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CHEMICAL CHARACTERISTICS AND NUTRIENT STATUS OF BILLABONGS OF THE ALLIGATOR RIVERS REGION, NORTHERN TERRITORY (FINAL REPORT)

prepared by

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Supervising Scientist for the Alligator Rivers Region

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CHEMICAL CHARACTERISTICS AND NUTRIENT STATUS OF BILLABONGS OF THE ALLIGATOR RIVERS REGION, NORTHERN TERRITORY

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01

CONTENTS

SUMMARY

A major feature of tropical Australia is the sharp climatic distinction between the Wet and the Dry, a characteristic climatic pattern which imposes a distinctive hydrological regime on running and standing bodies of water. During the Wet, vast quantities of water pour down rivers from the Arnhem Land escarpment to inundate the lowlands of the Alligator Rivers. All existing bodies of water are flushed. When the rains cease, the floodwaters recede, leaving behind a series of billabongs filled with the dilute water of the Wet. During the ensuing Dry, water levels fall continuously as more than 2 metres of water evaporates, with no replenishment from rain. Some billabongs receive groundwater inflows; a few near the escarpment are spring-fed, perhaps to flow throughout the Dry.

Chemical changes occur as water levels drop. Solutes become concentrated as water evaporates, wind and buffalo resuspend fine sediments, and spring or groundwater inflows may influence the chemical composition. The magnitude and direction of change varies from billabong to billabong, depending on morphometry, position, sediment type, and so on. In December, the flood-waters come again, replacing this individuality with the uniform standards of one big lake.

Then, the water is dilute (K_{25}<20μScm^{-1}), near neutral, and dominated by sodium bicarbonate. Nutrient levels are at their lowest but, on a world scale, total phosphorus levels are high and the billabongs would be regarded as meso-eutrophic to hypereutrophic. N:P ratios are low, and in terms of inorganic nitrogen the billabongs are ultra-oligotrophic. The sheer volume of water, from intense rainfall and rapid runoff, ensures that billabongs over a wide area of the Magela, Nourlangie and Coopers Creek catchments enter the Dry with this common water chemistry. This uniformity is short-lived, and by the end of the Dry three main groups of billabongs can be distinguished by the nature and extent of chemical change they have undergone.

Least changed are the channel billabongs of the three creek systems. They are still dilute, have suffered scant change in pH, and their ionic and nutrient character is still that of the Wet. That they have changed so little can be attributed, in large measure, to the characteristically low surface area to volume ratios of channel billabongs. Under these conditions, the effects of evaporation are at a minimum. Implicit in this is the assumption that any inflowing groundwater is also unchanged from Wet season chemistry.

In all other billabongs a number of changes take place. All become turbid. Prominent amongst the changes in ionic character is the decided move to sodium chloride dominance. Usually, this is accompanied by marked increases in conductivity as the waters concentrate, and a decline in pH as the Dry progresses. Two groups can be recognized. In one, the floodplain billabongs (plus Corndorl), the change to sodium chloride dominance is accompanied by significant enrichment by sulphate from groundwater inflows. In the other, containing most backflow billabongs (plus Kulukuluku and Leichhardt), sulphate plays little part. In both groups, nutrient concentrations increase rapidly during the Dry, earlier on the floodplain than in the backflow billabongs. In the former, inorganic nitrogen constitutes a much higher proportion of total nitrogen than in the latter. Except in floodplain billabongs, N:P ratios are low and limitation of production by nitrogen, not phosphorus, is suspected. Phosphorus levels now indicate hypereutrophy, while inorganic nitrogen levels indicate a range from meso-eutrophic to hypereutrophic.

Throughout the Dry nutrient cycles can be envisaged as a closed, endorhoeic system, with external inputs from biotic and, perhaps, groundwater sources, with evaporative concentration, and with internal loading from resuspended sediments. In marked contrast to temperate lakes, there is no output other than biotic migration.

The classification into 3 groups on the basis of major ion chemistry and on the basis of nutrients is congruent, and coincides, with few exceptions, with the traditional division on geographical, morphological and hydrological criteria into channel, backflow and floodplain billabongs.

1. INTRODUCTION

It is almost an article of faith that water analyses be carried out, though it is not always clear why they are done nor what they reveal. However, it is the sum of the physical and chemical conditions that determines the type of waterbody, and probably which organisms live in it. It is inconceivable that a broad limnological investigation of an unstudied region should ignore water chemistry any more than any other "base-line" information (Fox *et al.* 1977).

Even in the most dilute natural waters all major ions are usually present in quantities exceeding the requirements of the biota (Moss 1980), and they have little effect on productivity. However, that the ionic character of natural waters has biological significance, in determining the distribution of organisms, is apparent from the possession by most, if not all of them, of ionic regulation mechanisms (Bayly and Williams 1973). Further, the toxicity of heavy metals and other pollutants to native biota depends heavily on the chemical nature of the water into which they are discharged. The nutrient elements, notably phosphorus and nitrogen, are usually present in quantities insufficient to satisfy biotic demand and, as limiting nutrients, their supply regulates the productivity of both aquatic and terrestrial ecosystems. A knowledge of nutrient levels and cycles is essential to an understanding of the dynamics of the freshwater environment. At the pragmatic level, chemical analysis underlies the protection of water quality in public supplies, and intimate understanding of nutrient chemistry is the key to proper resource management, and the avoidance or abatement of the ills of eutrophication.

With the stark climatic contrast and distinctive hydrological regime of the Alligator Rivers Region, considerable physical and chemical change must attend the seasons. This study set out to characterize the pattern of seasonal change in the chemical nature of the billabongs of the Magela, Nourlangie and Coopers Creek Catchments, the Dry season refuges of a large aquatic biota.

Details of climate, geography, and hydrology, together with descriptions of the billabongs, which have appeared elsewhere (Hart and McGreggor 1980; Walker, Waterhouse & Tyler 1982) are summarised in Figure 1.1 and Table 1.1.

Table 1-1: A classification of billabongs in the three catchments of the Alligator Rivers Region (after Walker, Waterhouse and Tyler 1982).

Billabong Classification	Catchment	Billabong Name
Channel	Magela	Mudginberri
		Buffalo
	Nourlangie	Noarlanga
	Coopers	Nimbawah
		Murganella Rd.*
" /Escarpment rockpool	Magela	Bowerbird
" /Backflow	Baroalba/ Magela	Goanna
" /Floodplain	Magela	Island
	Nourlangie	Kulukuluku
Backflow	Magela	Georgetown
		Coonjimba
		Gulungul
		Corndorl
	Nourlangie	Umbungbung
Floodplain	Magela	Ja Ja
		Mine Valley
		Leichhardt
		Jabiluka
		Nankeen
	Nourlangie	Jingalla
	East Alligator	Red Lily

* Not included in Walker, Waterhouse and Tyler (1982). Located at junction of Coopers Creek and the road to Murganella, map reference Oenpelli 906618. Hereafter called simply Murganella.

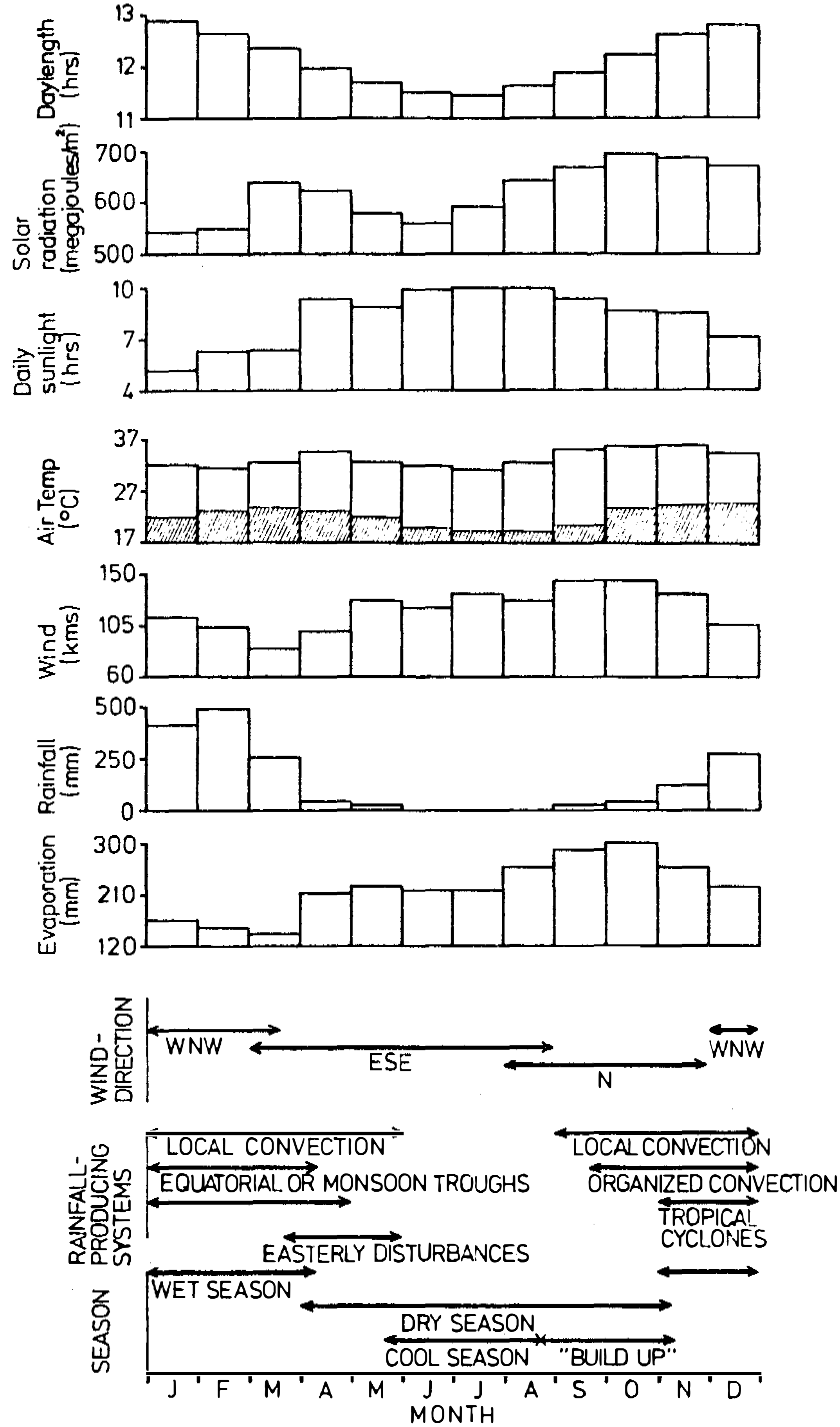


Fig 1.1. Synopsis of seasonal meteorological attributes of the Alligator Rivers Region. (After Walker, Waterhouse and Tyler, 1982).

