March 1978 - Figure 88).

In the Gordon River lakes when redox potential did decrease rapidly with depth it did so at depths just below the main oxygen decrease (Figures 86, 87 and 88). Redox remained relatively constant down to just below this depth, then decreased very rapidly in the upper monimolimnion. Low redox potentials then remained relatively constant to the bottom. In all three lakes minor variations in the redox profiles are thought to be the result of disturbance of the intensely stratified water columns by the sampling apparatus, or instrumental deficiencies rather than some real event.

Redox potentials of surface waters of Lake Fidler and Sulphide Pool were lower than theoretical oxygen potentials of about 0.5 volts (Hutchinson 1957). Higher redox potentials were recorded in the surface waters of Lake Morrison, values of 0.5 volts being similar to those in some oligotrophic and meromictic lakes in Norway (Kjensmo 1970). Kjensmo (1970) suggests that low redox potentials are associated with the presence of large quantities of reducing organic substances, and Visser (1964) found that humic acids extracted from *Sphagnum* bogs produced redox potentials between 0.32 and 0.38 volts. Mixolimnetic redox potentials in Lake Fidler and Sulphide Pool were mostly between 0.2 and 0.3 volts, and occasionally fell below 0.2 volts. There was no obvious relationship between redox and dissolved organic material (measured as gilvin - G440) in the Gordon River lakes. The lower mixolimnetic redox potentials in Lake Fidler than in Lake Morrison were not surprising because the former contains lower levels of dissolved organic matter than the latter, which should allow greater redox potentials to occur. There may well be other organic fractions which do not impart colour to the water, but which are readily reduced.

4.3.8 Phosphorus

Phosphorus is a rare element in the surface waters of Tasmania and is virtually undetectable in the Gordon River basin. Small amounts of organically bound phosphorus are imported from the catchments to the Gordon River meromictic lakes. Most of the phosphorus in the surface waters of these lakes is not in the ortho-phosphate form and therefore not directly available to phytoplankton (Figure 108). Frey (1967) reports similar low nutrient input to meromictic lakes near Syracuse which have low mixolimnetic production, a feature common to most meromictic lakes (Kuznetsov 1959, Kjensmo 1967, Weimer and Lee 1973). Fairly large algal populations have been recorded in meromictic lakes where orthophosphate occurs in sufficiently high concentrations in the mixolimnion to sustain a large population (Duthie and Carter 1969 - Sunfish Lake).

The monimolimnia of some meromictic lakes act as efficient nutrient traps (Anderson 1958, Kuznetsov 1959, Sorokin 1970, 1972), and large amounts of phosphorus, mostly in the ortho form, occur in the monimolimnia of all three Gordon River lakes (Figure 108), probably as a result of restricted interchange between surface and monimolimnetic waters, consequently the mixolimnia contain limited populations of phytoplankton. However, input of saline water from the Gordon River could cause some mixing at the chemocline allowing limited amounts of phosphate to enter the photic zone. Although no mixolimnetic algal blooms were recorded, occasional increases in algal biomass could well have been caused by phosphate release from the monimolimnion (e.g. Sulphide Pool on the 30th January 1977 and 14th March 1978, and Lake Fidler on the 15th March 1978, Figures 109 and 110).

In the mixolimnion most of the phosphorus was organically bound and not directly available to algae, while in the monimolimnion the mineralisation of settling particulate organic matter caused most of the phosphorus to occur in the orthophosphate form (Weimer and Lee 1973), and this could be available to primary consumers. The plates occurred at the upper edge of the monimolimnion where phosphate was sufficiently plentiful not to limit growth. Limited information on the Gordon Lakes suggests that high monimolimnetic phosphorus levels were present as orthophosphate all year round. The discrepancy between total phosphorus and orthophosphate in Lake Fidler on the 25th August, 1977 is most probably due to a "raining down of bodies" when the concentration of the plate decreased. Due to chemical stratification and absence of mixing, the rate of descent of the particles would be very slow and therefore a significant amount of the total phosphorus would be organically bound. Alternatively, increased allochthonous organic inputs to the lakes in winter would allow particulate material to enter the monimolimnion.

Iron appears to be particularly important to the occurrence of large amounts of phosphate in the monimolimnion of meromictic lakes (Ohle 1938, cited in Kjensmo 1967). Kjensmo (1967) reports very low orthophosphate concentrations from several softwater, high iron meromictic lakes in Norway. High iron content suggests that phosphate is adsorbed to ferric hydroxide and precipitated. Slight increases in phosphate in the bottom of the monimolimnion during summer stratification was probably due to release from the sediments when ferric iron was reduced (Kjensmo 1967).

In contrast, some non-iron meromictic lakes contain large amounts of phosphate in their monimolimnia. In Sunfish Lake, Ontario, phosphate increases from 10 - 50 µg/l in the surface waters to 400 - 1200 µg/l at the bottom (Carter 1967). Similarly, low iron in the Gordon lakes permits phosphate to remain in solution and not to become adsorbed and fixed into the sediments. Even so, due to the inability of this phosphate to circulate into the mixolimnion, the Gordon River meromictic lakes are only able to sustain low mixolimnial productivity.

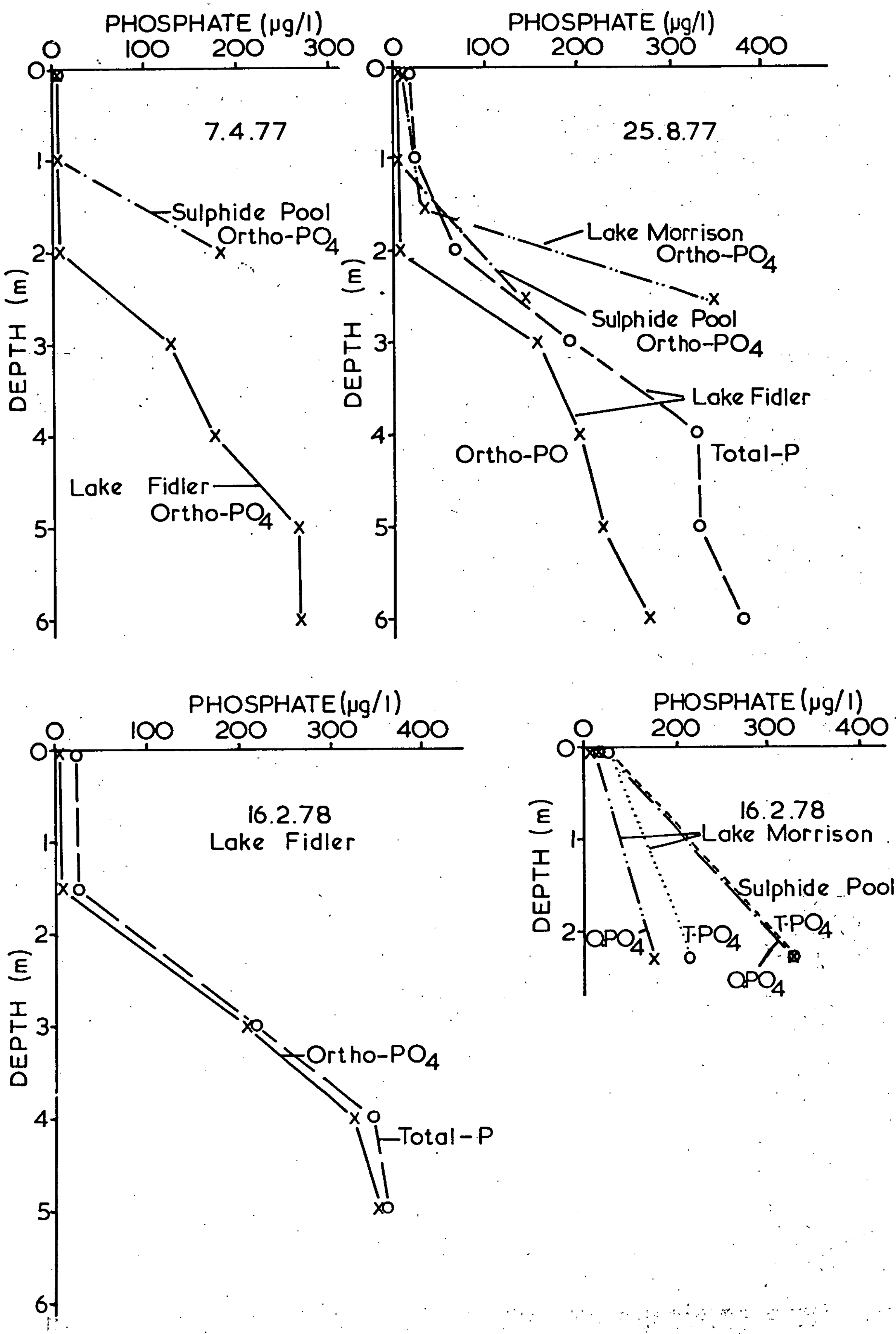

FIGURE 108: DEPTH DISTRIBUTION OF ORTHO-PHOSPHATE AND TOTAL PHOSPHORUS IN THE GORDON RIVER LAKES, MEASURED AT VARIOUS STAGES OF THE STUDY.

4.3.9 Phytoplankton Biomass and the Bacterial plate

Meromictic lakes are not biologically unique, and the same processes occur in them as in holomictic lakes, but due to their incomplete circulation patterns, spectacular results are evident (Frey 1967). Meromictic lakes are generally considered unproductive systems due to their inability to circulate nutrients trapped in the bottom waters, upwards into the photic zone (Findenegg 1932, 1935). In the Gordon lakes, large quantities of phosphorus exist in the monimolimnion (see Section 4.3.8), but complete circulation is inhibited by the salt gradient present all year round, therefore limiting mixolimnetic productivity. Nutrients entering most meromictic lakes are bound up in some way (organically or on clay particles) and pass through the illuminated zone of the lake, becoming trapped in the bottom waters where decomposition processes release them for utilization by anaerobic sulphur bacteria.

In the Gordon River lakes phytoplankton production is further limited by marked attenuation of downwelling PAR by dissolved organic substances (see Section 4.4.1b). What nutrients are available are not efficiently utilized, except perhaps in the uppermost layers. These very dark water lakes contrast sharply with clear meromictic lakes. The monimolimnion of Hot Lake contains significant amounts of magnesium sulphate and hydrogen sulphide, and a layer of green sulphur bacteria in its upper layers, and because of the clarity of the water a mat of blue-green algae occurs on the bottom (Anderson 1958). In the Gordon lakes PAR in the region of the plate is undetectable.

The scope of this project did not allow for a detailed investigaiion of the plankton, due mainly to the complexity of the population forming the plate (discussed below), which would comprise a separate study requiring special techniques. Some observations have been made on net haul plankton from upper layers, and on close interval samples for lower layers. Net haul samples essentially exclude nannoplankters which pass through the net, therefore these samples indicate presence only of organisms and do not necessarily imply absence of a particular species from the lake, also rare organisms in these samples could be contaminants from previous samples.

The temporal distributions of phytoplankton biomass (methanol extractable pigments) in Lake Fidler and Sulphide Pool are presented in Figures 109 and 110 respectively, and depth profiles of biomass and turbidity for Lake Fidler, Sulphide Pool and Lake Morrison in Figures 86, 87 and 88 respectively.

Algal biomass in the mixolimnia of Lakes Fidler and Morrison was extremely low, with larger populations recorded from Sulphide Pool (probably the most productive lake of the three). Occasionally algal populations were recorded in the photic zones of these lakes, mostly in the summer. As close interval sampling was not always concentrated in this region of the lakes, many populations may have been missed, for they were far less spectacular than the bacterial populations below.

Examples of these mixolimnetic populations were most pronounced in Sulphide Pool in January and February 1977, when *Mallomonas* sp was very abundant, and to a lesser extent *Euglena acus* Ehrenb. This species of *Mallomonas* occurs in Perched Lake (see Section 6 chapter 3) and in other west coast dystrophic lakes and lagoons, while *Euglena acus* occurs in the meromictic lakes and very sparsely in Gordon Lagoon, and is not recorded from the other dystrophic sites in Tasmania. These two species were also abundant in the mixolimnion of Sulphide Pool in December 1977 and March 1978, and probably dominated the sparse phytoplankton at other times of the year. Phytoplankton of this lake was also more diverse than in either Lake Fidler or Morrison, with a wide array of desmids and to a lesser extent diatoms, evident.

Phytoplankton of Lake Fidler was depauperate and only insignificant photic zone (see Bindlers 1976) blooms were recorded. A noticeable population of the diatom *Rhizosolenia eriensis* H.L. Smith occured in March 1978 at a depth of 0.1 to 0.3 m. Extremely small surface populations were recorded from February to July 1977, and in December 1977, the most frequent organisms were *Mallomonas* sp., *Phacus* sp. and *Trachelomonas* sp., with *Rhizosolenia eriensis* also being recorded. As in Sulphide Pool and Perched Lake many desmids and diatoms were observed though none in significant numbers.

Phytoplankton biomass was virtually absent from the mixolimnion of Lake Morrison except for a small population which occurred at about 1 m depth in February and March 1978 (Figure 88), but unfortunately no samples for microscopic examination exist. Again species diversity of diatoms and to a lesser extent desmids were high and numbers low. Several unusual species of *Dinobryon* were observed, but these were attached to detritus and probably not true plankters.

Turbidity profiles presented in Figures 86, 87 and 88 often indicate additional layers of particulate matter, but no great emphasis can be placed on these data, as the method of measurement is not very reliable at low values, and could also be influenced by sporadic inputs of particulate material from the inflows. In many cases turbidity corresponds closely to chlorophyll data, and in many cases it does not, suggesting that the microbiology of these lakes could be more complex than presently thought. It cannot be stated with any certainty that where turbidity appears to be in excess of chlorophyll, populations of non-pigmented bacteria occur.

The most striking biological feature of these lakes is the large increase in pigmented organisms in the region of the chemocline, known as the "bacterial plate" (or "plate"), a feature common to many meromictic lakes (see Anderson 1958, Kuznetsov 1959, Kjensmo 1965, Frey 1967, Northcote and Halsey 1969, Duthie and Carter 1970, Sorokin 1970, and Sorokin and Donato 1975). This plate is most spectacular in Lake Fidler (Figures 86 and 109), due principally to this lake being the deepest of the three. In Sulphide Pool and Lake Morrison the Lower regions of the plate are in contact with the sediments, and biomass does not decrease markedly from plate maxima to very low levels, recorded from the bottom waters of Lake Fidler; however, biomass does decrease from the plate maxima down to the muds.

In both Lake Fidler and Sulphide Pool the plate population displays a definite seasonal pattern (Figures 109 and 110), and is apparently intimately related to thermal patterns (Figures 74 and 78). The plate organisms wax with the breakdown of inverse stratification in winter, and numbers increase rapidly once monimolimnetic waters start warming. Plate biomass reached a maximum in late summer - early autumn, when stratification was intense. As the lakes started cooling and thermal stratification started breaking down, so too the plate populations waned. This pattern is particularly clear in Lake Fidler (Figure 109). However, in Sulphide Pool the plate maxima were not as narrowly defined depthwise as in Lake Fidler, and two maxima were recorded in the second warm period.