2. MATERIALS AND METHODS

For routine chemical characterization, surface water samples were taken at approximately monthly intervals at a fixed sampling site at, or near, the deepest point of each billabong. Preliminary investigations had shown that in most billabongs there was scant chemical difference between surface and deeper waters, so that for all intents and purposes, a single sample from the surface would suffice. This was to be expected from prevailing stratification behaviour (Walker, Waterhouse & Tyler 1982). Samples for major ion analyses were collected, stored and transported in pre-washed polyethylene bottles. During 1978 analyses were carried out in Adelaide by Australian Mineral Development Laboratories (AMDEL), on unfiltered samples, and in subsequent years by the Botany Department, University of Tasmania, on filtered samples. For interlaboratory comparisons some bicarbonate analyses during 1979 and early 1980, along with cation analyses during February/March 1981, were duplicated, with determinations made at both the University of Tasmania and the Jabiru laboratory of the Office of the Supervising Scientist. Samples distined for nutrient analysis were partitioned immediately into six sub-samples in sealable, sterilized, polyethylene bags (trade-name "Whirl-paks") and immediately placed on ice until return to the Jabiru laboratory, when they were deep-frozen. The analyses were carried out by the Nutrient Analysis Laboratory of the Botany Department, University of Western Australia. An index of all the chemical parameters measured, and the methods employed in Jabiru, Hobart, Adelaide and Perth, appears in Table 2.1.

In the tables of results (Appendix I) major ion analyses are reported as mgl^{-1}. Ionic orders of dominance are determined from relative ionic proportions (μeq%), where each ion is expressed as a percentage of the total microequivalents of cations and anions respectively. Graphical representation is by means of ternary diagrams (adapted from Hem 1970), which present the relative ionic proportions. In the diagrams each corner of an equilateral triangle represents 100% of a given ion. Actual percentages of any

PARAMETER	FILTRATION?	EQUIPMENT	METHOD	SOURCE.
Field pH	No	Metrohm E604 pH meter	Electrometric	APHA (1971)
Laboratory pH	Yes	Radiometer PHM26 meter (HOB)	Electrometric	APHA (1971)
	No	Radiometer PHM61 meter (ADEL)	Electrometric	
Conductivity (K_{25})	Yes	Radiometer CDM3 meter (HOB)	Electrometric	APHA (1971)
	No	Phillips Conductance bridge GM4249 (ADEL)	Electrometric	
Sodium (Na)	Yes	Varian Techtron AA5 AAS[1] (HOB)	Air/acetylene flame spectrophotometry	APHA (1976)
	No	As above (ADEL)	Nitrous oxide/acetylene flame spectrophotometry (with Cs additions)	
	Yes	Perkin Elmer ? (JAB)	Air/acetylene flame spectrophotometry (with Cs/La additions)	
Potassium (K)	Yes	As for sodium (HOB, JAB)	As for sodium (HOB, JAB)	
	No	As for sodium (ADEL)	As for sodium (ADEL)	
Calcium (Ca)	Yes	Cecil CE292 spectrophotometer (HOB)	Glyoxabil-bis-(2 hydroxyanil) method	Kerr (1960)
	Yes	As for sodium (JAB)	As for sodium (JAB)	
	No	As for sodium (ADEL)	As for sodium (ADEL)	
Magnesium (Mg)	Yes	As for sodium (HOB, JAB)	As for sodium (HOB, JAB)	
	No	As for sodium (ADEL)	As for sodium (ADEL)	
Chloride (Cl)	Yes	Radiometer CDM3 meter coupled with Titrator II (HOB)	Conductometric titration with $AgNO_3$.	Golterman (1969)
	No	Metrohm Multidosimat E415 coupled with Titrator E526 (ADEL)	Argentometric method.	APHA (1975)
Sulphate (SO_4)	Yes	Cecil CE292 Spectrophotometer (HOB)	Barium chloride, turbidimetric method	APHA (1976)
	No	Technicon Autoanalyser II (ADEL)	Ion-exchange followed by use of methyl thymol blue	APHA (1975)
Bicarbonate (HCO_3)	Yes	Radiometer PHM26 meter coupled with Titrator II (HOB)	Potentiometric titration	APHA (1976)
	No	Metrohm Multidosimat E415 coupled with Titrator E526 and pH meter (JAB)	Potentiometric titration	
	No	Radiometer PHM61 meter coupled with ABU11 Autoburette (ADEL)	Potentiometric titration	
Orthophosphate-phosphorus (PO_4-P)	No	Varian Techtron 634 Spectrophotometer (PER)	Single solution method	Major et. al., 1972
'Organic' phosphorus (OP)	—	—	Subtraction (difference between PO_4-P and TP)	Atkins [illegible], 1979
Total phosphorus (TP)	No	As for PO_4-P (PER)	Perchloric acid digestion, then as for PO_4-P.	Major et. al., 1972
Ammonia (NH_4-N)	No	As for PO_4-P (PER)	Cyanurate method	Dal Pont et. al. 1974
Nitrate and nitrite (NO_3/NO_2-N)	No	Technicon Autoanalyser (PER)	Copper cadmium reduction, then diazotization	APHA (1976)
Organic nitrogen (ON)	—	—	Subtraction (difference between NH_4-N and KN[2])	APHA (1971)
Total nitrogen (TN)	No	Technicon Autoanalyser II (PER)	Kjeldahl digestion, then as for NH_4-N to give KN; Addition of KN to NO_3/NO_2-N.	APHA (1971)

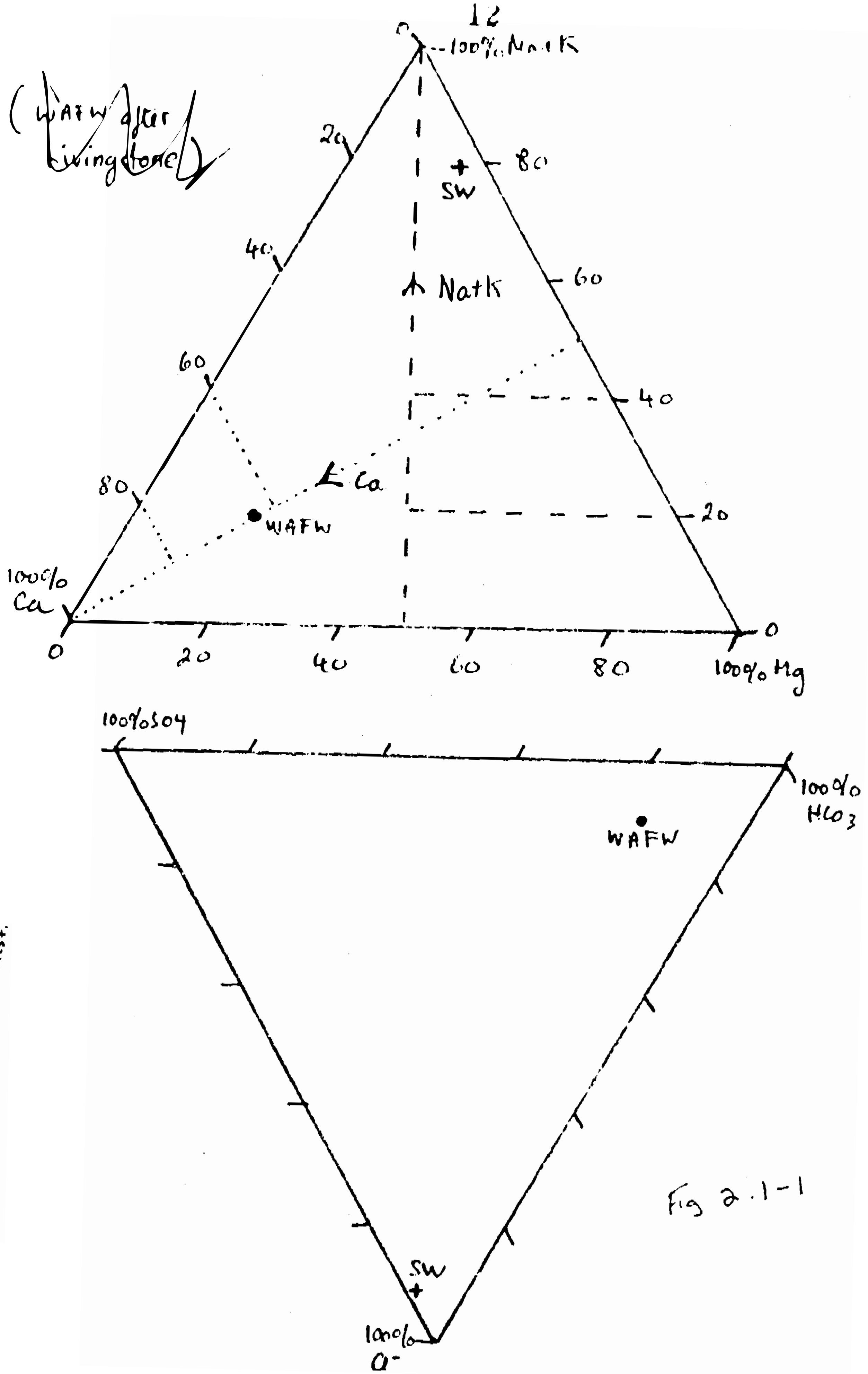
[1] AAS = Atomic absorption spectrophotometer

[2] KN = Kjeldahl nitrogen.

Table 2-1: Analytical methods used by Jabiru (JAB), Perth (PER), Adelaide (ADEL) and Hobart (HOB) laboratories.

ion in a sample are measured along ~~with~~ any perpendicular from the opposite side (Fig. 2.1-1). Since potassium is present in most natural waters in very low relative and absolute amounts, it is frequently ignored in ternary diagrams. Here it is combined with the dominant monovalent cation, sodium. Carbonate is usually represented in combination with bicarbonate in ternary diagrams, as in an alternative graphical procedure, the Maucha diagram (Maucha 1932). Since pH values of the billabongs were always less than 8.3, carbonates would not be present, as dictated by pH-dependent equilibrium reactions. Two convenient reference points are seawater proportions, and those of World Average Freshwater (Bayly and Williams 1973). The ternary diagram simplifies discussion of chemical events, and chemical behaviour of a billabong during a season can be spoken of, teleologically, in terms of the movement of a point, the ionic proportions of that billabong, about the diagram.

For the examination of the shallow, groundwater table around Jabiluka billabong, boreholes were sunk by hand-operated auger to 1.5-2 metre depth. They were then cased with perforated 60 mm plastic piping, wrapped in 3 layers of 1 mm nylon monofilament mesh, with a thin screen of blue metal shielding the casing from the sides of the borehole (Fig. 2.2). The height of each cased borehole relative to the zero level on the gaugeboard at Gauging Station 821017 was then determined by theodolite.



This diagram being redrawn by graphic artist.

Fig. 2.1-1 Ternary diagrams for displaying cationic and anionic proportions. WAFW = World Average Freshwater (after Livingstone 1963), SW = Seawater.

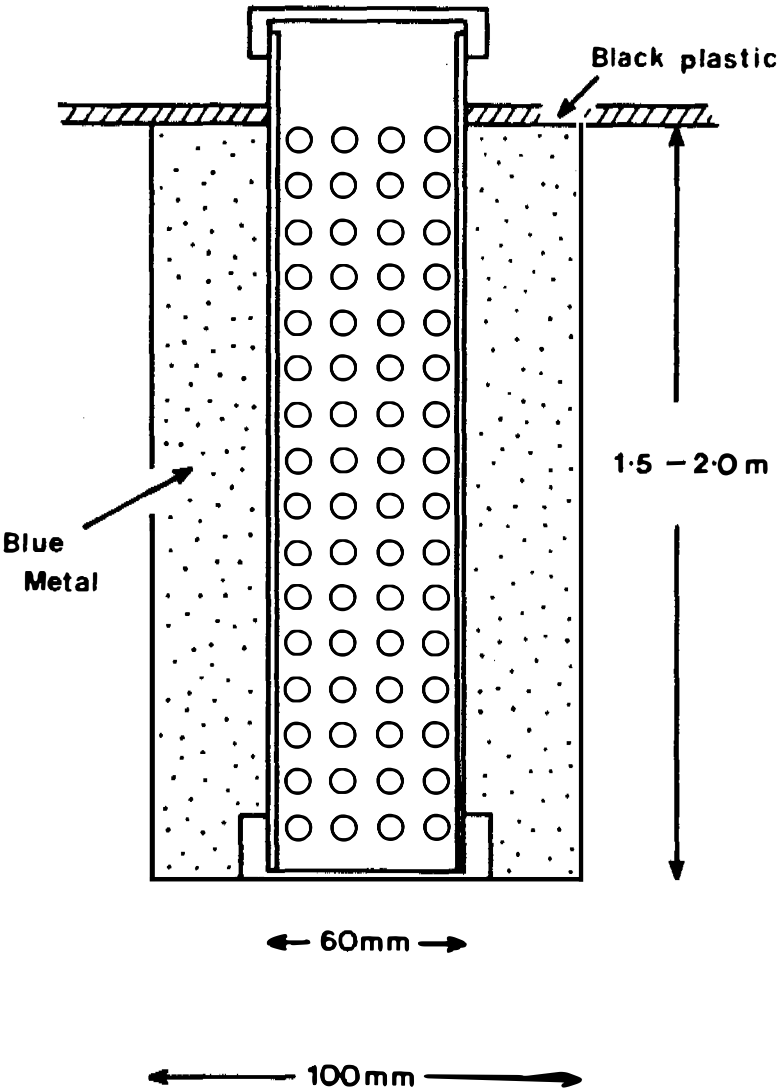


Fig. 2.1-2 Detail of construction of the bore used for sampling groundwater at Jabiluka.

3. RESULTS - MAJOR IONS AND 'GLOBAL'* PROPERTIES

3.1 Preamble

A number of authors have considered the natural events which determine the chemical nature of running and standing bodies of freshwater (Curry 1972; Truesdale 1974; Gorham 1961; Rodhe 1949).

Gorham (1961) considered that five principal environmental factors - climate, geology, topography, biota and time - interact to determine ionic composition and concentration of inland waters. Gibbs (1970) proposed that the factors influencing world water chemistry could be reduced to three mechanisms. First, ions are supplied from the atmosphere in the form of dry precipitation, or rain. Gibbs (1970) termed this type of water a 'precipitation dominance end member', dominated by sodium chloride. Second, contact with soluble rocks leads to accretion of mineral substances such that total ionic concentrations increase and alkaline earth bicarbonates become dominant. This process leads to the 'rock dominance end member'. The third process operates only in arid regions where evaporation leads to high ionic concentrations and a preferential salting-out of divalent cations and carbonates, leaving a hypersaline water dominated by sodium chloride, the 'evaporation/crystallization end member'.

Except in arid parts of the world, where evaporation/crystallization processes take place, the ionic nature of surface waters will depend primarily on the extent to which rock contact modifies the chemical composition of rainwater. In the absence of any lithological modification, water chemistry is akin to dilute seawater, and this is a common experience in maritime areas where surface waters are isolated from rock contact by peats (Gorham and Cragg 1960; Tyler 1974), or where rocks are siliceous and inert, or when runoff is rapid, minimising rock contact.

plural

The effects of rock contact, in modifying the chemical nature of surface water, are clearly evident in limestone or dolomite areas. Waters then

* "Global" does not translate from the French. It refers to integrative properties such as pH and, electrical conductivity, as opposed to specific characteristics

assume the composition of the so-called "World Average Freshwater", the mean composition of the world's rivers or lakes (Conway 1942; Livingstone 1963, Rodhe 1949). The composition of the 'precipitation dominance end member' (seawater) and that of the 'rock dominance end member' (World Average Freshwater) are taken as convenient reference points on Ternary diagrams, against which the composition of natural inland waters can be compared.

3.2 Interlaboratory comparisons.

There was good agreement between cation determinations made in the Hobart and Jabiru laboratories (Table 3.2-1). The maximum discrepancy was of the order of 15% of the higher value. The interlaboratory comparison was made with samples collected during February/March 1981, on very dilute waters with conductivities lower than $30 \mu S cm^{-1}$. At such low ionic concentrations percentage analysis error would be expected to be maximal. In general the agreement between the two laboratories' analyses was better for the monovalent than the divalent cations. Hobart analyses always indicated lower concentrations for all cations, particularly calcium. An United States Environmental Protection Agency standard, of much higher total ionic strength, was used as a further check on analytical accuracy. Excellent agreement, within 3% of the reported value for all 4 cations, was obtained by both laboratories (Table 3.2-2). This comparison suggests that the Hobart method for calcium may give a slight underestimate. Analytical differences of the magnitude indicated by the interlaboratory comparisons are trivial, and inconsequential in the interpretation of billabong water chemistry.

Of the anions routinely determined, only bicarbonate analyses were subject to interlaboratory comparisons. Analyses in Jabiru were made on unfiltered, refrigerated samples soon after collection from the billabongs, whereas the delay until analysis of filtered samples in Hobart could be several months. Bicarbonate analyses began in Jabiru in July 1979 and continued until early June 1980, when equipment failure and increased workload forced a premature halt.

Probably because of adjustments within the carbonate-bicarbonate-carbonic acid equilibrium system during transit and storage, the Hobart values for bicarbonate usually differed from those determined at Jabiru. Rarely, Hobart values were slightly higher than those from Jabiru. Generally, the Hobart results were underestimates by about 20% (Table 3.2-3).

Table 3.2-1 Comparison of analyses of filtered water samples carried out by B. Noller, OSS Jabiru and by Botany Dept., University of Tasmania. Results are in mgl^{-1}.