The plate organisms have not been completely identified. In Lake Fidler it appears to be composed of distinct layers. The upper layer consists principally of *Cryptomonas* sp. and a minute green flagellate (Plate 27).where D.O. is very low, with a transition zone of *Cryptomonas* sp. and purple sulphur bacteria (e.g. *Cromatium* and/or *Achromatium*) below at the oxic-anoxic zone. Green sulphur bacteria occur below these in the anaerobic upper monimolimnion. A similarly constituted plate has been recorded from Lake Bolovod (Kuznetsov 1959, Sorokin 1970).

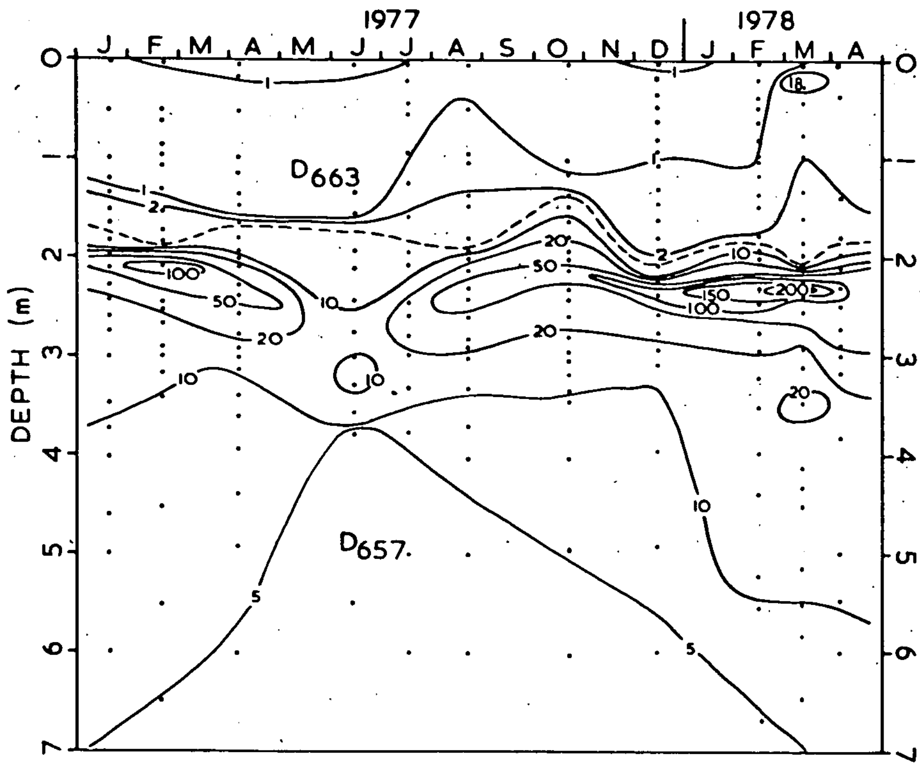

FIGURE 109: PHOTOSYNTHETIC PIGMENTS (μg/l) ISOPLETHS FOR LAKE FIDLER. ABOVE THE BROKEN LINE (- - -) ABSORPTION MAXIMUM IS AT 663 nm, AND BELOW AT 657 nm.

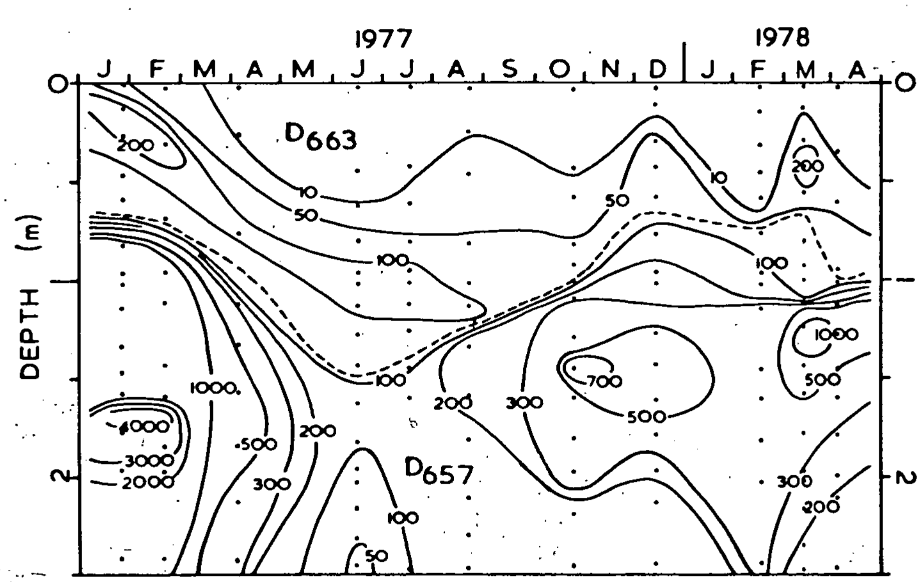

FIGURE 110: PHOTOSYNTHETIC PIGMENT (μg/l) ISOPLETHS FOR SULPHIDE POOL. ABOVE THE BROKEN LINE (- - -) ABSORPTION MAXIMUM IS AT 663 nm, AND BELOW AT 657 nm.

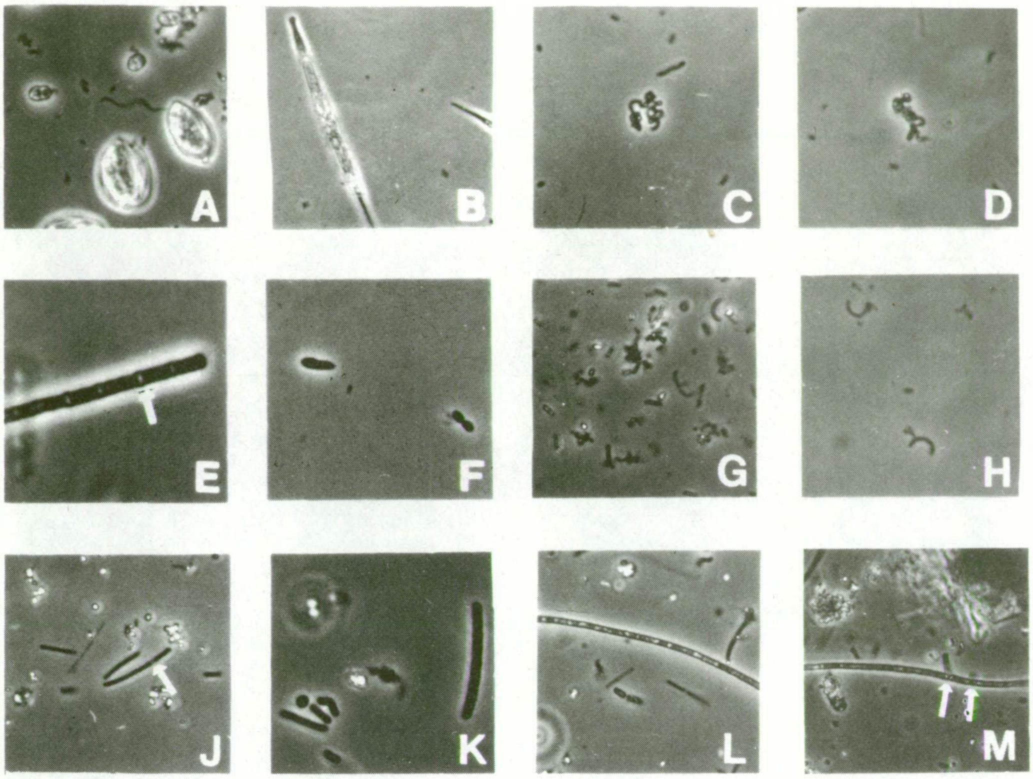

PLATE 27: PHOTOMICROGRAPHS OF SESTON FROM THE GORDON RIVER LAKES.

A. Cryptomonas and the minute green flagellate from the upper regions of the plate in Lake Morrison.

B. Euglena acus.

C & D. Tightly coiled bacterial filaments from the lower regions of the plate in Lake Fidler.

E. Filament showing cellular differentiation and heterocyst-like structures (↑) from Lake Fidler.

F. Bacterial budding, plate, Sulphide Pool.

G. Bacteria of various lengths from the upper plate in Sulphide Pool.

H. Spiralled bacteria from Sulphide Pool.

J. Straight dense bacterial trichomes from below the plate in Lake Fidler, arrow (↑) indicates possible cell division.

K. Large dense bacterial filaments of various lengths from below the plate in Lake Fidler.

L. Long bacterial trichome containing refractive particles (possibly sulphur), with slightly irregular walls, below the plate in Lake Fidler.

M. Same as L above, arrow indicates cross walls and possible trichome division.

Intermingled with these are various other bacterial forms, some of which possess vacuole-like structures typical of the Cyanophyceae (Plate 27). Some trichomes possess cross-walls, and others are short rods. Bacterial budding has also been observed. Many unidentifiable particles were photographed, e.g. refractile sulphur-like particles which do not dissolve in pyridine.

In Lake Fidler particulate material decreased rapidly with depth below the plate and most of the monimolimnion possessed low turbidity and methanol extractable pigments. The population of the monimolimnion was principally composed of bacteria, as well as a variety of non-living particles, some of which could be dying cells from the plate raining down through the monimolimnion. Figure 109 suggests that these organisms also fluctuate seasonally, being lowest in winter and most abundant in summer. No similar monimolimnial assemblages occur in Sulphide Pool or Lake Morrison, as the bottom of the plate is in contact with the lake bottoms.

4.4 Light Penetration

When the weather is clear and sunny roughly 80% of irradiance incident onto a lake surface is parallel (Kirk 1977a). The remaining 20% is mainly blue diffuse light from the clouds in the sky, which increases with increasing haze and cloud.

The spectral energy distribution of incident sunlight has been summarized by Wetzel (1975). Only a narrow band of the sunlight range of 300 - 3000 nm (Strickland 1958) is photosynthetically active radiation (PAR) and is utilized by photosynthetic organisms (400 - 700 nm band). Commercial quantum meters measure within this range (Kirk 1977b).

The angle of incidence of sunlight varies with the solar elevation. The spectral distribution also varies with solar altitude, so that there is more red light than blue light when the sun is low in the sky (Jerlov 1976). Blue light is more readily scattered than red light, and when the sun is low the distance of the light path through the atmosphere is greater than when the sun is high. Therefore the proportion of red light incident on a lake surface increases with decreasing solar elevation.

4.4.1 Factors affecting the attenuation of photosynthetically active radiation (PAR).

a. Pure Water

In pure water, free of coloured organic compounds, the absorption of light is extremely small, particularly at the short wave end of the PAR spectrum (Strickland 1958), and there is no particular wavelength of maximum transmission, only a broad maximum between 370 - 570 nm (Hulbert 1945 and Strickland 1958 , Figure 111). Absorption increases from about 580 nm to a plateau of about 610 nm to 680 nm (Sullivan 1963), and then increases very rapidly beyond 700 nm.

In the sea all longwave radiation outside of the PAR range is completely absorbed in the top 2 m (Strickland 1958) while in turbid, uncoloured coastal waters the maximum transmission occurs at about 550 nm. In the Gordon River lakes, which contain large amounts of dissolved organic material and low turbidity in the surface waters, the penetrating light was insignificantly absorbed by water itself in the shortwave region of the PAR spectrum. The percentage of light absorbed by water itself compared to that absorbed by organic colour increased towards the longwave region of the spectrum, and the percentage absorption by water increased with decreasing organic colour (Table 19).

Table 19: Percentage of light absorbed by water in the top 1 m compared with that absorbed by organic colour (G440) in the Gordon River lakes in January 1977. The Gordon River is included for comparison. It is assumed that light scattering is negligible and that water and dissolved organic colour are the only components absorbing PAR, and that the concentration of these yellow substances remains constant with depth.

	Wavelength (nm)				
	550	600	650	700	G440
Sulphide Pool	1	4	8	24	11.88
Lake Morrison	1	6	11	28	8.68
Lake Fidler	1	6	11	33	8.50
Gordon River	2	12	25	78	2.33
Perched Lake	5	48	100	100	2.08

In very dark waters (e.g. Sulphide Pool) absorption by the water itself was insignificant compared with that attributable

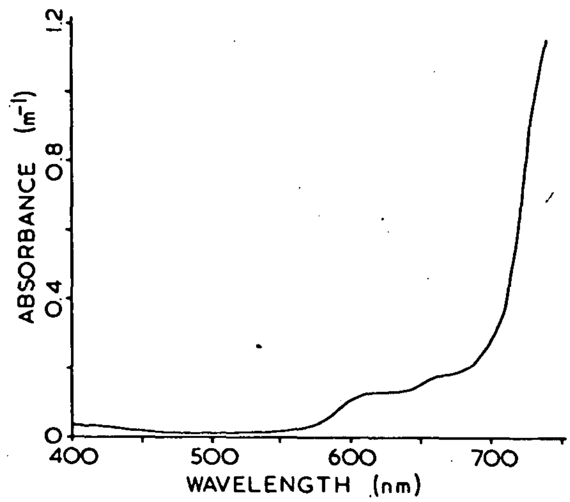

FIGURE 111: ABSORPTION SPECTRA OF PURE WATER, CONSTRUCTED FROM DATA OF HULBERT (1945) AND SULLIVAN (1963) BY STEANE (1979).

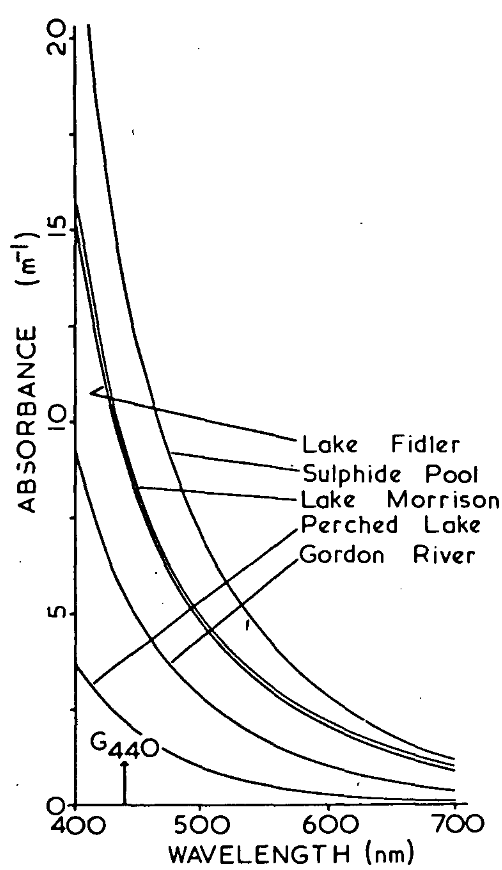

FIGURE 112: ABSORPTION SPECTRA OF DISSOLVED ORGANIC SUBSTANCES (GILVIN G .m-1) IN RELATION TO DISTILLED WATER FROM THE GORDON RIVER AND ADJACENT LAKES IN JANUARY 1977.

to gilvin, even at long wavelengths (above about 650 nm) but became relatively more significant as concentration of dissolved organic material decreased. Perched Lake was the least coloured and absorption by pure water remained considerable at wavelengths down to 600 nm. At shorter wave-lengths absorption by water would become insignificant.

b. Dissolved Organic Colour - Gilvin

Chlorophyll absorption bands at the red end of the spectrum are only of limited value to photosynthesis due to the rapid attenuation of light by water itself (Figure 112). The photosynthetic activity of many algae will therefore be markedly affected by the availability of blue light which is in turn greatly affected by the concentration of organic colour in the water (Kirk 1976).

The measurement of organic colour at 440 nm is physiologically meaningful because it corresponds approximately to the midpoint of the photosynthetic action spectrum of many algae (Kirk 1976, see Figure 121), and to the area of maximum absorbance by dissolved humic material in the PAR spectrum. Because of the extreme attenuation by organic colour (Figures 114, 115 and 116) the phytoplankters in the Gordon River meromictic lakes will not be able to utilize light at these wavelengths for photosynthesis.

Extremely high concentrations of organic colour occur in south west Tasmanian lakes and coastal lagoons (King and H.E.C. 1978) in comparison with figures presented for mainland Australia by Kirk (1976) and for humic Venezuelan waters by Lewis and Caufield (1977). The organic colour in sea waters investigated by Kirk were, in some cases too low to measure, (maximum G440 values of 0.08 m^{-1}). His freshwater samples ranged from 0.42 to 2.90 m^{-1}. Maximum gilvin of the Venezuelan waters was 5.5 m^{-1}.

Dissolved organic colour in the lakes of the Gordon River area ranged from gilvin = 1.70 to 2.80 m^{-1} in Perched Lake, to Lakes Fidler and Morrison where gilvin ranged from 5.18 to 8.88 m^{-1}, and sulphide Pool where it reached 11.88 m^{-1} (Table 20), and was equivalent to 35 to 255 platinum units (using the relationship of Hazen units (Pt units) = 22 x G440 - derived by King and Tyler 1978b). Absorption spectra, relative to distilled water, of the organic colour in the Gordon River lakes in January 1977 are shown in Figure 114. However, a greater gilvin concentration was recorded in Lake Fidler on 15th December 1977 when the Gordon River flooded as a result of high rainfall (King

TABLE 20: Secchi transparency, extinction coefficients and related information in the Gordon River lakes. Turbidity and chlorophyll values calculated as the average for the water column from the surface to the lower limit of the photic zone (down to 1% of surface PAR).

DATE	E.S.T.	WEATHER	GILVIN (m^{-1})	FTU	CHL (µG/L)	SECCHI (M)	1% PAR (M)	E (m^{-1})
LAKE FIDLER								
19/10/76	1600	calm haze	6.18	0.4	-	1.4	1.57	1.17
27/1/77	1700	calm sun	8.50	0.8	-	1.5	1.20	1.46
22/2/77	1030	clam cloud	6.20	0.9	0.6	1.7	-	-
7/4/77	1230	calm cloud	8.25	1.2	0.7	1.6	-	-
16/6/77	1415	calm cloud	8.00	3.4	0.9	1.8	1.16	1.41
13/7/77	1550	calm cloud	7.28	3.0	-	1.3	-	-
25/8/77	1230	calm cloud	7.20	2.4	1.5	1.6	-	-
26/10/77	0930	calm sun	7.65	1.4	1.2	1.6	1.35	1.31
13/12/77	1630	calm cloud	7.13	1.9	1.1	1.5	1.04	1.62
14/12/77	2010	calm sunset	7.13	1.9	1.1	1.4	1.36	1.32
15/2/78	1110	calm sun	5.70	1.8	0.8	1.8	1.42	1.25
15/3/78	1220	breeze cloud	5.18	1.1	5.1	1.9	1.63	1.11
5/4/78	1310	calm sun	4.53	1.3	1.7	1.7	-	-
SULPHIDE POOL								
28/1/77	1030	calm sun	11.88	-	-	1.2	-	-
23/2/77	1130	calm sun	11.63	1.4	163	1.0	-	-
11/4/77	1240	calm sun	12.08	2.6	20	1.3	-	-
16/6/77	1030	calm sun	10.50	3.6	19	0.8	0.78	2.17
12/7/77	1600	calm cloud	12.15	3.3	18	1.0	-	-
25/8/77	1650	clam cloud	11.48	3.0	18	1.1	-	-
25/10/77	1410	breeze sun	11.58	3.0	22	0.9	0.97	1.74
13/12/77	1245	calm cloud	6.30	2.1	85	1.1	0.69	2.55
17/2/78	1120	calm cloud	10.43	2.6	20	1.1	-	-
14/3/78	1450	calm sun	10.85	1.5	56	0.9	0.64	2.19
5/4/78	1055	calm sun	9.58	14.2	39	1.3	0.93	1.88

TABLE 20 (CONTINUED)

DATE	E.S.T.	WEATHER	GILVIN (m^{-1})	FTU	CHL (µG/L)	SECCHI (M)	1% PAR (M)	E (m^{-1})
LAKE MORRISON								
29/1/77	1145	calm cloud	8.68	-	-	0.9	-	-
17/6/77	1445	calm cloud	8.88	2.4	0.5	1.4	1.18	1.44
14/7/77	1030	calm cloud	8.38	-	-	1.4	-	-
26/8/77	1230	windy cloud	7.93	1.5	7.0	1.4	-	-
15/12/77	1125	breeze cloud	8.20	2.0	2.2	1.3	0.98	1.76
16/2/78	1220	breeze cloud	7.28	3.8	6.0	1.3	-	-
16/3/78	1330	calm cloud	5.53	2.5	2.3	1.4	1.28	1.41
6/4/78	1200	calm cloud	4.58	-	-	1.7	-	-
PERCHED LAKE								
20/10/76	1300	breeze sun	2.80	-	-	3.6	2.65	0.68
26/1/77	1930	calm sun	2.08	-	-	3.4	-	-
23/2/77	1000	calm cloud	1.95	-	-	3.3	-	-
10/4/77	1015	calm cloud	2.10	-	-	3.8	-	-
15/6/77	1210	calm cloud	2.27	-	-	4.0	2.55	0.75
12/7/77	1650	calm cloud	2.63	-	-	3.1	-	-
24/8/77	1700	calm sun	2.65	-	-	3.1	-	-
25/10/77	0930	calm cloud	2.33	-	-	3.8	2.95	0.64
12/12/77	1520	breeze cloud	2.23	-	-	4.9	3.34	0.56
14/2/78	1220	breeze cloud	1.93	-	-	4.2	3.35	0.59
14/3/78	1040	calm sun	1.70	-	-	4.2	3.17	0.61
14/4/78	1230	calm cloud	1.75	-	-	3.6	3.05	0.64

and Tyler 1978b) and discharge from the Gordon power station which elevated river flow from 41 m^3/sec late on the 14th December to 290 m^3/sec on the 16th December, as measured at Butler Island Camp.

The concentration of dissolved colour increased in the lake's surface waters from 7.13 m^{-1} (160 Pt units) on the 14th December to 13.27 m^{-1} ($>$ 300 Pt units) on the 15th December as a result of considerable inflow of Gordon River water into the lake, inundating the fringing herb fields and adjacent rainforest peats, (see Section 2.2), and mobilizing large quantities of soluble and particulate organic material. The lake level increased from 0.87 m on the 14th December when the herb fields were exposed, to 1.62 m on the 15th December, when most of the forest area behind the levee bank separating the lake from the river was inundated (Plates 20, 21 and 22). This flooding would have been a fairly common phenomenon prior to control of river flow by the Hydro-Electric Commission, for considerable quantities of water-deposited debris is caught up in the forest vegetation around the lake, some at heights considerably above the flood level discussed above (personal observation).

Organic colour enters the lakes as seepage and creek inflows, and, in the case of Lakes Fidler and Morrison, via direct inflow from the Gordon River. These influent waters would enter the lakes and flow out at specific density levels. Dilute creek water mixed only with the lake surface waters (e.g. see Lake Fidler and Inflow 2 between April and July 1977 in Figures 113 and 114), while the more concentrated Gordon River water would flow out at some intermediate level within the mixolimnion or monimolimnion depending on density. Figure 102 shows high gilvin variability (measured as the standard deviation of all determinations - see also Buckney 1976) at 0.1 m and at 1.5 m depth. Variability in the surface waters (0.1 m) would result from dark creek waters particularly (Inflow 2, King and Tyler 1978b), mixing with less coloured waters from Inflow 1 and from the Gordon River. Prior to 25th August 1977 colour in the river and in the lake showed no apparent relationship (Figure 113).

Difference in the concentration of gilvin between the two lake Fidler inflow creeks was a factor of the variation of rainforest peats in the lake's catchment. Of the two inflows, Inflow 1 was less coloured than the surface waters of Inflow 2, suggesting that it drained predominantly the fibrous peats of the river valley slopes, while Inflow 2 contributed significant amounts of colour to the lake, from the muck peats overlying the alluvium in the valley floor. Similarly, in the northern hemisphere the leachate from leaves and forest litter contributes large amounts of organic material to lakes, rendering them dystrophic

(Hoak 1962, Slack 1964, Hall 1970). Rainfall can be considered uniform within the catchments of the three lakes, and contributed no colour to the lakes at all.

The rapid increase in colour in Inflow 2, together with increasing colour in the Gordon River from 22nd February to 8th April 1977 caused a noticeable increase in surface lake water colour (Figure 113). The depth to which this coloured water mixed by mid June can only be explained by wind action on the surface of the lake. From July 1977 to the termination of the study both the Gordon River and Inflow creek 2 gradually became less coloured as did Lake Fidler (Figure 113) while Inflow creek 1 gradually became darker. The sharp decrease in colour in the creeks and in the Gordon River from the 14th February to the 14th March 1978 which further contributed to the lower surface colour in the lake, was difficult to explain, but could well have resulted from extraordinary high local rainfall.

Colour in Lake Morrison surface waters fluctuated and showed no apparent relationship with rainfall up to December 1977 thereafter colour became significantly reduced (Table 20). This probably resulted from relatively uncoloured Gordon River inflows, and possibly by reduced organic input from the catchment (similar to Lake Fidler Inflow 2).

No seasonal variation in colour was apparent in Sulphide Pool, and its surface water showed no response to reduced colour in the Gordon River after November 1977 when powerstation discharge commenced.

After Lake Gordon discharge commenced, Lake Morrison, which was much less resistant to mixing across the chemocline, displayed a very similar reduction in colour to that in Lake Fidler, by admixture with much clearer Gordon inflows. This event coincided with a decrease in the salinity gradient between the top and bottom lake waters (Table 14), and the concomitant reduction in meromictic stability.

This gradual reduction in surface colour values after powerstation discharge was not obvious in Sulphide Pool (Figure 99 and Table 13), because this lake has no direct channelized connection with the Gordon River, and therefore was not influenced by the reduction of river colour after power station discharge commenced (King and Tyler 1978).

From Table 20, Figures 117, 118, 119 and 86, 87 and 88, the effect of the extremely high concentrations of dissolved organics on algal biomass in the oxic mixolimnion becomes apparent. In Sulphide Pool (see Figure 115), 90% of incident PAR was absorbed by colour (Table 21) within the top 0.2 to 0.3 m of the water column, and 99% of incident light was absorbed within the top 0.64 and 0.97 m (Figure 115). The lower limit of photic zone is generally defined as the depth at which PAR is reduced to 1% of that penetrating the surface - Bindloss 1976. Downwelling PAR in less darkly coloured Lakes Fidler and Morrison was attenuated less rapidly, but even so the lower limits of the photic zone lay between only 1.04 to 1.63 m (Figure 114) and 0.98 to 1.28 m (Figure 116) respectively (Table 20). Perched Lake, the least coloured of the Gordon River lakes, obviously has the deepest photic zone, ranging from 2.55 to 3.35 m (Table 20).

The profound effect of dissolved organic colour on Secchi transparency and the vertical extinction coefficient E (E - derived from the slope of the lines plotted in Figures 114, 115 and 116) of the lakes can be seen from Tables 20 and 21 and Figures 117 and 118). In the absence of appreciable turbidity which can originate either from terrestrial sources or from phytoplankton growth, organic colour is the most significant factor contributing to the attenuation of light (Brezonik 1978). The plot of Secchi transparency against reciprocal gilvin shows a good correlation over the range of gilvin values encountered for all Gordon River lakes, but no relationship existed within any one lake. This may well be attributable to the crudeness of Secchi measurements, and to intermittent turbidity caused by mixolimnetic algal populations (e.g. see Sulphide Pool 0.22 m on 14.3.78 in Figure 87), or coloured turbid density layering caused by Gordon River inflows.

Similarly a good relationship was obtained between vertical extinction coefficient E and gilvin over the range of lakes studied. The best relationship within a particular lake was recorded in Lakes Fidler and Morrison which underwent significant variations in colour during the study period (Tables 12 and 14). The colour of Sulphide Pool showed some variation while both E and colour showed minimal variation in Perched Lake. The concentration of organic colour in the lakes was therefore the major factor influencing the depth of the lower limit of the photic zone (Table 20)

The 1% light level was not as meaningful biologically as the Secchi transparency depth. Figures 86, 87 and 88 show the relationship between Secchi, photic zone and the depth distribution of planktonic biomass (measured as chlorophyll and as turbidity, on the 16-17th June 1977 and 14-16th March 1978). Secchi depths were in almost all cases greater than the lower limit of the photic zone (1%) (Table 20). Secchi

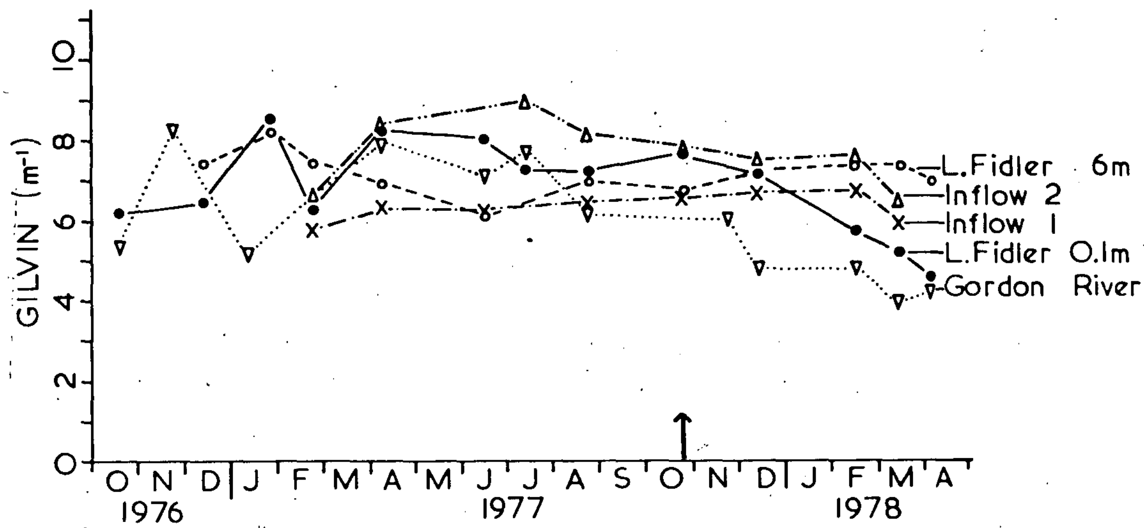

FIGURE 113: TEMPORAL VARIATION OF GILVIN IN LAKE FIDLER, TWO INFLOW CREEKS AND FOR THE GORDON RIVER MEASURED AT BUTLER ISLAND CAMP. (DATA FROM KING AND HEC 1978). ARROW (↑) INDICATES WHEN GORDON POWER STATION COMMENCED DISCHARGING.