Sample Site	Date	Na OSS	Na Tas.	K OSS	K Tas.	Mg OSS	Mg Tas.	Ca OSS	Ca Tas.
Umbungbung	21/1/81	1.81	1.80	0.66	0.52	1.40	1.18	1.26	1.14
Bowerbird	27/1/81	1.08	1.00	0.11	0.20	0.28	0.23	0.10	0.11
Nankeen	9/2/81	1.33	1.25	0.35	0.32	0.66	0.59	0.45	0.49
Leichhardt	9/2/81	1.39	1.18	0.48	0.48	0.67	0.56	0.48	0.48
Ja Ja	9/2/81	1.22	1.18	0.38	0.32	0.62	0.51	0.44	0.37
Mine Valley	9/2/81	1.40	1.29	0.43	0.32	0.61	0.52	0.45	0.36
Goanna	12/2/81	1.41	1.31	0.61	0.48	0.62	0.51	0.72	0.47
Gulungul	17/2/81	1.66	1.15	0.60	0.36	0.48	0.46	0.32	0.40
GS009	18/2/81	1.15	0.98	0.16	0.20	0.45	0.40	0.29	0.22
Corndorl	18/2/81	1.39	1.37	0.55	0.44	0.63	0.47	0.65	0.47
Corndorl	18/2/81	1.29	1.29	0.51	0.36	0.68	0.50	0.67	0.49
Nimbawah	19/2/81	2.83	2.74	0.54	0.48	1.47	1.31	1.24	0.92
Murganella	19/2/81	2.71	2.56	0.70	0.60	1.33	1.13	1.59	1.36
Umbungbung	20/2/81	1.59	1.46	0.21	0.20	1.05	0.83	0.97	0.73
Noarlanga	20/2/81	1.61*	0.94	0.66*	0.12	0.59	0.52	0.44	0.36
Jingalla	24/2/81	1.84	1.68	0.36	0.32	0.71	0.62	0.57	0.56
Kulukuluku	24/2/81	1.24	0.97	0.28	0.32	0.62	0.53	0.53	0.41
Goanna	16/3/81	2.08	2.03	0.57	0.56	0.66	0.58	0.77	0.53
Gulungul	17/3/81	1.50	1.45	0.29	0.28	0.61	0.50	0.45	0.37
Jabiluka	18/3/81	0.70	0.75	0.32	0.32	0.42	0.32	0.30	0.22
Mid-Magela Flood Plain	18/3/81	1.83	1.84	0.65	0.64	0.40	0.38	0.26	0.22
Leichhardt	18/3/81	1.01	1.09	0.65	0.60	0.49	0.39	0.45	0.31
Mine Valley	18/3/81	0.74	0.77	0.27	0.28	0.40	0.31	0.28	0.27
Nankeen	18/3/81	0.72	0.72	0.33	0.32	0.41	0.31	0.31	0.27
Murganella	18/3/81	2.25	2.17	0.66	0.60	0.91	0.73	0.91	0.77
Nimbawah	18/3/81	2.33	2.21	0.44	0.36	1.00	0.89	0.78	0.64
Noarlanga	20/2/81	1.06	1.03	0.26	0.24	0.63	0.56	0.49	0.46
Georgetown	23/3/81	1.65	1.56	0.44	0.40	1.71	1.49	0.72	0.62

* These values appear unduly high considering that there was good agreement for the divalent cations in this sample and that there was good agreement for all cations for a sample taken 4 days later at downstream Kulukuluku.

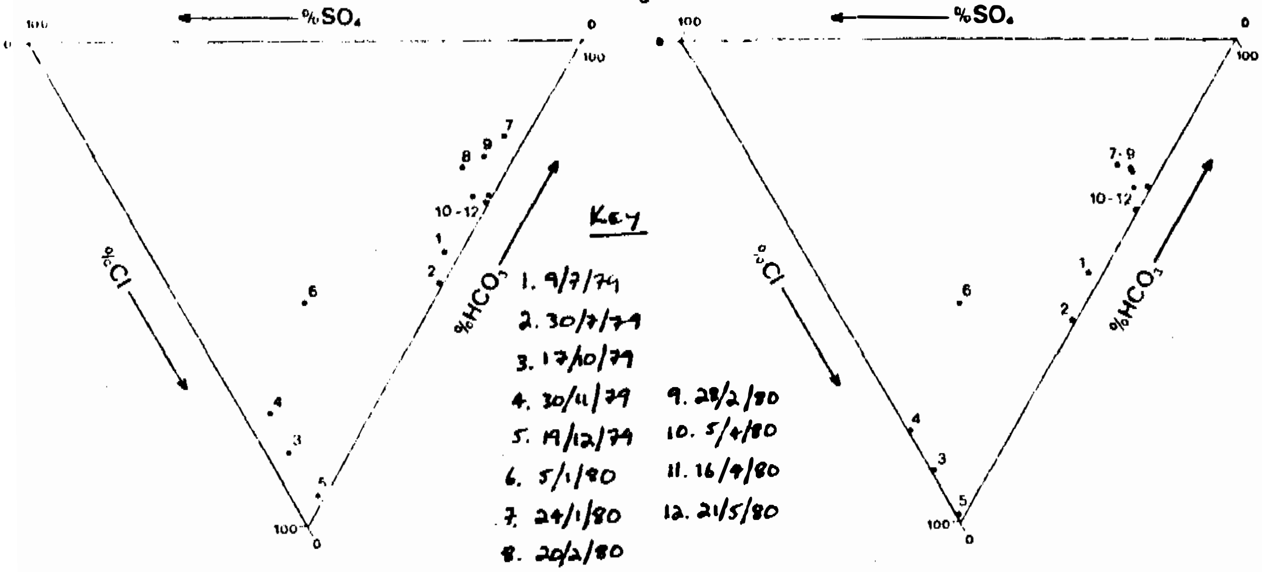
Table 3.2-2 Comparison of analyses of United States Environmental Protection Agency (EPA) Mineral Reference # 1 (No. 871) carried out by B. Noller, OSS Jabiru and by Botany Department, University of Tasmania.

Ion	Analysis, mgl^{-1}			% Discrepancy from EPA value	
	OSS	Tas.	EPA	OSS	Tas.
Na	8.50	8.46	8.20	+4	+3
K	1.57	1.64	1.60	-2	+3
Ca	9.02	8.70	9.00	0	-3
Mg	2.30	2.06	2.10	+10	-2

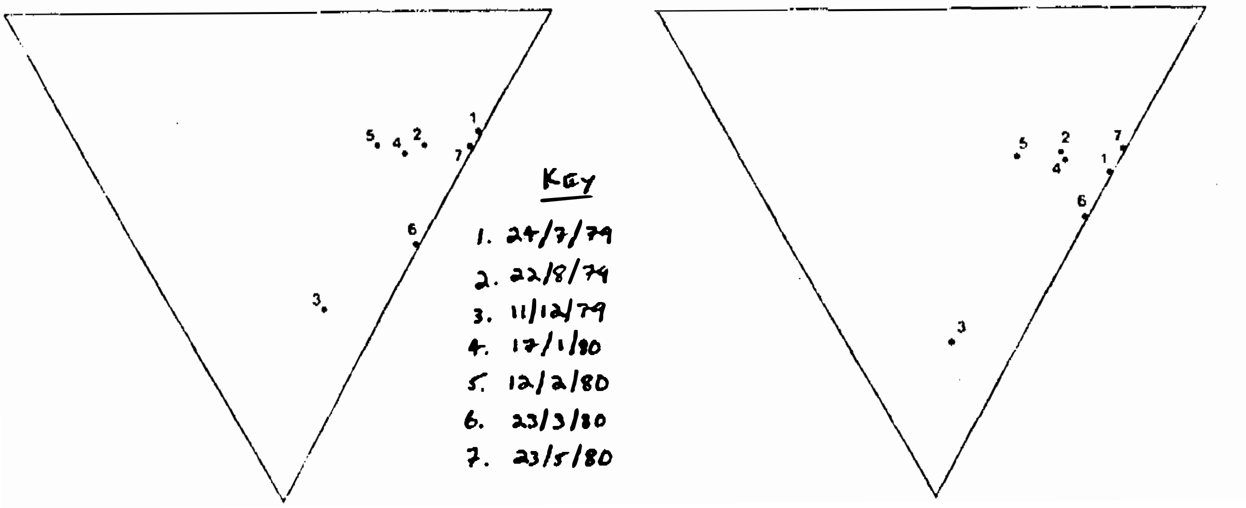
Table 3.2-3 Comparison of bicarbonate analyses (μeql^{-1}) carried on the same samples by Jabiru and Hobart laboratories.

Billabong	Season					
	Mid-Wet		Mid-Dry		Late-Dry	
	Jabiru	Hobart	Jabiru	Hobart	Jabiru	Hobart
Bowerbird	123	66	160	102	152	93
Georgetown	201	152	196	188	79	46
Gulungul	98	98	280	232	49	0
Goanna	112	106	336	248	395	356
Mudginberri	90	70	132	126	130	124
Island	79	94	300	110	71	67
Ja Ja	66	66	-	0	106	28
Mine Valley	88	60	310	154	75	53
Leichhardt	74	74	320	247	293	82
Jabiluka	73	62	210	133	68	56
Nankeen	76	80	149	138	139	70
Noarlanga	74	62	240	160	190	-
Umbungbung	110	90	344	332	842	88
Kulukuluku	103	100	-	182	219	180
Red Lily	628	688	1130	1080	2407	2336