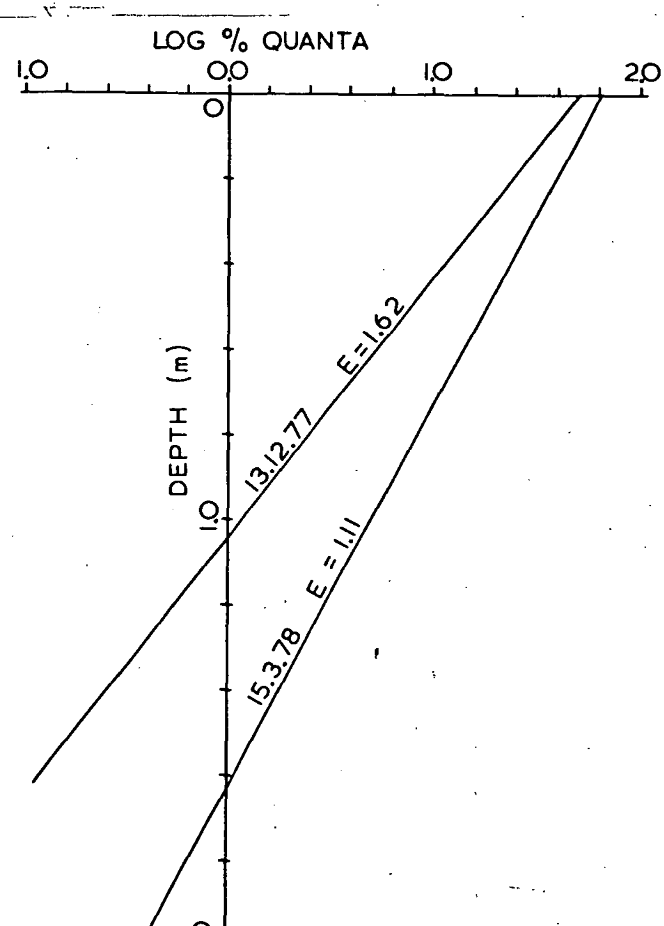

FIGURE 114: RANGE OF ATTENUATION OF PAR IN LAKE FIDLER. PLOT IS OF QUANTUM IRRADIANCE (μE. cm^{-2}. sec^{-1}, 400-700 nm WAVEBAND) AT DEPTH AS A PERCENTAGE OF IRRADIANCE JUST ABOVE THE LAKES SURFACE, AND THE SLOPE OF THE LINE GIVES THE ATTENUATION COEFFICIENT E.

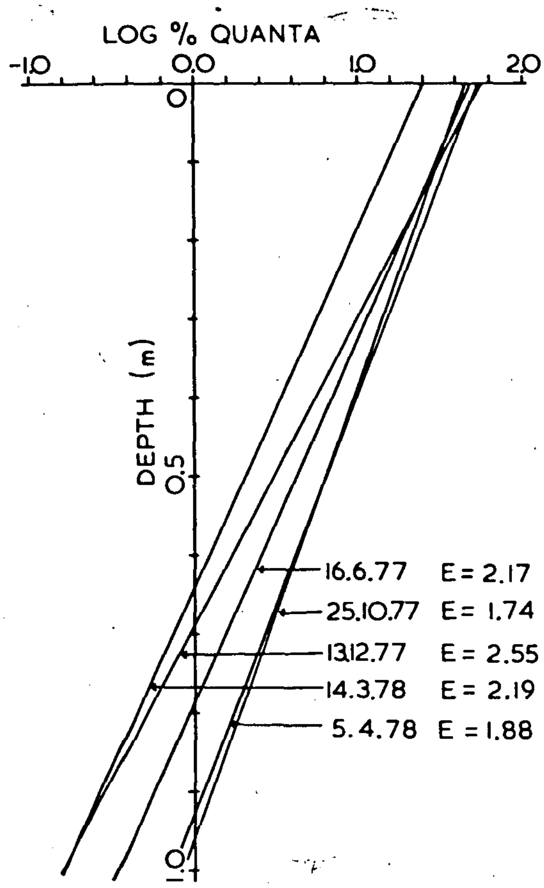

FIGURE 115: ATTENUATION OF DOWNWELLING PAR IN SULPHIDE POOL.

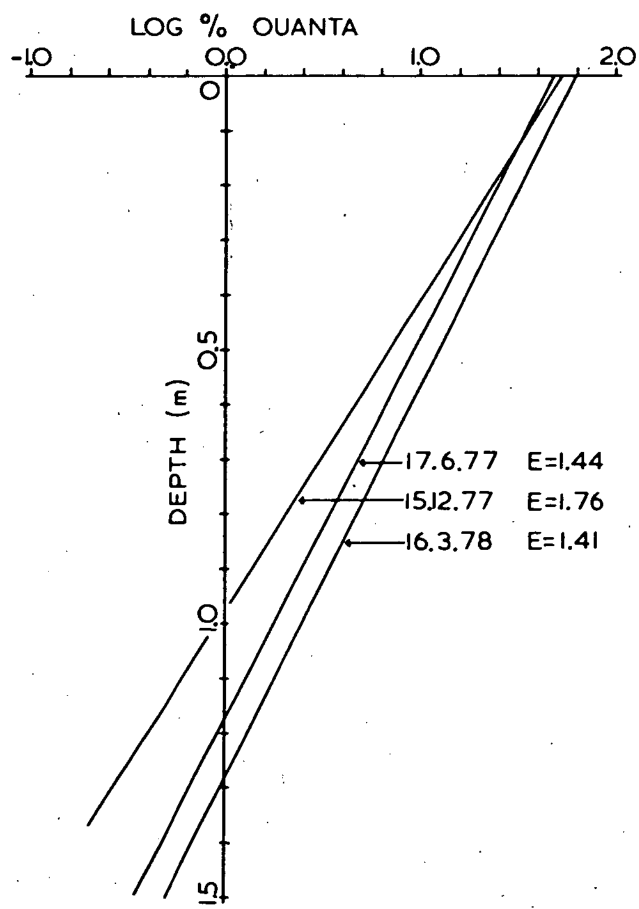

FIGURE 116: ATTENTUATION OF DOWNWELLING PAR IN LAKE MORRISON.

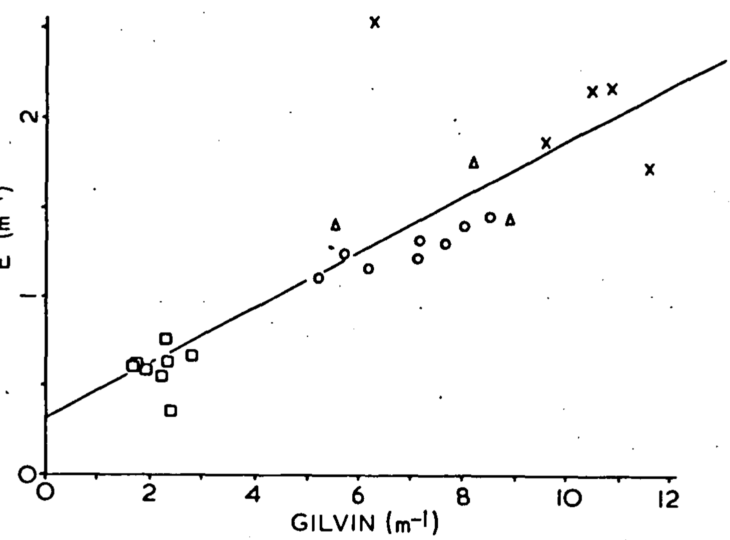

FIGURE 117: RELATIONSHIP BETWEEN VERTICAL ATTENTUATION COEFFICIENT (E.m-¹) AND DISSOLVED ORGANIC COLOUR (GILVIN G440.m-¹) IN LAKE FIDLER (o), SULPHIDE POOL (x), LAKE MORRISON (Δ), AND PERCHED LAKE (□). CALCULATED REGRESSION EQUATION IS E = 0.33 + 0.16 GILVIN, n = 24, r = 0.85.

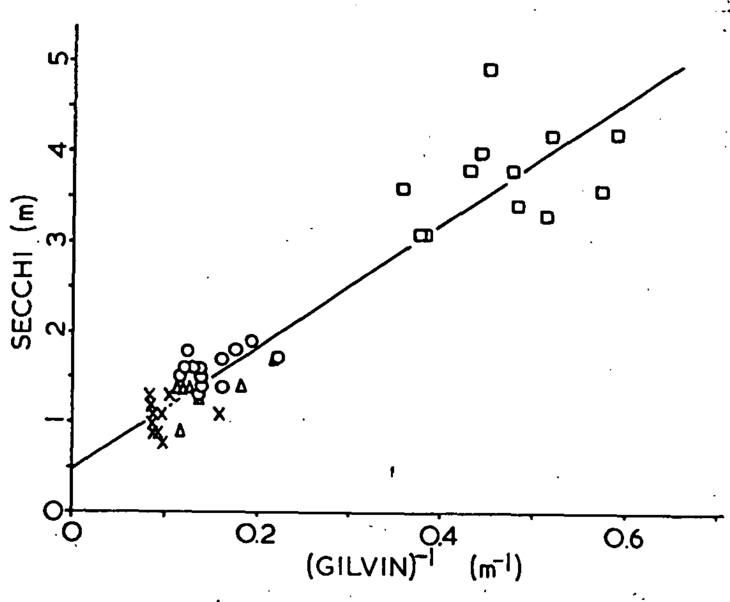

FIGURE 118: RELATIONSHIP BETWEEN SECCHI TRANSPARENCY AND RECIPROCAL GILVIN (G440 m-¹) IN THE GORDON RIVER LAKES. LEGEND AS FOR FIGURE 117. CALCULATED REGRESSION EQUATION IS SECCHI = 0.50 + 6.80, n = 44, r = 0.95.

transparency coincided with the level of maximum biomass, while the 1% level coincided closely with the upper limit of the algal plate. In these highly coloured, non-turbid waters the ratio of photic zone: Secchi transfarency was $<$ 1, contrary to conversion factors reported elsewhere of between 2 and 5 times. (Verduin 1956; Riley 1941 and Bindloss 1976).

c. Photosynthetic Pigments

The contribution of chlorophyll concentration to the attenuation of PAR (calculated extinction coefficients - E) and transparency in the Gordon lakes is presented in Figures 119 and 120 respectively.

According to Talling (1960) chlorophyll-a concentrations above about 10 µg/l can contribute to the attenuation of PAR. Owing to the presence of occasional mixolimnetic algal plates at intermediate depths in the Gordon lakes (e.g. Sulphide Pool on the 30th January 1977) chlorophyll has been calculated as the mean value for the photic zone (see Bindless 1976). This data agrees well with Talling's proposal, for photic zone chlorophyll concentrations in Lakes Fidler and Morrison were extremely low (Table 20; see also Figures 109 and 110) and displayed no relationship with E, thus contributing very little to the attenuation of PAR. But Sulphide Pool contained appreciable amounts of cholorophyll within the photic zone, particularly during the summer, which contributed to the attenuation of PAR (Figure 119). A similar relationship between chlorophyll and E was found by Bindless (1976) in waters considerably less coloured than those of the Gordon River.

No relationship was obtained between Secchi transparency and reciprocal chlorophyll concentrations (Figure 120) because of the overwhelming influence of yellow substances in the water on Secchi transparency and the low concentrations of photosynthetic pigments in the surface waters of Lakes Fidler and Morrison. Probably, turbulence and turbidity caused by lowering the Secchi disc through the algal plates (e.g. Lake Fidler on 1the 14th March 1978), caused the Secchi depth to be underestimated. The lack of more detailed close interval chlorophyll data within the photic zone and the crudeness of Secchi measurements also contributed. Brezonik (1978) records similar scatter in data from 55 Florida lakes, and attributes this scatter, at least in part, to the high organic colour levels in some lakes.

The plate in Lake Fidler occurred between a depth of 2 and 3 m and between 1 and 2 m depth in Lake Morrison and in Sulphide Pool. These plates were generally just below the Secchi depth as well as the lower limit of the photic zone (Figures 86, 87 and 88).

Chlorophyll extracted in either methanol or acetone showed a principal absorption peak at 663 nm or at 657 nm. Samples from above the plate absorbed at 663 nm (probably Cryptomonas sp.) while those from below at 657 nm (sulphur bacteria). The approximate boundary between the two for Lake Fidler and Sulphide Pool is shown by the the dotted line in Figures 109 and 110. Since a variety of algae was present above the plate, and sulphur bacteria were observed in samples from the plate it seems possible that the 657 nm type was a bacterial chlorophyll. A typical absorption spectrum is shown in Figure 121, and Figure 122 compares the absorption spectrum of chlorophyll-a with chlorophyll-b and some bacterial chlorophylls (Frobisher et al 1974). Chlorophyll-a can absorb light in two regions of the spectrum, one well defined peak between 655 to 665 nm, and in the shortwave region at 410 and 430 nm . In non-coloured waters longwave PAR would be abundant in shallow waters, and short wavelength blue light would penetrate deeper (Cole 1975) due to the selective absorption of longwave red light by the water (Steane 1979). However, in the darkly coloured Gordon lakes shortwave blue light was rapidly attenuated by dissolved organic matter (compare Figures 112 and 128), so that light harnessing by chlorophyll in this region of the PAR spectrum would be negligible, except possibly in the surface waters. For example, in Sulphide Pool in January 1977 there was 298 µg chl /l at 0.3 m at which depth not only was PAR reduced to roughly 10% or less of that at the surface (Figure 87) but also would be lacking in blue wavelengths (Figure 129). The high algal populations in the top 0.1 m of this lake would themselves play a significant role in shortwave PAR attenuation.

Wavelengths of maximum penetration in Lake Filder and Sulphide Pool lay between about 690 to 710 nm (Figures 128 and 129), and in this region of the PAR spectrum light was absorbed mainly by the water itself, and to a lesser extent by organic colour. Absorption by chlorophyll between 655 and 665 nm was extremely small in comparison with the above mentioned absorbing components.

Table 21: Correlation coefficients and number of observations of factors affecting Secchi transparency and extinction coefficients in Gordon River lakes. No data for turbidity and chlorophyll for Perched Lake. Number of samples is indicated in brackets.

	Secchi (m)	E_1 (m^{-1})
Gilvin (m^{-1})		0.85 (24)
$(G_{440})^{-1}$	0.94	
Turbidity (FTU)		0.27 (16)
$(\text{Turbidity})^{-1}$	0.14	
Chlorophyll (μg chl /l)		0.86 (14)
$(\text{Chlorophyll})^{-1}$	0.54	

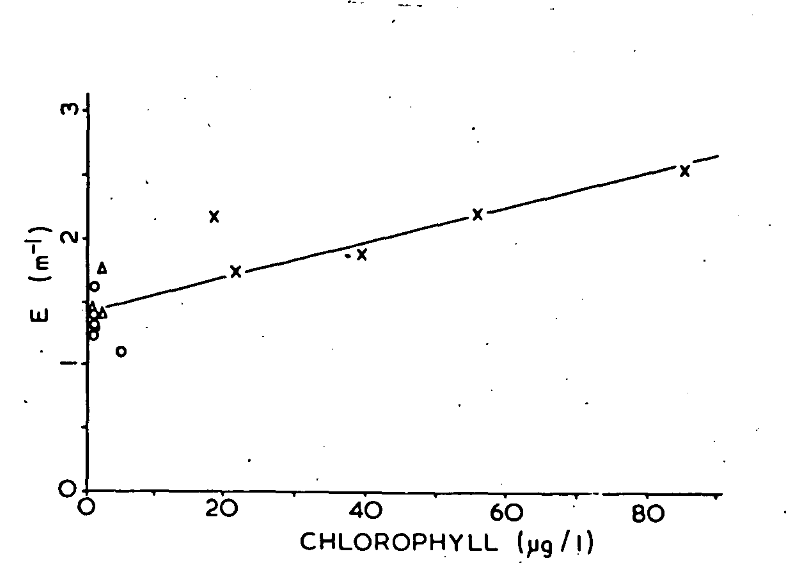

FIGURE 119: RELATIONSHIP BETWEEN VERTICAL ATTENTUATION COEFFICIENT AND BACTERIAL—CHLOROPHYLL IN THE GORDON RIVER LAKES. LEGEND AS FOR FIGURE 117. CALCULATED REGRESSION EQUATION IS E = 1.42 + 0.01 BAC.-CHLOROPHYLL, n = 14, r = 0.86.

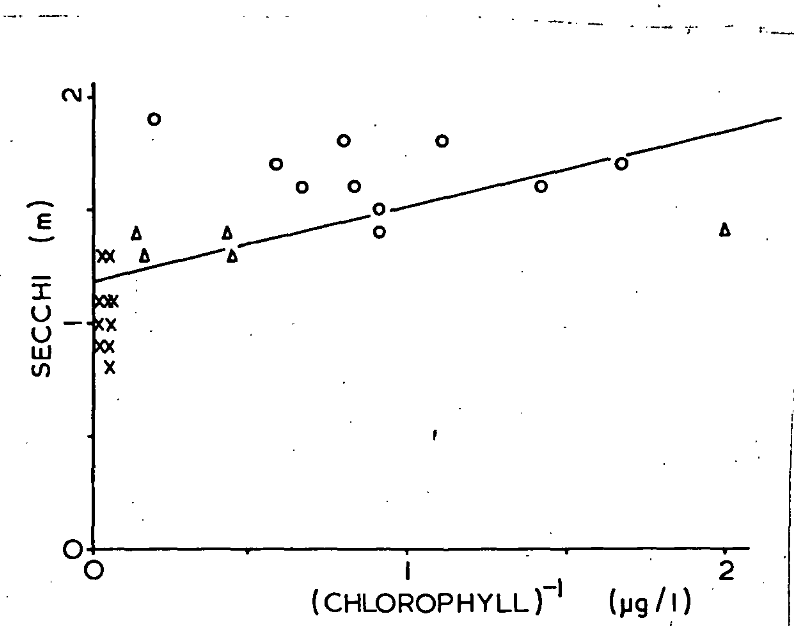

FIGURE 120: RELATIONSHIP BETWEEN SECCHI TRANSPARENCY AND RECIPROCAL BACTERIAL-CHLOROPHYLL IN THE GORDON RIVER LAKES. LEGEND AS FOR FIGURE 117. CALCULATED REGRESSION EQUATION IS $\text{SECCHI} = 1.19 + \frac{0.33}{\text{bac.-chloro.}}$, n = 25, r = 0.60.

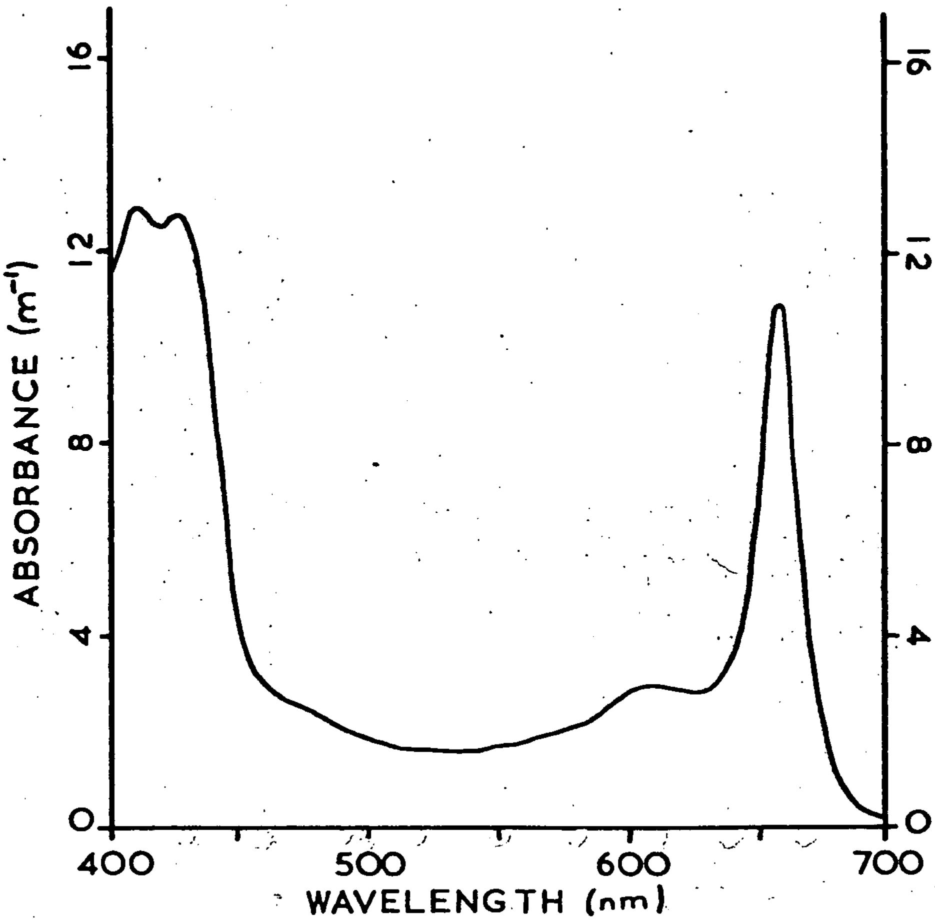

FIGURE 121. TYPICAL ACTION SPECTRUM OF BACTERIAL-CHLOROPHYLL EXTRACTED IN 90% METHANOL FROM ALGAL PLATES IN THE GORDON RIVER LAKES. LONG WAVE-LENGTH ABSORPTION PEAK SHIFTED FROM 663 nm IN THE MIXOLIMNION TO 657 nm IN THE BACTERIUM PLATE IN THE MONIMOLIMNION.

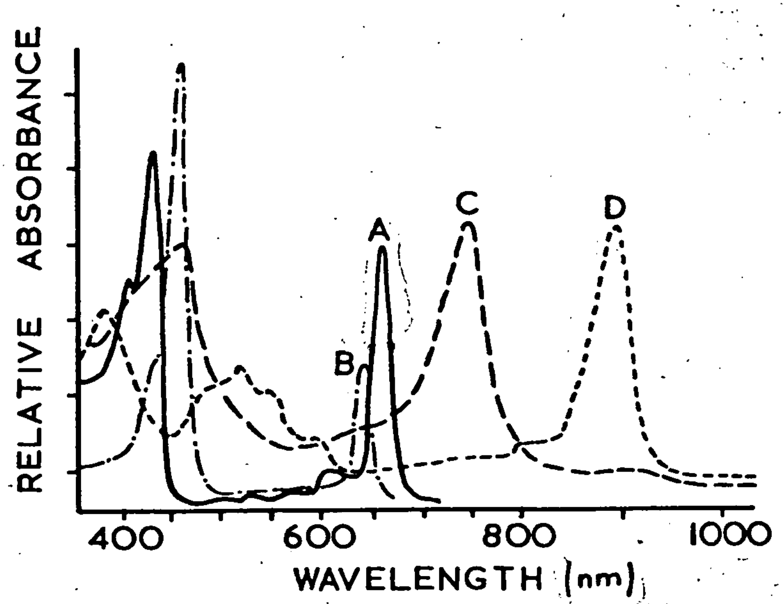

FIGURE 122. ABSORPTION SPECTRA OF ETHER PURIFIED CHLOROPHYLL-A (A), CHLOROPHYLL-B (B), AND PIGMENTS OF GREEN (C) AND PURPLE (D) BACTERIA. (REDRAWN FROM Frobisher *et al*, 1974).

d. Turbidity

Turbidity undoubtedly contributes to the attenuation of PAR (Smith and Tyler 1967); the vertical extinction coefficient increases and Secchi transparency decreases with increasing turbidity. However, in dark, turbid waters, the effect of seston on PAR attenuation is masked by appreciable absorption due to organic colour. Between these two extremes, lakes containing low colour and high turbidity can have similar E values and Secchi depths as lakes with high colour and low turbidity (Steane 1979).

The effect of turbidity on the secchi transparency and extinction coefficient in the Gordon River lakes are illustrated - Figures 123 and 124.

In the Gordon lakes there was no obvious relationship between either E or Secchi transparency and turbidity, even though allowances were made for subsurface algal plates or turbid density layers by calculating mean turbidity for the photic zone (Table 20). These values were low, - below 3.6 FTU (the 14.2 FTU recorded from Sulphide Pool on the 5th April 1978 probably resulted from disturbance or an upward migration of algal cells, or was due to distrubance of the extremely sharp upper edge of the major bacterial plate (Figures 109 and 110).

4.4.2 Relationship between Vertical Extinction Coefficient and Secchi Transparency

The relationship between vertical extinction coefficient and reciprocal Secchi transparency is presented in Figure 127, and between Secchi transparency and photic zone in Figure 126. The former relationship for the Gordon River lakes, differs from the formula proposed by Pool and Atkins (1929), namely

$$E = \frac{0.74}{\text{Secchi}}$$

Data presented by Steane (1979) for non-turbid moderate to very low coloured waters agrees fairly well with this formula. However, the data presented here for highly coloured waters which occasionally contained small quantities of particulate organic turbidity (see Figures 86, 87 and 88), either living or non-living, deviates from the Pool and atkins relationship. Thus

$$E = 0.2 + \frac{1.83}{\text{Secchi}}$$

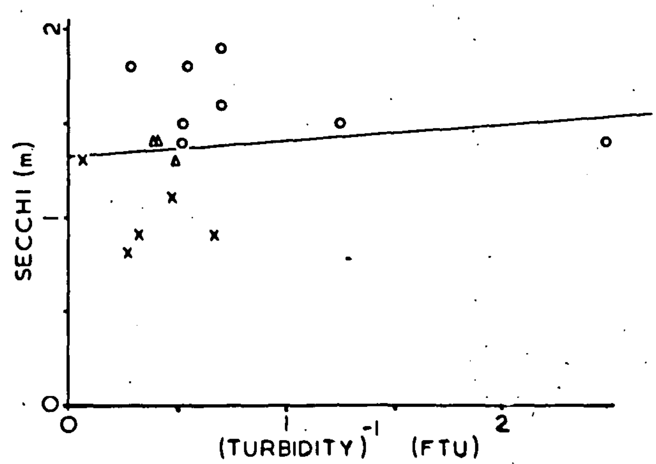

FIGURE 123: SECCHI DISC TRANSPARENCY AND RECIPROCAL TURBIDITY IN THE GORDON RIVER LAKES. LEGEND AS FOR FIGURE 117. CALCULATED REGRESSION EQUATION IS SECCHI = 1.16 + $\frac{0.26}{\text{turbidity}}$, n = 29, r = 0.36.

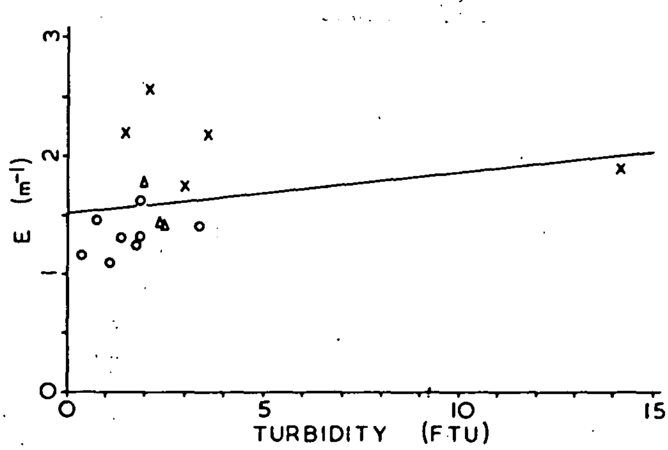

FIGURE 124: VERTICAL ATTENUATION COEFFICIENT AND TURBIDITY IN THE GORDON RIVER LAKES. LEGEND AS FOR FIGURE 117. CALCULATED REGRESSION EQUATION IS E = 1.52 + 0.03 TURBIDITY, n = 16, r = 0.27.

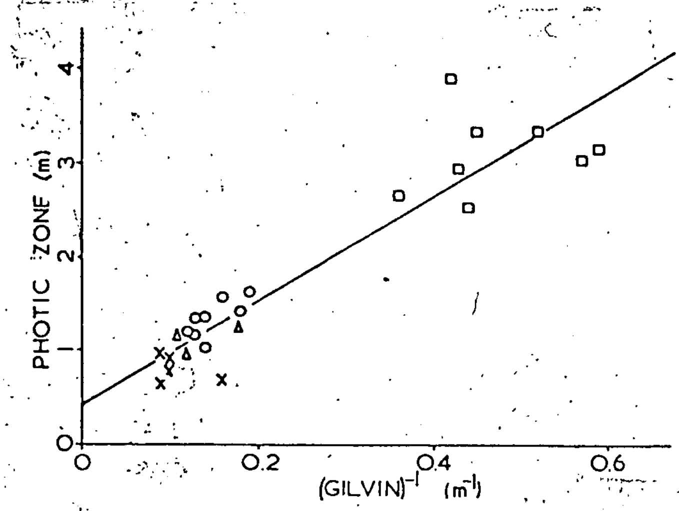

FIGURE 125: PHOTIC ZONE AND RECIPROCAL DISSOLVED ORGANIC COLOUR IN THE GORDON RIVER LAKES. LEGEND AS FOR FIGURE 117. CALCULATED REGRESSION EQUATION IS

$$\text{PHOTIC ZONE} = 0.43 + \frac{5.54}{\text{GILVIN}} \quad , \; n = 24 \; , \; r = 0.93.$$

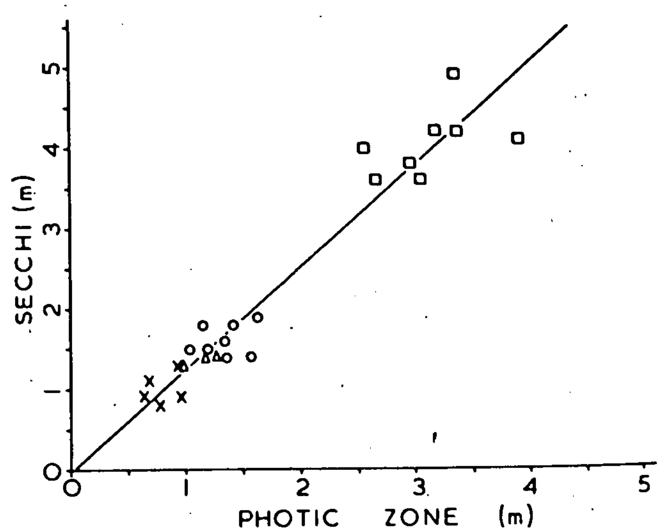

FIGURE 126: SECCHI DISC TRANSPARENCY AND PHOTIC ZONE DEPTH (DEPTH AT WHICH PAR IS REDUCED TO 1% OF SURFACE) IN THE GORDON RIVER LAKES. LEGEND AS FOR FIGURE 117. CALCULATED REGRESSION EQUATION IS SECCHI = 1.27 PHOTIC ZONE — 0.02. n = 24 r = 0.96.