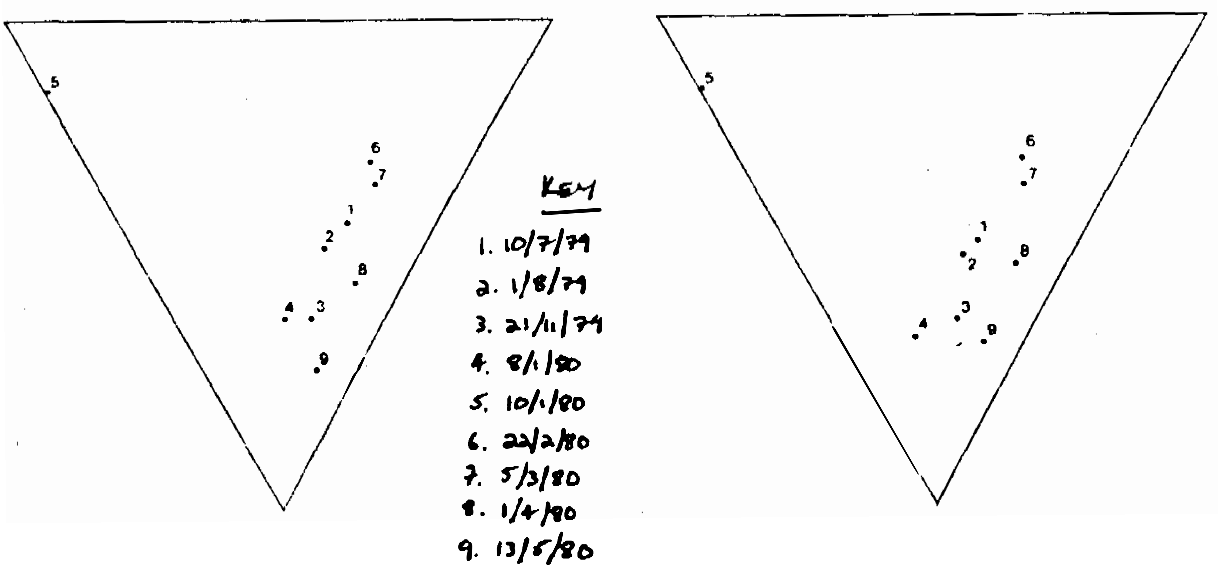
Gulungul



Noarlanga



Leichhardt



Occasionally, Hobart values were as low as 30% of Jabiru results and on a few occasions bicarbonate concentrations fell to zero between Jabiru and Hobart. This inadequacy of bicarbonate analyses is no serious handicap for, though the magnitude of bicarbonate may not be correct, it is clear (Fig. 3.2-1) that it does not substantially alter perception of seasonal events in anionic behaviour. Significantly, the serious underestimates of bicarbonate occurred at times near maximum ionic concentration when bicarbonate, determined at Jabiru, constituted only small proportions of total anionic concentration.

The anomalies in bicarbonate analysis are not surprising considering the dilute nature of most billabong waters. Not only are the absolute concentrations of bicarbonate low but, consequently, so is the buffering capacity of the carbonate-bicarbonate-carbonic acid system. The latter is evident from the difficulty which attends measurement of pH in these waters.

Under these circumstances, bicarbonate is a labile ion and such caprice is to be expected. In contrast, the strongly buffered, bicarbonate waters of Red Lily billabong (Table 3.2-3) suffered little or no change during storage.

3.3 Temporal characteristics*

During February, at the height of the Wet, with the creeks and rivers in spate and floodplains inundated by as much as 2 metres of water, billabong chemistry appeared to resemble closely that of the major inflows, as represented by Mudginberri for the Magela, Noarlanga for the Nourlangie and Nimbawah for Coopers Creek (Fig. 3.3-1). In general, the waters were characterised by low conductivities, below $20 \mu S cm^{-1}$, and pH's of 6.4-7.0, with cationic dominance orders of Na>Mg>Ca>K and anionic dominance of HCO_3> >Cl>SO_4 (Table 3.3-1). These sodium bicarbonate waters plot in a bunch on

* 1980 was chosen for consideration of temporal characteristics because information was most complete for that year.

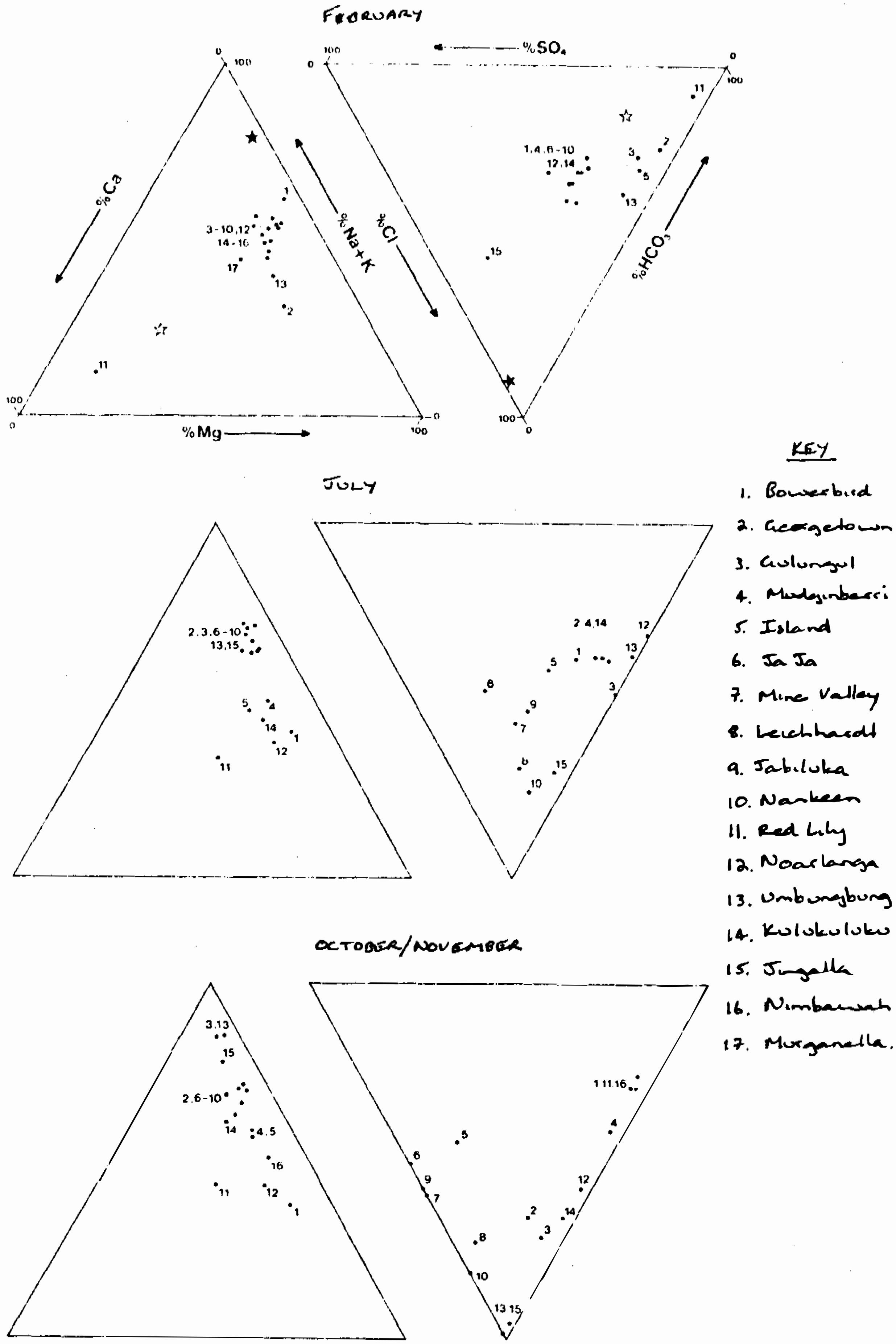


Fig. 3.3-1 Ternary diagrams showing ionic proportions of the billabongs in the mid-Wet (February), ~~1980,~~ mid-Dry (July), and late Dry (October/November 1980

Table 3.3-1 Some chemical characteristics of billabongs in February 1980.

Billabong	K_{25}	pH	Cation dominance order	Anion dominance order
Bowerbird	17	6.4	2.	1.
Georgetown	21	6.8	3.	1.
Gulungul	16	6.5	1a	1.
Mudginberri	15	6.4	1a	1.
Island	19	6.5	1a	1.
Ja Ja	13	6.2	1a	1.
Mine Valley	12	6.0	1a	1.
Leichhardt	16	6.4	1a	1.
Jabiluka	14	6.1	1a	1.
Nankeen	15	6.4	4.	1.
Umbungbung	17	6.6	3.	1.
Noarlanga	13	6.2	1b	1.
Kulukuluku*	15	-	1b	-
Jingalla	20	6.4	1a	1.
Nimbawah*	38	6.5	1a	-
Murganella*	36	6.8	1a	-
Red Lily	71	7.3	4.	1.

Cation dominance orders	Anion dominance orders
1. a) Na>Mg>Ca>K	1. HCO_3>Cl>SO_4
b) Na = Mg>Ca>K	
2. Na>Mg>K>Ca	
3. Mg>Na>Ca>K	
4. Ca>Mg = Na>K	

* These data are for February 1981.

the ternary diagrams (Fig. 3.3-1), somewhat displaced from seawater proportions. As is not unusual (Buckney and Tyler 1973) anionic proportions were more dispersed than corresponding cation proportions. Very similar chemical attributes for the Magela, Nourlangie and Coopers drainage basins were indicated.

A number of exceptions did occur (Table 3.3-1), notably the backflow billabongs Georgetown and Umbungbung, and Red Lily and Jingalla. The backflow billabongs received inputs from their own catchments as well as that from the main creek, with inflow from the latter source intermittent, dependent on the vagaries of the backflow condition (see Walker, Waterhouse & Tyler 1982). Consequently, these billabongs are likely to display a blend of chemical characteristics intermediate between that from their own catchments and that of the main watercourse. Unfortunately, no data on ionic composition of Georgetown Creek, nor for the runoff into Umbungbung, is available. However, the apparent effect of such runoff was to emphasize the dominance of bicarbonate in both and to promote magnesium as the dominant cation.

Red Lily is unique among the waterbodies studied, in being dominated by calcium bicarbonate during the Wet. In addition to receiving floodwaters of unknown composition from the East Alligator River, this billabong receives runoff from a number of escarpment outliers.

The prevailing condition of the Wet, then, is for most billabongs to be dominated by sodium bicarbonate.

By July, the mid-point of the Dry, the comparative homogeneity, which had characterised Wet season ionic character, had disappeared. Conductivities now ranged from 17 to 145μScm^{-1}, and pH's varied between 5.8 and 7.1 (Table 3.3-2). The ternary diagrams for July (Fig. 3.3-2) reveal that two opposing shifts in cationic proportions had occurred since the Wet, one a shift towards greater monovalent dominance, the other towards magnesium, separating the billabongs into two distinct groupings. The channel billabongs (Bowerbird,

Table 3.3-2 Some chemical characteristics of billabongs in July 1980.

Billabong	K_{25}	pH	Cation dominance order	Anion dominance order
Bowerbird	17	5.8	3.	1.
Georgetown	38	6.2	1a	1.
Gulungul	45	7.0	2b	1.
Mudginberri	23	6.1	1a	1.
Island	30	5.9	1a	2b
Ja Ja	53	5.7	2b	3.
Mine Valley	81	5.9	2a	2c
Leichhardt	110	6.8	2a	2c
Jabiluka	66	6.7	2b	2a
Nankeen	107	6.6	2b	2a
Umbungbung	64	6.6	2b	1.
Noarlanga	25	6.9	3.	1.
Kulukuluku	37	6.5	1b	1.
Jingalla	145	6.8	1a	2a
Nimbawah	-	-	-	-
Murganella	-	-	-	-
Red Lily	178	7.5	1c	1.

Cation dominance orders

1.a) Na>Mg>Ca>K
  b) Na = Mg>Ca>K
  c) Na = Mg = CA>K
2.a) Na>Mg>K>Ca
  b) Na>Mg>K = Ca
3. Mg>Na>Ca>K
4. Mg>Na>K>Ca

Anion dominance orders

1. $HCO_3 > Cl > SO_4$
2.a) $Cl > HCO_3 > SO_4$
  b) $Cl = HCO_3 > SO_4$
  c) $Cl > HCO_3 = SO_4$
3. $Cl > SO_4 > HCO_3$

Table 3.3-3 Some chemical characteristics of billabongs in October/ November 1980.

Billabong	K_{25}	pH	Cation dominance order	Anion dominance order
Bowerbird	18	5.9	3.	1.
Georgetown	52	5.7	1a	3.
Gulungul	83	5.9	2b	3.
Mudginberri	27	6.0	1a	1.
Island	48	5.3	1b	2a
Ja Ja	165	4.3	2a	2b
Mine Valley	630	3.7	1b	2a
Leichhardt	188	5.4	2a	2a
Jabiluka	174	4.1	1b	2a
Nankeen	255	4.2	1a	2a
Umbungbung	303	4.3	5.	2a
Noarlanga	30	6.0	3.	3.
Kulukuluku	70	6.0	1a	3.
Jingalla	2600	7.45	1a	2a
Nimbawah	70	6.5	1a	1.
Murganella	86	6.4	1a	1.
Red Lily	233	7.1	1c	1.

Cation dominance orders

1.a) Na>Mg>Ca>K
  b) Na>Mg>Ca = K
  c) Na>Mg = Ca>K
2.a) Na>Mg>K>Ca
  b) Na>Mg = K>Ca
3. Mg>Na>Ca>K
4. Mg>Na>K>Ca
5. Na>K>Mg>Ca

Anion dominance orders

1. $HCO_3 > Cl > SO_4$
2.a) $Cl > SO_4 > HCO_3$
  b) $Cl = SO_4 > HCO_3$
3. $Cl > HCO_3 > SO_4$

Mudginberri, Island, Noarlanga and Kulukuluku), with conductivities ranging from 17 to 37μScm^{-1}, had more or less equimolecular proportions of Na and Mg. By contrast, in the backflow and floodplain billabongs, with a conductivity range of 38-145μScm^{-1} and, especially, Goanna, the ionic order was Na>>Mg. As in the Wet, Red Lily was individualistic, being dominated by Ca.

As with the cations, changes in anionic proportions resulted in two major groupings (Table 3.3-2; Fig. 3.3-2). However, whereas for the cations backflow and floodplain billabongs were allied, and channel billabongs separate, here it is the floodplain billabongs which have become isolated by a migration towards chloride.

By the late Dry (October/November) the billabongs displayed a wide range of chemical composition (Fig. 3.3-3). Conductivities ranged from 18 to 2600μScm^{-1} and pH values spanned 3.8 units (Table 3.3-3). With the cations, it is still possible to recognize the two groupings of the mid-Dry, backflow and floodplain billabongs on the one hand, and channel billabongs on the other. Anionic proportions are very scattered but, in contrast to the Wet when HCO_3 was the dominant anion, most billabongs are now Cl dominated. Sulphate, always the least anion in the Wet, has assumed dominance over HCO_3 in several billabongs by the end of the Dry (Table 3.3-3).

It is apparent, then, that with few exceptions, the height of the Wet was characterised by a common water chemistry, dominated by $NaHCO_3$. By the late Dry, in contrast, an impressive array of ionic concentration and composition occurred in the billabongs. Despite this heterogeneity the billabongs can be grouped according to their changes in ionic composition during the Dry. Some change very little. Most become sodium chloride dominated, and of these, some have significant increases in sulphate. Again, Red Lily is unique. The groupings resulting from these seasonal changes, shown in relation to the traditional classification (Table 3.3-4), form the

TABLE 3.3-4 A chemical basis for classification of billabongs

Chemical grouping	Traditional classification	Billabong	Generalised characteristics
Sodium/magnesium bicarbonate	Channel	Mudginberri	Maintain ionic composition
		Noarlanga	of Wet throughout the year.
		Nimbawah	$K_{18}<80\mu Scm^{-1}$ (all year)
		Murganella	$5.8<pH<6.5$ (late Dry)
	"/Escarpment rockpool	Bowerbird	
Sodium chloride	Channel	Buffalo	Progression during Dry
	"/Floodplain	Kulukuluku	toward SW[1] composition
	"/Backflow	Goanna	$30<K_{18}<550\mu Scm^{-1}$ (late Dry)
	Backflow	Georgetown	$4.0<pH<6.0$ (late Dry)
		Coonjimba	
		Gulungul	
		Corndorl	
		Umbungbung	
	Floodplain	Jingalla	
		Woolwonga	
		Leichhardt	
Sulphate	Channel/ Floodplain	Island	Strong selective concentra-
	Floodplain	Ja Ja	tion of SO_4 in addition to
		Mine Valley	progression to SW[1] during
		Jabiluka	Dry.
		Nankeen	$50<K_{18}<1000\mu Scm^{-1}$ (late Dry)
			$3.5<pH<5.5$ (late Dry)
Calcium bicarbonate	Floodplain	Red Lily	WAFW[2] composition in Wet,
			progression toward SW[1] in
			Dry.
			$K_{18}>50\mu Scm^{-1}$ (Wet)
			$200<K_{18}<350\mu Scm^{-1}$ (late Dry)
			$pH>7.0$ virtually at all times

[1]SW = Seawater

[2]WAFW = World Average Freshwater

basis for the presentation of a more complete water chemistry of the billabongs (below).

3.4 Sodium/magnesium bicarbonate billabongs

This group is made up of the channel billabongs from all three creek systems (with the exception of Buffalo), and Bowerbird, a channel/rock pool billabong. The distinguishing feature is that they predominately maintain the ionic composition of the Wet (Figs. 3.4 1-5). Thus, the approximately equimolar proportions of Na and Mg, together with the predominance of bi-carbonate, were not only characteristic of the Wet (see Section 3.3), but also of the Dry. The scatter of anionic proportions was usually greater than that for cations. A few renegades were displaced from the main group-ing. Some of these have explanations, some do not. For the three Magela and Nourlangie billabongs in this group - Bowerbird, Mudginberri and Noarlanga - conductivity values during the year generally ranged from 15 to 30μScm^{-1} (Figs. ~~3.4-6-8~~ 3.4.6,7,10), whilst for two Coopers Creek channel billabongs, Nimbawah and Murganella, much smaller in size and volume than the three discussed above, conductivity could rise by 50μScm^{-1} (Figs. 3.4~~.9,10~~ 8,9). These conductivity rises were small by comparison to those experienced in almost all other billabongs. In all the billabongs of this group, pH fluctuations were slight (Figs. 3.4.6-10). A slight downward trend in pH was evident for Bowerbird, Mudginberri and Noarlanga.

Bowerbird, near the headwaters of the Magela, appeared to experience a shift towards Mg dominance as the Dry progressed (Fig. ~~3.4-7~~ 3.4.10). This is probably caused by the persistent inflow maintained throughout the Dry by perennial springs. As surface water runoff declined after the Wet, spring water would increasingly determine inflow chemistry, thus enhancing geo-chemical influences which generally favour divalent rather than monovalent cationic dominance.