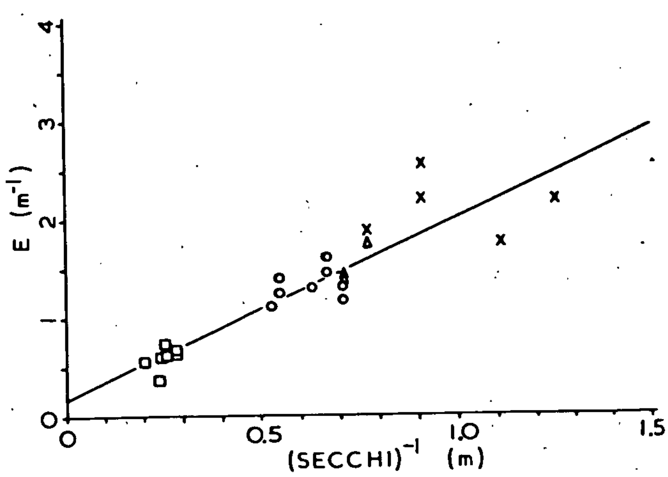

FIGURE 127: VERTICAL ATTENUATION COEFFICIENT AND RECIPROCAL SECCHI DISC TRANSPARENCY IN THE GORDON RIVER LAKES. LEGEND AS FOR FIGURE 117. CALCULATED REGRESSION EQUATION IS $E = 0.2 + \frac{1.83}{\text{SECCHI}}$, $n = 24$, $r = 0.91$.

The extreme colour of the Gordon lakes and the difficulty in accurately measuring Secchi depth may well account for this difference.

The relationship between photic zone depth (derived from the computation of E) and Secchi transparency should be similar, but this too departs from the Poole and Atkins formula and from the relationship presented by Bindloss (1976) for Loch Leven, a highly coloured lake capable of supporting dense crops of phytoplankton. Bindloss found an approximate estimate of photic depth by multiplying Secchi by three. Other conversion factors noted in the literature range from 2.7 (Lemoalle 1973) to 5 (Verduin 1956), and Talling (cited in Bindloss 1967) found a conversion factor of between 2 and 3 for a range of lakes in Africa and England. Conversion factors calculated for the Gordon lakes were mostly < 1 (except for Lake Fidler on the 19th October 1976; 1% = 1.12 Secchi, and Sulphide Pool on the 25th October 1977; 1% - 1.08 Secchi - Table 20). The lowest factor recorded was from Sulphide Pool on the 13th December, 1977 (1% = 0.63 Secchi).

Deviation of the Gordon lakes from the relationship between E and Secchi found by Poole and Atkins (1926) and by Steane (1979), and the conversion factors for Secchi to photic depth recorded elsewhere are directly attributed to the extremely high concentration of yellow substances in the Gordon lakes. The severe attenuation of PAR by these substances completely overrides attenuation components operative in other water types e.g. pure water, algal cells, particulate organic and mineral turbidity. This fact was reinforced by the significant correlation between photic depth and reciprocal gilvin presented in Figure 125.

4.4.3 Spectral Distribution of Underwater PAR

The most significant factor attenuating different wavelengths of light in the Gordon River lakes was dissolved organic matter, which strongly extinguishes shortwave blue light, but also absorbs to a lesser extent in the red longwave region of the PAR spectrum. Water absorbs only in the longwave region of the spectrum, from about 600 nm onwards. The data presented in Table 19 indicates that high concentrations of organic colour absorb more strongly than pure water at the red end of the PAR spectrum.

Figures 128 and 129 present the spectral distribution of quantum irradiance at various depths in Lake Fidler and Sulphide Pool respectively.

The spectrum of the radiation incident upon the surfaces of the two lakes peaked somewhere beyond 700 nm, and tapered off to the shortwave region of the PAR spectrum. The unevenness of these air scans for both lakes was due to a thin stratum of cloud when measurements were made, scattering blue light and thus allowing relatively more red light to reach the lake surface (Jerlov 1976).

At a depth of 0.05 m virtually all the blue light was absorbed by the dissolved organic matter, and at 0.5 m all light below 550 nm was absorbed. Wavelengths of maximum penetration lay at or slightly above 700 nm, and the rapid attenuation of light at longer wavelengths was almost entirely due to absorption by the water.

Due to the overwhelming absorption of PAR by dissolved organics, and to a lesser extent by water itself, the attenuation of various wavelengths by seston cannot be confidently inferred. However, the slight plateau in the scans at about 660 - 670 nm for each lake can be attributed to absorption by phytoplankton (chlorophyll-a absorbs between 657 to 665 nm - see Figures 121 and 122). Absorption at about 440 nm at a depth of 0.05 m cannot be attributed purely to chlorophyll because similar troughs occur in the ambient air scans.

The spectral distribution of underwater PAR can have a significant effect not only on the growth of benthic and planktonic organisms which inhabit a lake. Kirk (1976) discusses the possible advantages of certain pigment compositions under various spectral conditions. In waters containing moderate colour or turbidity with light in the 400 - 500 nm range being strongly attenuated, the short wavelength absorption band of chlorophyll-a would be of little use, but algae containing carotenoids with increased absorption at 500 - 550 nm, and phycobilins absorbing at 540 - 650 nm might have some advantage over algae which do not contain these pigments.

However, in waters containing large amounts of colour or turbidity where the irradiance peaks are close to 700 nm, Kirk (1976) claims that no algal group can be considered able to effectively utilize the available light. These organisms must then utilize their long wavelength chlorophyll-a absorption band.

A prolific algal plate occurred in each of the Gordon River lakes at depths to which very low intensities of long wavelength radiation penetrated. Thus organisms were able to utilize only their long wavelength

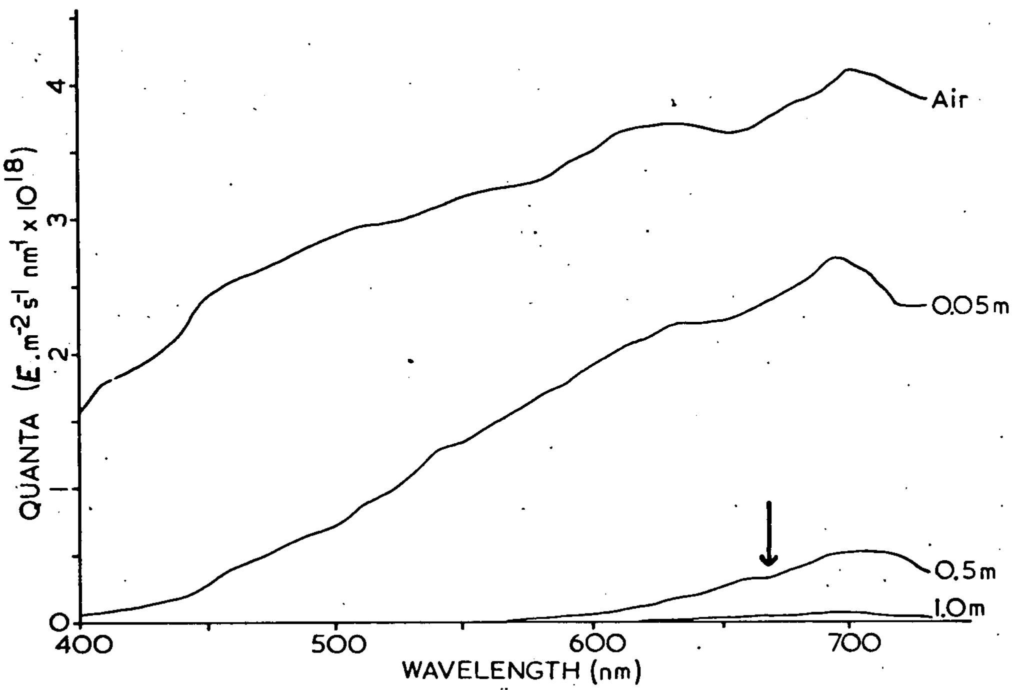

FIGURE 128: SPECTRAL DISTRIBUTION OF QUANTUM IRRADIANCE MEASURED AT VARIOUS DEPTHS IN LAKE FIDLER ON THE 14TH DECEMBER 1977 (G440 = 7.13m-1). ARROW INDICATES ABSORPTION BY BACTERIAL-CHLOROPHYLL.

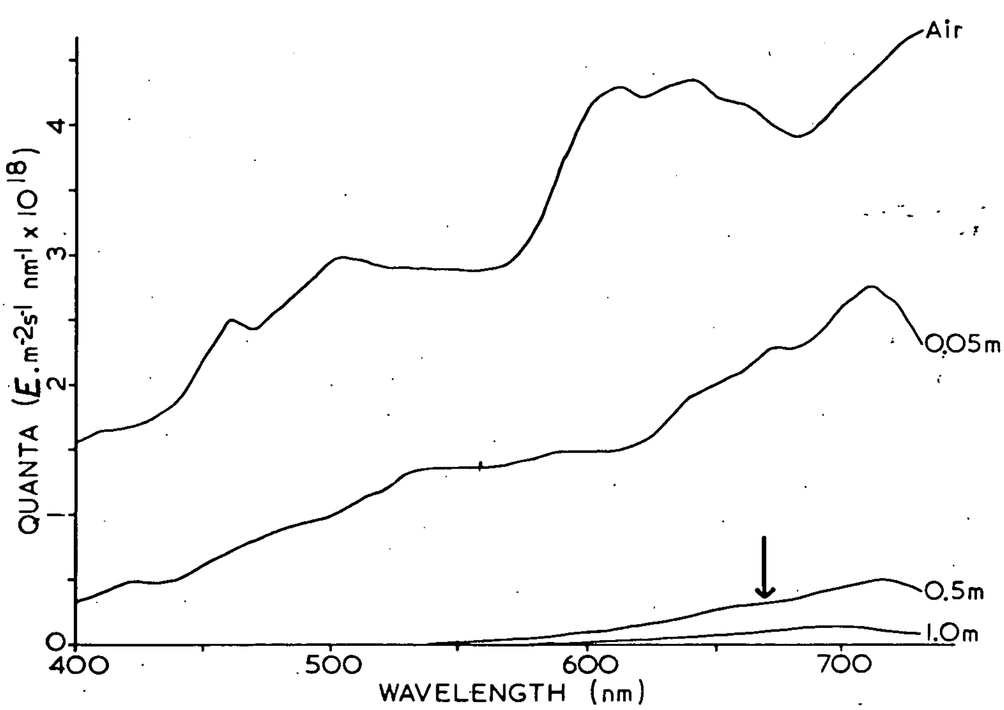

FIGURE 129: SPECTRAL DISTRIBUTION OF QUANTUM IRRADIANCE MEASURED AT VARIOUS DEPTHS IN SULPHIDE POOL ON THE 13TH DECEMBER 1977 (G440 = 6.30.m-1). ARROW INDICATES ABSORPTION BY BACTERIAL-CHLOROPHYLL.

absorption band for photosynthesis. The algal plates were most probably composed of a mixed population of blue-green algae, purple and green sulphur bacteria as is commonly reported to occur in meromictic lakes (Anderson 1958, Kuznetsov 1959, Kjensmo 1965, Frey 1967).

5. Conclusions.

The meromictic lakes occur along the right hand bank of the lower Gordon River. They were formed when levee banks separated them from the mainstream of the river. Prior to October 1977 when discharge from the Gordon Power Station commenced, the lower reaches of the Gordon River experienced intrusion of an underflow of saline water (about 20‰) from Macquarie Harbour. Admixture of riverwater with this salt wedge elevated the salt content of the river surface, which on entry to the lakes, established a bottom layer of saline water (about 4‰), and hence meromixis.

Geology in the vicinity of the lakes consists of alluvium overlying Gordon limestone and sandstone shale sequences. Apart from rainfall, the lakes also exchange water with the Gordon River via inflow - outflow creeks. No such creek has been located for Sulphide Pool, and the levels of all three lakes fluctuate in harmony with that of the Gordon River. Establishment and maintenance of meromixis in the lakes was intimately related to the salt wedge in the river. Altered river flow (Hydro-Electric development - commissioned October 1977) has flushed saline water from the river, and already Lake Morrison has lost its salt gradient and is apparently evolving towards holomixis, suggesting that regular supply of salts to these lakes is paramount to maintain meromixis. This fact discounts the possibility of only very occasional salt input to maintain the salt gradient. The salt budget of Sulphide Pool remains confusing, and without evidence of an inflow - outflow creek by which sea salts can enter this lake, salt migration through the levee is suggested, or perhaps the existing salts are relictual. However, relictual salt is unlikely as Sulphide Pool is about as deep as Lake Morrison which rapidly lost its salt gradient in the absence of regular salt replacement. Furthermore, freshwater would be most likely to migrate through levee banks and not the deeper saline water.

When the new dam above Olga River begins filling, Gordon River flow will be temporarily stopped below the dam, thereby permitting the salt wedge to become re-established. This will afford a perfect opportunity to investigate more closely the whole question of the salt budget of these lakes.

Vegetation and topography shelter the lakes from the unpredictable westerly weather, reducing the effect of wind on the lakes' surfaces.

Temperature patterns are typical of lakes which do not circulate completely, being intimately related to the salt layering, and are in harmony with the local ambient air temperatures. The lakes become stratified in summer, begin cooling in autumn, and when isothermal do not circulate. However, the mixolimnion continues cooling, establishing inverse stratification in winter. As spring approaches the mixolimnion warms until the lake becomes isothermal again, and further warming produces summer stratification.

An unusual warming of the monimolimnion occurs during the summer, which cannot be adequately explained with present information. Geothermal heat flow is one proposal, and to a lesser extent biological heat. The major problem is explaining heat loss from the bottom waters at the end of the stratified period. Upward heat exchange is one possibility, but is likely to be largely reduced by the salt gradient. Undoubtedly the surrounding rainforest also plays an important role in overall lake temperatures, as well as saline and fresh Gordon River inflows.

The mixolimnia were mostly undersaturated with respect to dissolved oxygen, which decreased rapidly with depth to the oxycline, and the monimolimnion contained appreciable amounts of total dissolved sulphides, another typical characteristic of a meromictic lake. Flushing out of salt from Lake Morrison towards the end of the study permitted oxygenated waters to be mixed down to the bottom. Sulphide production in the water body itself undoubtedly occurs but the major portion appears to be produced within the sediments and released to the overlying waters. Levels of sulphide and dissolved silica are apparently also released from the sediments to overlying waters and are also related to temperature fluctuation in bottom waters.

Diurnal heating and cooling of the lake surface only occurred to shallow depths. Minimal diurnal variation in dissolved oxygen indicated very low primary production levels, another characteristic of dystrophic meromictic lakes.

The waters of all three meromictic lakes were darkly coloured due to the presence of considerable amounts of dissolved organic material leached by rainfall from the surrounding rainforest and peats. These dissolved organics created a high oxygen demand, maintaining mixolimnetic oxygen below saturation, sometimes to very low levels. Organic colour also restricted light penetration. Variation of gilvin in the lakes displayed different patterns, with some indication of seasonality in Lake Fidler, possibly in relation to thermal patterns, and no clear variation with depth. In Sulphide Pool and Lake Morrison no seasonal pattern was evident but there were decreases in colour from surface to bottom waters. Colour in both lakes Fidler and Morrison responded to reduced colour in the Gordon River after power station discharge commenced. In the former, lake colour in the top 3 m decreased below levels previously recorded, while in Lake Morrison the entire lake became clearer as chemical stratification was eroded by the cessation of salt input from the river.