Mudginberri and Noarlanga were very similar to one another in their

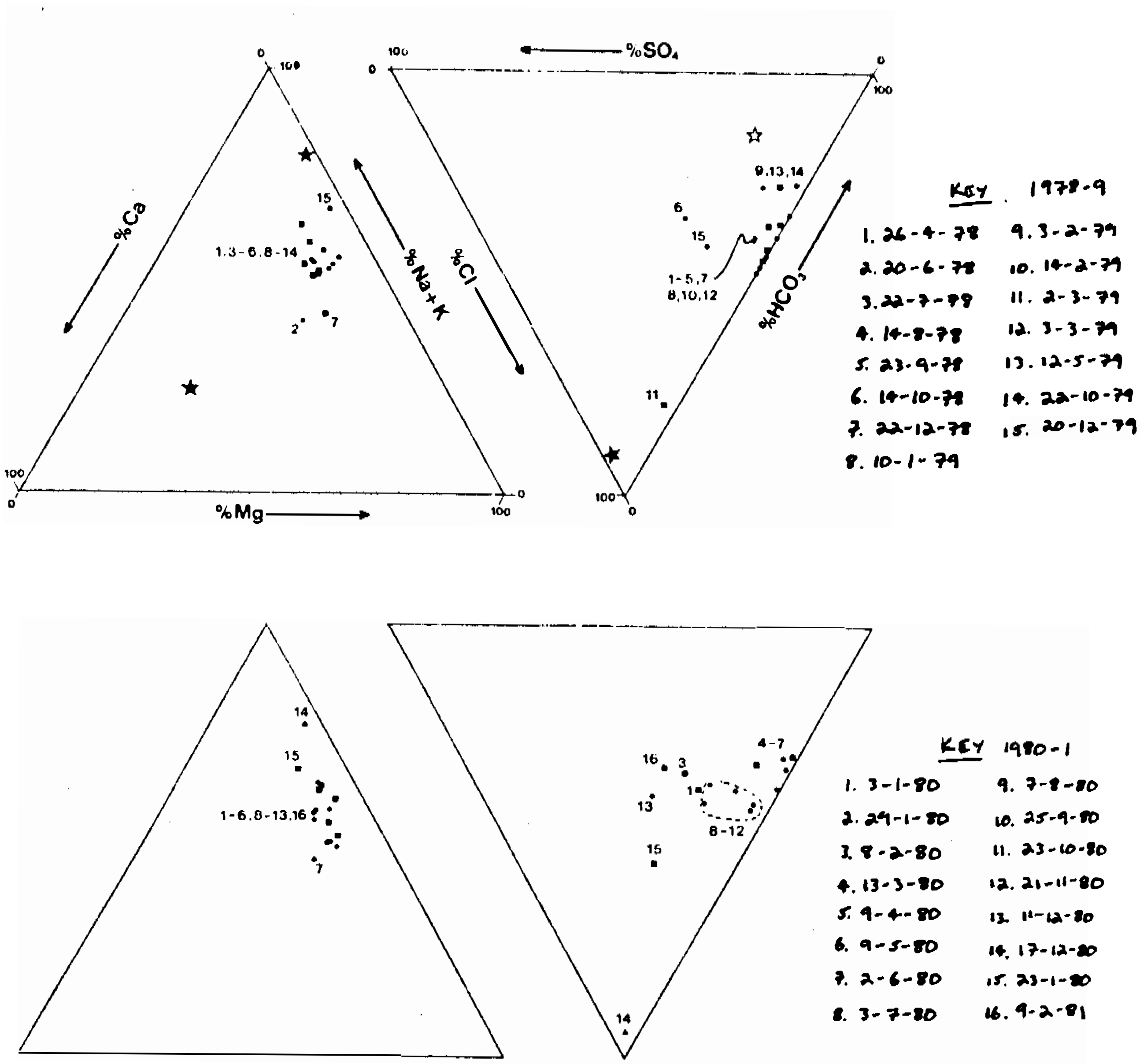


Fig. 3.4.1 Ternary diagrams showing the seasonal pattern of ionic proportions in Mudginberri billabong during the Dry (●), Wet (■) and the Dry/Wet interchange prior to complete flushing (▲).

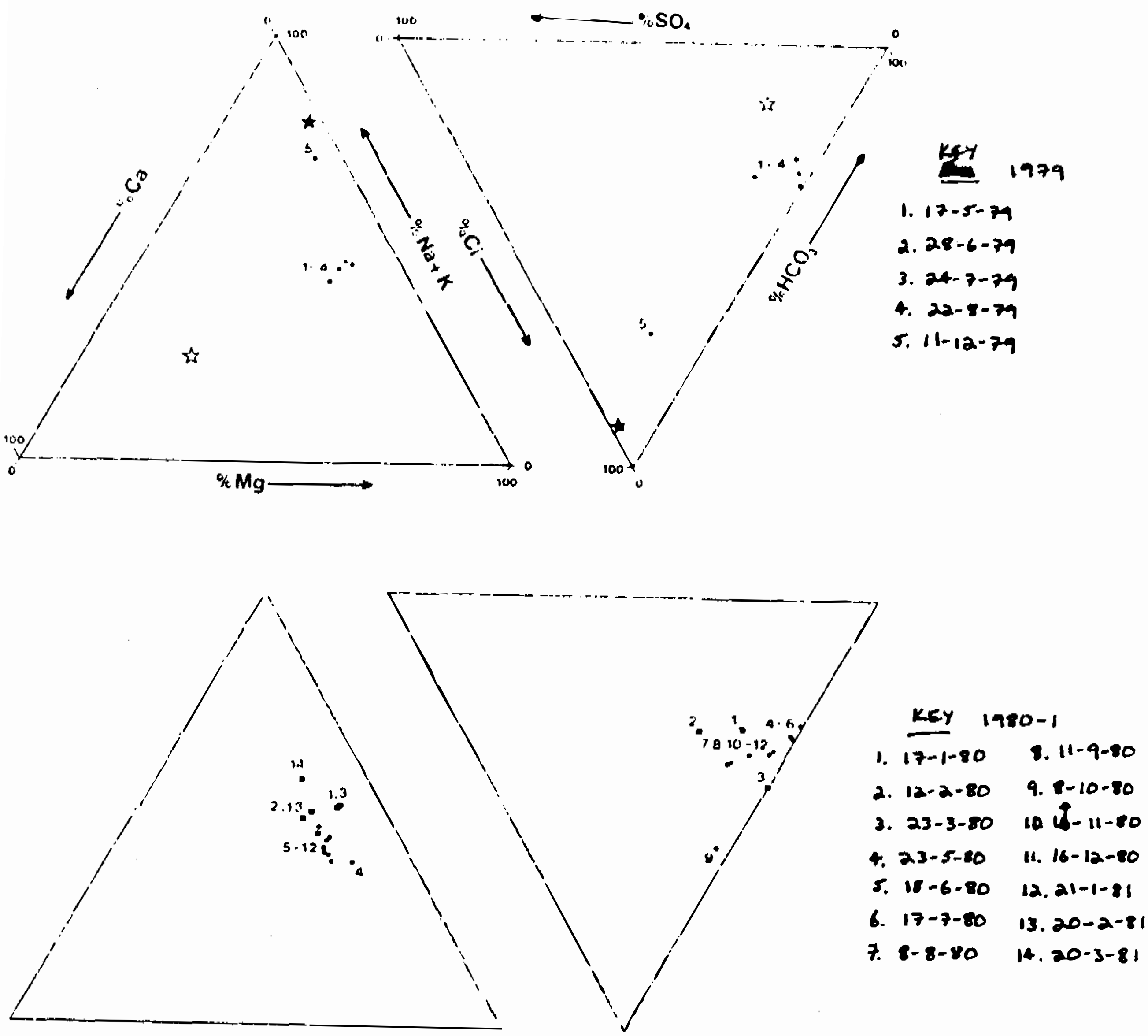


Fig. 3.4.2...Ternary diagrams showing the seasonal pattern of ionic proportions in Noarlanga billabong. Symbols as for Fig. 3.4-1.

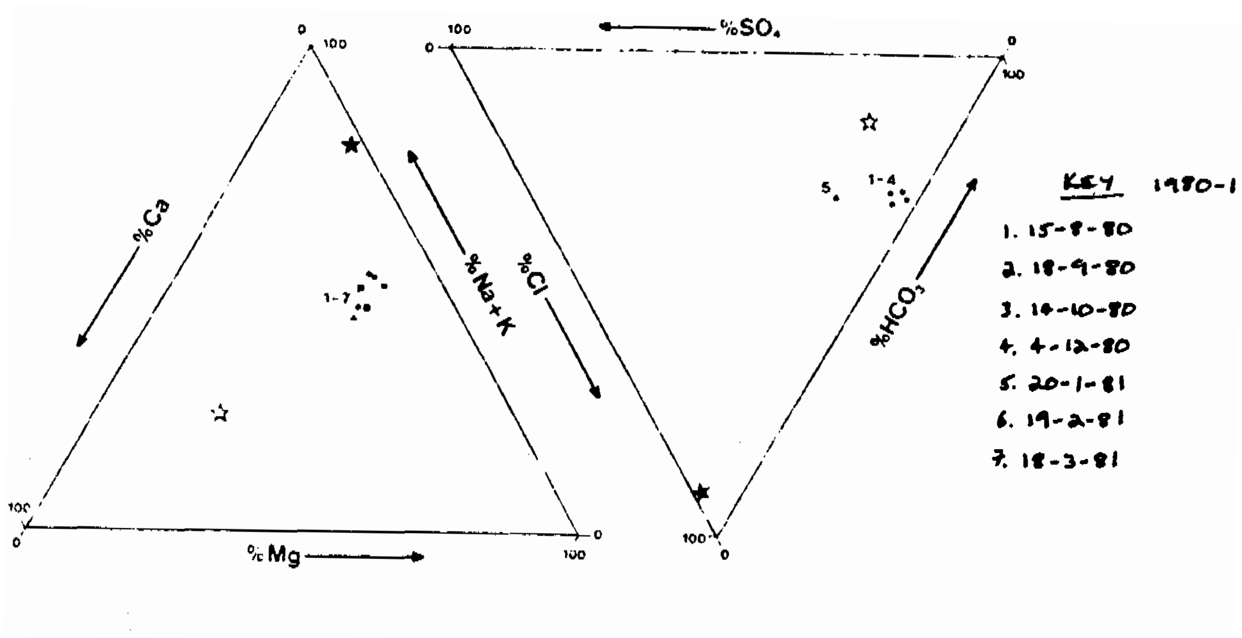


Fig. 3.4.3...Ternary diagrams showing the seasonal pattern of ionic proportions in Nimbuwah billabong. Symbols as for Fig. 3.4.1.