The mixolimnia of all three lakes were acid, and contained only small amounts of bicarbonate. Both pH and bicarbonate increased with depth, and in Lake Fidler pH reached a maximum at the bacterial plate, then decreased again in the monimolimnion (Figure 86). Bicarbonate produced by the plate must then have been transported to lower layers and accumulated.

The bicarbonate and pH data suggest the occurrence of minor algal populations which developed in the mixolimnion, and were only short-lived. Biomass information suggests similar populations (see Section 4.3) though not necessarily coinciding with either pH or bicarbonate.

Ionic composition of all three lakes was that of sea water (Figures 98, 100 and 101), and only slight modification to composition occurred due to geochemically modified river water inflows (see Chapter 2), and to biologically important ions (e.g. bicarbonate). Processes controlling concentration and composition of the lake waters do not conform to the simple scheme of Gibbs (1970), for a dilution concentration mechanism is proposed which explains large variations in concentration of marine proportioned waters, eliminating geochemical modification as an intermediate step. The modified scheme now encompasses estuarine and saline lake systems.

Concentration of all major ions increased minimally with depth in the mixolimnion of Lake Fidler, then increased markedly in the chemocline then varied minimally with depth to the bottom (Figure 102). Over the study period, concentration varied (calculated standard variation) mostly at about 1.5 m depth and just above the sediments, suggesting that limited mixing occurred when Gordon River inflows entered the lake at specific depths. Temporal variations of some major ions displayed anomalies which are difficult to explain, but could be due to these Gordon River inflows, but why some ions are affected and not others is not clear.

In both Sulphide Pool and Lake Morrison the concentration of major ions increased little from the surface to about 0.5 m depth, thereafter increasing markedly to the sediments. On some occasions the upper limit of the chemocline was just below the surface at 0.1 m depth, indicating that these two lakes are probably amongst the shallowest meromictic lakes so far reported. Unfortunately this is no longer true for Lake Morrison which is presently not meromictic.

Seasonal variation of silica in the lakes was slight, except for an anomalous increase at all depths in Lake Fidler in February 1977. As for the major ions, silica concentration increased rapidly from the dilute mixolimnetic waters across the chemocline, and in the case of Lake Fidler, increased minimally with depth in the monimolimnion.

There were surprizingly low accumulations of both iron and manganese in the lakes, particularly in the bottom anoxic waters, therefore biogenic processes are not important in maintaining meromixis in the Gordon Lakes. The sharp decrease in redox potential at the oxycline also indicated that dissolved sulphides could have caused iron to precipitate. Low iron and manganese values are most probably due to their scarcity in the area.

Phosphorus occurs in extremely small amounts in south west Tasmania. In Lake Fidler phosphorus was virtually undetectable in influent creeks, and only small amounts, mostly organically bound, were recorded from the mixolimnion. Phosphorus increased markedly with depth through the chemocline, and then increased less dramatically down to the sediments. As for the Gordon Lakes, the monimolimnia of many meromictic lakes act as efficient nutrient traps (see section 4.3.8). High phosphorus accumulation in the monimolimnia of meromictic lakes appears to be closely related to low iron concentrations (Kjensmo 1967), for phosphate can be adsorbed on to ferric hydroxide and precipitated.

In addition to phosphorus, nitrate measurement was also attempted, but unfortunately when samples were passed through the cadmium reduction column, sulphate was reduced to elemental sulphur and clogged the columns.

Intimately associated with the stratification of major ions and nutrients, a plate of algae/bacteria occurred in the vicinity of the oxycline. In Lake Fidler the plate occurred between 1.5 and 2.5 m depth, with low chlorophyll above and below this zone. In Sulphide Pool and Lake Morrison and lower portions of the plate were in contact with the sediments with no relatively clear zone below. Taxonomy of organisms comprising the plate is complex, requiring special investigation.

Finally, factors affecting attenuation of photosynthetically active radiation (PAR) in the meromictic lakes as well as the spectral distribution of PAR at various depths was investigated. Major factors affecting down-welling PAR in fresh waters are, the water itself, dissolved organic colour, photosynthetic pigments and turbidity. Water absorbs small amounts of PAR of wavelengths from about 500 to 700 nm and absorption increases significantly above 700 nm. In contrast, colour absorbs only moderately at long wavelengths, increasing exponentially towards the short wavelength end of the spectrum. Because of this extreme attenuation of blue light phytoplankters have to utilize long wavelength light only for photosynthesis. An unusual feature of these meromictic lakes was that, due to the extreme colour, the lower limit of the photic zone (depth of 1% of surface PAR, Bindloss 1976) lies at a shallower depth than that of the Secchi disc (Figures 86, 87 and 88, Table 20). In broad terms the secchi transparency represented the upper limit of the plate, the *Cryptomonas* zone. Organisms inhabiting the plate therefore live at depths below which the light climate would be normally inadequate for photosynthetic activity. In the plate, light levels are reduced below which they can be reliably measured.

Water released from Lake Gordon has diluted the colour of the Gordon River, which in turn has lowered colour of the surface waters of Lakes Fidler and Morrison, which would significantly increase penetration of PAR, and therefore influence primary productivity. The algal bloom which developed just below the surface in Lake Fidler in March 1978, and the doubling of the plate biomass from 1977 to 1978 could be due to improved light penetration. However, in Sulphide Pool surface colour in 1978 was slightly lower than in 1977 and plate biomass was substantially lower in 1978 than in 1977. Biomass variations are therefore more likely to be associated with stratification, dissolved gasses and nutrient availability. The role of light in plate productivity is ambiguous at this stage.

Phytoplankton biomass influenced light penetration insignificantly in Lakes Fidler and Morrison, but in Sulphide Pool high biomass significantly attenuated PAR in the upper waters of the lake. Assessing the influence of biomass on light penetration was very complex for gilvin varied with depth in some lakes and occasionally a narrow mixolimnetic phytoplankton plate may have been present which was not measured.

The mixolimnetic waters of these lakes contained very small amounts of particulate material which did not contribute to PAR attenuation, in the presence of high colour.

Because colour was the principal factor attenuating PAR in the Gordon lakes, long wavelength red light penetrated deepest but to shallow depths only, and blue light was severely attenuated even by a very shallow depth of lake water.

CHAPTER 5

Concluding remarks

CONCLUDING REMARKS

The Gordon River Basin is a unique area, largely untouched by man. The high rainfall and complex geology make this area very suitable for investigating those factors which cause variability in the ionic composition of river waters. Though the Gordon River flow pattern itself has been significantly altered by hydro-electric development, many catchments remain unaffected and these could be used for detailed long term study. Now that some basic data exists relating water chemistry to flow (and hence rainfall) more detailed investigation is required to ascertain more precisely the effect of various rock types on river chemistry, and to compare catchments of differing geological and vegetational composition. These studies should be planned similarly to the "Hubbard Brook" investigation (Likens *et al* 1977), where various factors (e.g. atmospheric precipitation, springs and seepages) are closely monitored and related to stream chemistry and accurately measured flow, not extrapolated data from sites some distance away. Another major advantage would be easily accessable sampling sites which would permit frequent and complete sets of samples to be collected. In south west Tasmania the rugged terrain and adverse weather often hampers accessibility to sampling sites, and research grants do not usually allow for extensive use of helicopters in sampling programmes. However, several catchments within the Gordon Basin will permit a "Hubbard Brook" type investigation e.g. the upper Franklin and Collingwood Rivers.

River flows and chemical changes in the Gordon Basin respond rapidly to catchment rainfall. A complicating factor in interpreting these relationships is the presence of varying amounts of both sodium and chloride in the Gordon limestone (Rao and Naqvi 1977). This is clearly illustrated when chloride contributes a significant proportion of anions at low flows, and predictably dominates the anions at high flows. Bicarbonate expectedly dominates the anions at low flows and contributes insignificantly at high flows, sometimes being completely absent in very acid forest peat seepages. The cations display a more confused relationship with river flow. This is well illustrated in the Jane River where anionic dominance order fluctuates between bicarbonate and chloride according to flow, but no clear picture emerges in the cationic dominance, except that calcium and magnesium tend to dominate at low flows and sodium at high flows (Figure 42). A similar picture emerges from the upper Franklin River (Figure 33) and from the Gordon and Franklin River at their junction (Figure 26). Unfortunately these figures all lack an adequate spread of data points over the range of flows for each individual river.

Climate is the most important factor controlling the concentration of inland waters in Tasmania (Buckney 1974). This is confirmed from the Gordon River Basin where salinity decreases exponentially with increasing rainfall (e.g. Figures 28, 35, 39, 41 and 43). Geology and climate contribute almost equally in determining the variability of ionic concentration in rivers where dolomite and/or Gordon limestone sequences occur in the catchments, thus conforming to Gibbs' (1970) scheme of ionic variability. However, deviations from Gibbs' scheme have been noted, e.g. some small creeks and peat seepages undergo insignificant geochemical modification even at low flows (Chapter 2), and in the estuarine reaches of the Gordon River when dilute river water admixes with the underlying salt layer, increasing its concentration significantly, but causing less significant variations in composition. This is further illustrated in the meromictic lakes (Figure 38), indicating that Gibbs' (1970) scheme breaks down in estuarine and coastal lagoon environments.

In addition, factors such as catchment vegetation and soil types influence water chemistry. In south west Tasmania the peat soils, and to a lesser extent vegetation, impart organic acids to percolating rainwater, lowering pH and increasing colour. The peats and vegetation may well play an important role in nutrient and salt cycling, though this was not evident, due mainly to the fact that each catchment possessed a mosaic of vegetation types rather than one homogeneous type. For example, the vegetation in the catchments for both Roaring Creek and Smith River were almost entirely closed forest, but due to geochemical influences on the waters of the latter, different ionic proportions were recorded.

In Chapter 2 the suggestion is made that excreted, decomposed and bound organic ions may be weakly retained by the peats and vegetation during rain-free periods, so that at high flows, large amounts of this material are leached into the rivers, thus further complicating the interpretation of river chemistry.

Temporal variation in ionic concentration and composition in the middle and lower Gordon River has been altered by construction of the Gordon Dam Power Station (see Chapter 2). Very limited chemical information from the river prior to construction is available (King and HEC 1978), and no data exists from early stages of Lake Gordon filling, making it impossible to fully assess effects of impoundment, not only on river chemistry but on the fauna and flora as well. Further changes to river chemistry will occur when Stage 2 of the Gordon Power Development commences, and hopefully this event will be more fully documented.

Apart from a reduction in ionic concentration and a stabilizing of composition by release of water from the Gordon Power Station the flow pattern in the river has been significantly altered. Figure 5 illustrates that high winter flows have been reduced, but more significantly, low summer flows have been greatly increased by power station discharge. When the river was in its natural state environmental conditions must have been ideal for high production of both fauna and flora, for the waters were warm, slow flowing, contained appreciable amounts of alkaline earth bicarbonates, and light was able to penetrate to the bottom, even in those dark waters. No measurements of river productivity were made but it can be inferred that a poor light climate and cooler, less concentrated waters of sodium chloride domination from Lake Gordon (Steane and Tyler 1978) have greatly reduced aquatic production, and that many species will have been forced from the river, possibly seeking refuge in "pickup" rivers. The effect of power station discharge could be assessed, as both benthic fauna (Coleman 1978) and flora prior to discharge have been collected, only requiring a follow-up sampling. In addition, comparisons could be drawn between the Franklin and Gordon Rivers in order to determine the effect of discharge on river biota. This has been done to a limited extent for the fauna by Coleman (1978) but no information exists for the flora.

Further, the changed flow regime in the river had resulted in the saline wedge, which, previous to discharge, penetrated up the river during low summer flows, being flushed from the river (Kearsley 1978). Admixture of fresh river water with the saline water below no longer occurs and salinity in the surface waters in the lower reaches of the river remains consistantly low all year. This means that the salt supply to the meromictic lakes has ceased - this has already become evident in Lake Morrison. Figure illustrates the breakdown in chemical stratification in this lake during the summer immediately after discharge commenced, and more recent work has shown that chemical stratification no longer exists (Tyler and Baker, personal communication). Conductivity of surface and bottom waters were 88 μS/cm and 104 μS/cm respectively on 10th July 1980). Unfortunately information from Lake Morrison is limited due to logistic problems; nonetheless marked changes have occurred and the lake appears to have reverted from being meromictic to holomictic. As previously stated, when the lake created by Stage 2 of the Gordon Power Development begins filling, present water flows downstream of the dam will be diminished, and relatively uncontrolled river flows will again prevail for a short period. Hopefully this discharge lull will coincide with several summers when pickup river flows are low, allowing salt water to penetrate up the river again and the salt wedge can re-establish. These circumstances will provide a superb opportunity to monitor salt input to the lake and the re-establishment of meromixis, if it occurs at all. A detailed monitoring programme at this time will provide valuable information on the origin of meromixis in the Gordon Rover meromictic lakes, as well as the waxing and waning of the bacterial plate and other algal populations which may develop under changing salt levels and restrictive circulation patterns.

The present study unfortunately started too late to investigate the more pronounced influences of Gordon Dam construction on river chemistry, e.g. leachates from the dam site and from the underground power station excavations (Wilde 1978), which produced marked changes downstream, but apparently for a relatively short period only as they were not obvious during this study.

Chapter 3 describes Perched Lake which is elevated above the Gordon River at Butler Island. This moderately dystrophic lake, with water chemistry similar to sea water, is of the type to be expected for this south west area, and more closely resembles coastal lagoons (e.g. Gordon Lagoon) and sedge-land waters (Buckney and Tyler 1973b) than lakes of the highland areas of Tasmania (King, unpublished data, Buckney and Tyler 1973a). From the limited catchment surprisingly small amounts of organic matter are leached by rainfall and enter the lake. This moderate colour is still able to cause rapid attenuation of incident radiation, though not as marked as in the much darker meromictic lakes. Blue wavelengths of light are especially strongly attenuated in all these west coast humic lakes.

Perched Lake received no salt input from the Gordon River, and was therefore able to circulate freely, stratifying for several months in summer, and circulating freely in winter (Figures 6 and 52). Towards the end of the stratification period oxygen in the bottom waters is reduced to only about 20% of saturation, suggesting low primary production in the lake.

The lake is surrounded by limestone and sandstone, and surprisingly the ionic proportions align with sea water rather than with fresh water. However, slight chemical differences were detected at about 5 m depth, suggesting subterranean inflow of artesian water. This has also been suggested as an explanation for the thermal anomaly of hypolimnetic cooling, a phenomenon also occurring in the meromictic lakes. Nevertheless, hypolimnetic heating and cooling occurs in harmony with temporal thermal patterns in all four lakes (Chapters 3 and 4), so perhaps in Perched Lake, as was also suggested for the meromictic lakes, the process of geothermal heat exchange involving the surrounding forests would be more applicable. A more soundly based energy budget study on all these lakes would be required to establish the precise principles involved.

Typical of west coast dystrophic systems, the phytoplankton of Perched Lake was sparse, and for most of the study was dominated by *Dinobryon sertularia* and two species of desmid. All three taxa occur widely in west coast dystrophic lakes, with the unidentified *Staurastrum* sp. 1 (Plate 17) displaying wide variability, inferring that Perched Leke flora has close affinities with other south west waters.

An unusual feature of the phytoplankton was the occurrence of the dinoflagellate, probably *Prorocentrum* sp., a type previously recorded only from marine environments. It has also been recorded in very low numbers in some other west coast lagoons. The apparently disjunct distribution of this organism in coastal lagoon environments is surprising. Though *Dinobryon sertularia* occurs commonly in west coast dystrophic lakes, it was rare in Sulphide Pool and not apparent in either of Lakes Fidler or Morrison. Several closely related species were recorded which are unusual. Some taxa have stalked loricae which closely resemble *Stylobyron* or *Epipyxis* while another species has long urn-shaped loricae.

Recent studies have revealed that the *Xanthidium* sp. (Plate 17), which has been recorded from Perched Lake, Gordon Lagoon and the Bellinger Lakes (coastal lagoons approximately 5 km north of Strahan) appears to be a new species (J. Gerrath, personal communication). This organism displays wide morphological variation in the wild state. Similarly the *Staurastrum* sp. 1 (Plate 17) occurs commonly in Perched Lake and the Bellinger Lakes and sparsely in Gordon Lagoon and Ocean Beach Lagoon (5 km west of Strahan). This organism also varies considerably, displaying many morphological forms, and also appears to be a new species (J. Gerrath, personal communication). Some types resemble *St. longebrachiatum* var. *bifurcatum* Krieger 1932, or var. *australe* (Racib.) Krieger 1932, while others resemble *St. leptocladum* var. *africanum* West 1907 or *St. shiwanganduensis* Thomasson 1966. These taxonomic problems are currently under investigation.

Although the meromictic lakes have been known since early European settlement in Australia, they have only been known to science since the Lower Gordon River Scientific Survey. They represent a significant contribution to the world-wide distribution of this lake type, and more particularly to its distribution in Australia. It is conceivable that other meromictic lakes similar to those of the Gordon River occur elsewhere along the tidal reaches of rivers but, due to their relatively small size and inaccessability, have been neglected.

As a result of the small size of the Gordon River meromictic lakes they respond intimately to variations in weather conditions from year to year. This is clearly illustrated by differences in the distribution of temperature and dissolved gases within the lakes during the study period. The reasons for these differences are generally unclear, and would require more detailed investigation, particularly in relation to local weather conditions and to Gordon River influences upon the lakes.

This thesis essentially presents a characterization of the meromictic lakes and does not aim to explain many of the seasonal and spatial variations which occur, but explanations are attempted in many cases. Now that basic information exists, more detailed investigation into nutrient and other biologically important chemical species is required, as well as the biological requirements of the plate organisms, particularly in relation to light requirements.

Unfortunately alterations in river conditions due to Gordon Dam discharge have imposed lasting changes on the lakes, e.g. breakdown of the chemocline in Lake Morrison and the inflow of less coloured and concentrated waters from the Gordon River to the lakes. This study ended too soon to assess the likely effects of constant and sustained elevation in river and hence in lake levels, particularly in relation to the bacterial plate and sundry mixolimnetic phytoplankton populations. Obviously therefore, much of the information on the lakes contained within this thesis is not possible to reproduce, thereby necessitating a re-examination of the lakes to categorize them under present conditions.

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APPENDICES

APPENDIX I

Elevation above Mean Sea Level and distance along rivers from Butler Island for selected stations.

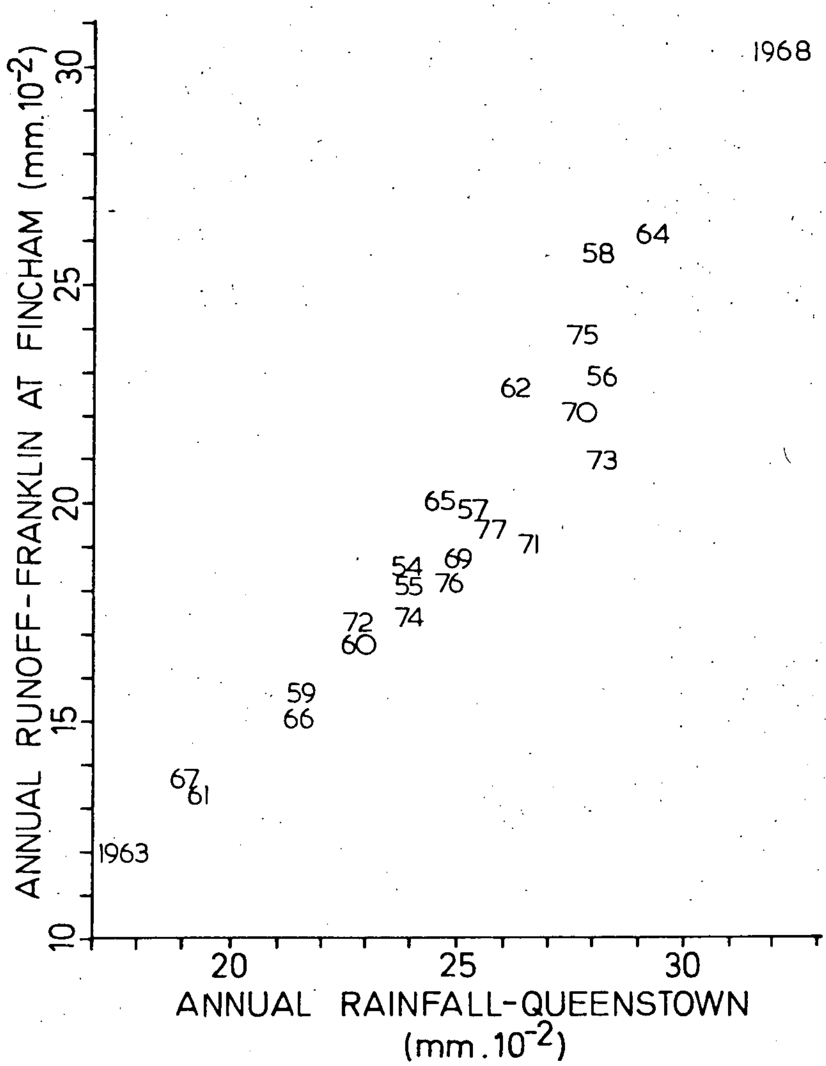
(Extracted from Watson 1978)

AWRC Sampling Station No.	Station Name (Site)	Grid Co-ordinates		Approx. Elevation above M.S.L.	Distance Upstream from Butler Island (Kilometres)
		Easting	Northing		
3081042	Gordon River at Butler Island Camp	392300	5286000	0	1
3081034	Gordon River above Franklin	396650	5283600	5	9
3081040	Franklin River 1 km upstream Gordon River	396750	5284550	5	10
3081032	Gordon River above Sprent	397450	5279600	10	15
3081024	Gordon River upstream Smith	402000	5273500	15	25
3081041	Cataract Creek above Sir John Falls	392550	5285800	20	2
3081012	Roaring Creek above Franklin	396550	5284700	20	10
3081019	Gordon below Denison	403800	5269750	20	30
3081023	Harrison above Gordon	402000	5273750	20	25
308013	Denison/Denison Camp	404300	5269800	23	31
3081025	Smith River opposite Olga Camp	401600	5273700	25	25
308004	Franklin below Jane	398200	5297100	40	27
3081007	Gordon River at Splits Camp	406850	5267000	40	34
3081030	Olga River 4 km from Mouth	400000	5270100	45	27
3081021	Denison above Maxwell River	407500	5272600	55	37
3081014	Gordon River below Albert Rapids	412250	5266400	65	41
308011	Jane River below Punt Hill	401250	5301400	67	35
3081027	Olga River (Hardwood Saddle)	404150	5254900	75	34
3081046	Andrew River - crossover Crotty Track	385750	5324850	220	68
308025	Collingwood River - crossover on Lyell Highway	411400	5331400	340	99
3081013	Franklin River - crossover on Lyell	419050	5325650	390	104

APPENDIX II

Alteration to average monthly flows and river heights in the Lower Gordon River, measured at Olga (AWRC No. 3081006). (Modified from Watson, 1978a)

Month	Controlled Condition				Natural Average Monthly Flows At Olga	Average Monthly River Height At Olga	Alteration to Average Monthly River Heights At Olga
	Average Monthly Release Gordon P.S. (m^3/s)	Average Monthly Pickup To Olga (m^3/s)	Average Monthly Flow At Olga (m^3/s)	Average Monthly River Height At Olga (m)	(m^3/s)	(m)	(m)
January	167.32	21.57	188.89	2.44	58.44	1.39	+ 1.05
February	135.98	15.07	151.05	2.21	38.51	1.16	+ 1.05
March	134.62	24.45	159.07	2.26	66.83	1.48	+ .78
April	91.18	48.20	139.38	2.13	135.98	2.10	+ .03
May	69.69	71.28	140.97	2.14	207.55	2.55	- .41
June	66.01	62.79	128.80	2.05	182.81	2.41	- .36
July	66.74	70.71	137.45	2.11	205.88	2.54	- .43
August	69.69	67.51	137.20	2.11	196.58	2.49	- .38
September	72.83	61.07	133.90	2.08	177.81	2.38	- .30
October	91.29	52.29	143.56	2.16	147.82	2.19	- .03
November	115.79	41.67	157.46	2.25	116.94	1.95	+ .30
December	164.18	37.98	202.16	2.52	106.20	1.86	+ .66



APPENDIX 3

RELATIONSHIP BETWEEN ANNUAL RAINFALL AT QUEENSTOWN AND ANNUAL RUNOFF AT FRANKLIN – MT. FINCHAM. (REDRAWN FROM WATSON 1978a.)

APPENDIX 4

Figure	Regression Equations	r	n
17	Turbidity = 1.05 - 0.001 Flow	-0.01	87
18	Gilvin (G440) = 0.04 Pt units + 0.30	0.99	75
26	Gordon River above Franklin		
	HCO_3 = 58.47 - 0.21 Flow	-0.88	12
	Cl = 39.90 + 0.20 Flow	0.90	12
	SO_4 = 1.65 + 0.01 Flow	0.26	12
	Ca = 30.12 - 0.03 Flow	0.19	12
	Mg = 26.47 - 0.002 Flow	-0.02	12
	K = 1.15 + 0.02 Flow	0.61	12
	Na = 42.36 + 0.01 Flow	0.03	12
	Franklin River above Gordon		
	HCO_3 = 55.35 - 0.06 Flow	-0.18	13
	Cl = 43.65 + 0.04 Flow	0.14	13
	SO_4 = 0.88 + 0.02 Flow	0.29	13
	Ca = 33.55 - 0.01 Flow	-0.05	13
	Mg = 28.19 + 0.04 Flow	0.19	13
	K = 1.34 + 0.001 Flow	0.25	13
	Na = 36.71 - 0.03 Flow	-0.07	13
	Gordon River at Butler Island Camp		
	HCO_3 = 58.76 - 0.08 Flow	-0.75	12
	Cl = 40.45 + 0.07 Flow	0.60	12
	SO_4 = 0.88 + 0.01 Flow	0.18	12
	Ca = 46.96 - 0.09 Flow	-0.69	12
	Mg = 25.20 + 0.03 Flow	0.45	12
	K = 5.39 - 0.02 Flow	-0.58	12
	Na = 22.66 + 0.08 Flow	0.71	12
27	K_{18} = 15.87 + 1.16 Salinity	0.89	169
30	Salinity = 4.37 - 0.02 Flow	-0.98	5
33	Franklin River		
	HCO_3 = 60.52 - 0.89 Flow	-0.49	8
	Cl = 34.18 + 1.05 Flow	0.44	8
	SO_4 = 5.43 - 0.16 Flow	-0.19	8
	Ca = 37.12 - 0.59 Flow	-0.38	8
	Mg = 29.90 + 0.14 Flow	0.29	8
	K = 3.25 + 0.000 Flow	0.00	8
	Na = 31.76 + 0.47 Flow	0.28	8
	Collingwood River		
	HCO_3 = 64.39 - 0.65 Flow	-0.81	8
	Cl = 28.42 + 0.67 Flow	0.72	8
	SO_4 = 6.96 + 0.004 Flow	0.01	8
	Ca = 38.68 - 0.41 Flow	-0.81	8
	Mg = 26.22 + 0.26 Flow	0.51	8
	K = 0.69 + 0.06 Flow	0.97	8
	Na = 34.36 + 0.10 Flow	0.17	8

APPENDIX 4
(Continued)

Figure	Regression Equations	r	n
42	HCO_4 = 76.36 - 0.54 Flow	-0.97	9
	Cl = 20.72 + 0.47 Flow	0.97	9
	SO_4 = 3.79 + 0.47 Flow	0.49	9
	Ca = 18.81 + 0.04 Flow	0.05	9
	Mg = 33.67 - 0.23 Flow	-0.06	9
	K = 0.87 + 0.002 Flow	0.12	9
	Na = 23.72 + 0.17 Flow	0.55	9

APPENDIX 5

Phytoplankton Species List

for

Perched Lake

APPENDIX: Phytoplankton in Perched Lake. The cell volumes (μm^3) for species contributing more than 1% of the biomass are shown.

Cyanophyceae		
Merismopedia glauca (Ehr.) Naegeli		summer, rare
Dinophyceae		
Peridinium sp.	6545	summer, very rare
Phalacroma sp.	1641	all year, rare
Chrysophyceae		
Dinobryon sertularia Ehr.	1910[1]	all year, abundant summer and autumn
Mallomonas sp.		all year, abundant summer
Bacillariophyceae		
Surirella tenera Greg.		winter, very rare
Cyclotella stelligera Cleve and Grun.		summer, very rare
Frustulia rhomboides (Ehr.) DeT.	1400	summer, rare
Frustulia spp.		summer, rare
Frustulia rhomboides var. *capitata* (A. Mayer) Patr.		summer, very rare
Melosira italica (E.) Kg.		summer, very rare
Cymbella sp.		summer, very rare
Eunotia spp.		summer, very rare
Tabellaria flocculosa (Roth) Kutz		all year, very rare
Chlorophyceae		
Eudorina elegans Ehr.		autumn, very rare
Asterococcus superbus (Cienk.) Scherffel	392	all year, abundant summer
Schroederia sp.	19	spring and summer, frequent
Elakatothrix cf. *viridis* (Snow) Printz	1319	summer and autumn, frequent
cf. *Sphaerocystis schroeteri* Chodat	49[2]	autumn, abundant
Scenedesmus quadricauda var. *longispina* (Chodat) G.M. Smith		summer, very rare
Spirogyra sp.		very rare

<u>Desmidiaceae</u>

Arthrodesmus cf. *triangularis* Lagerh.	694	all year, abundant autumn
Xanthidium sp.	6825	summer, rare
Cosmarium spp.		summer, very rare
Euastrum sp.		spring, very rare
Hyalotheca sp.		spring, very rare
Pleurotaenium spp.		spring and summer, very rare
Staurastrum aureolatum Playfair	1714	all year, rare
Staurastrum pingu Teiling		spring, rare
Staurastrum sp. 1	6080	all year, summer and autumn, abundant
Staurastrum sagitarrium Nordst.	36128	winter and spring, rare

[1] Volume of lorica. Number of loricae per colony counted.

[2] Cell volume. Eight cells per colony.