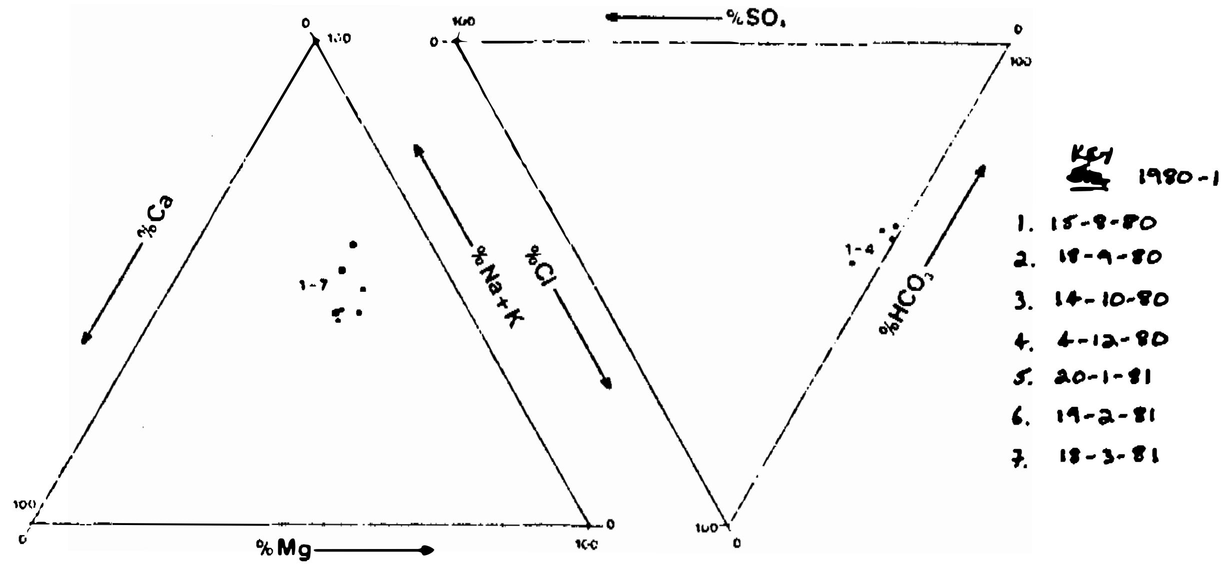


Fig. 3.4.4...Ternary diagrams showing the seasonal pattern of ionic proportions in. Murganella ...billabong. Symbols as for Fig. 3.4-1.

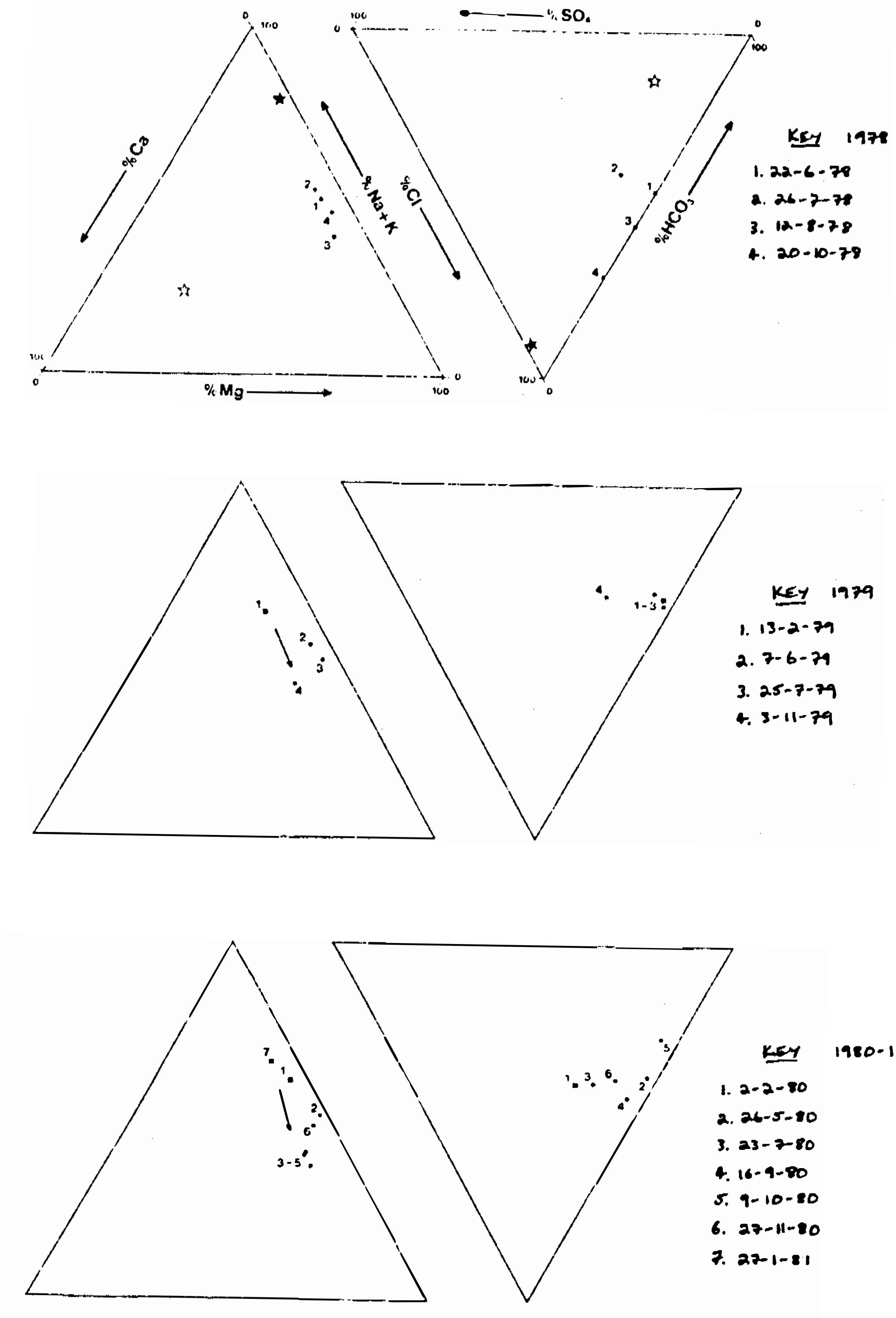


Fig. 3.4.5...Ternary diagrams showing the seasonal pattern of ionic proportions in Bowerbird billabong. Symbols as for Fig. 3.4-1.

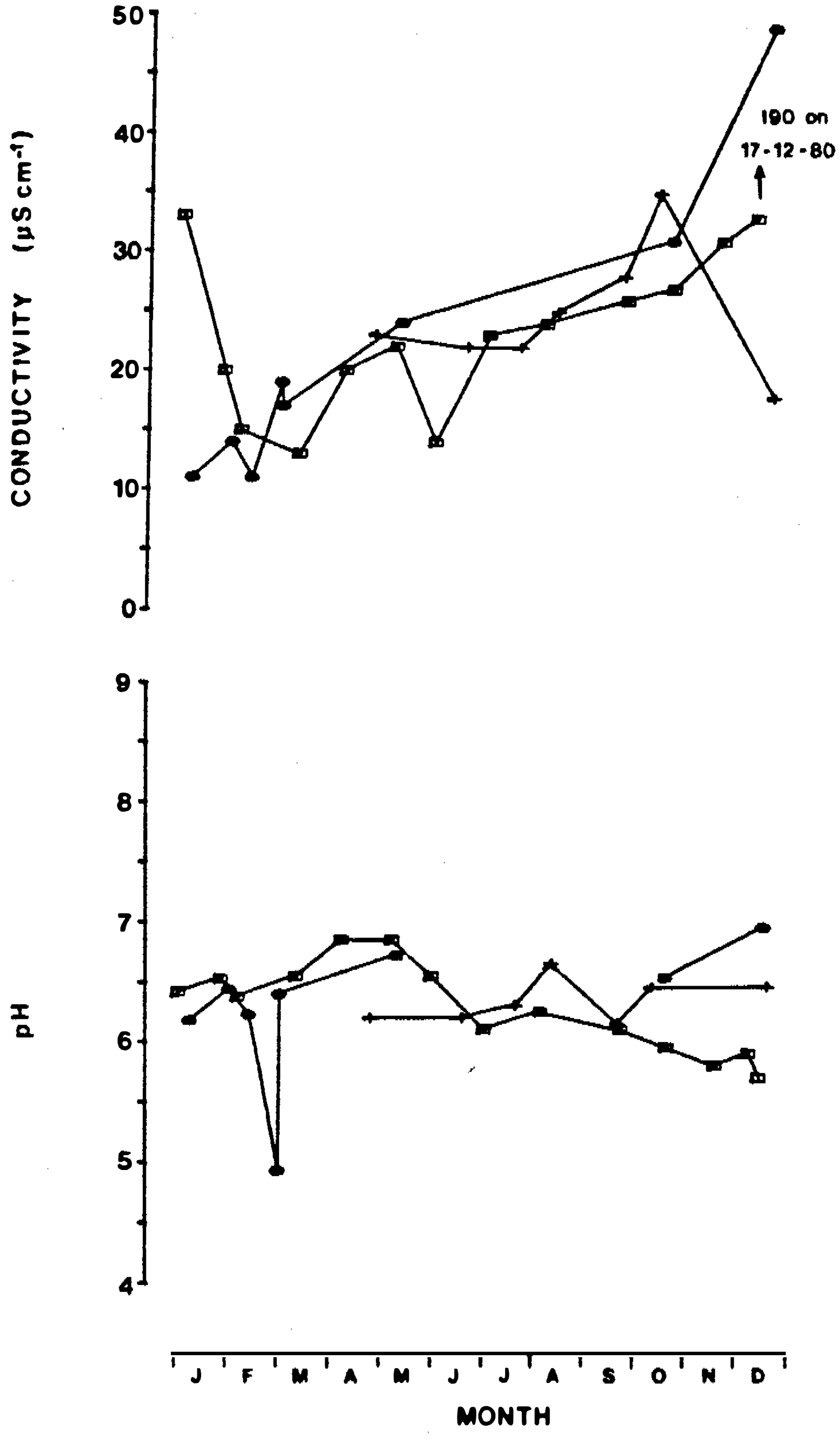


Fig. 3.4.6. Seasonal variations in electrical conductivity (K_{18}) and pH in Mudginberri billabong during 1978 (+), 1979 (✱) and 1980 (□).

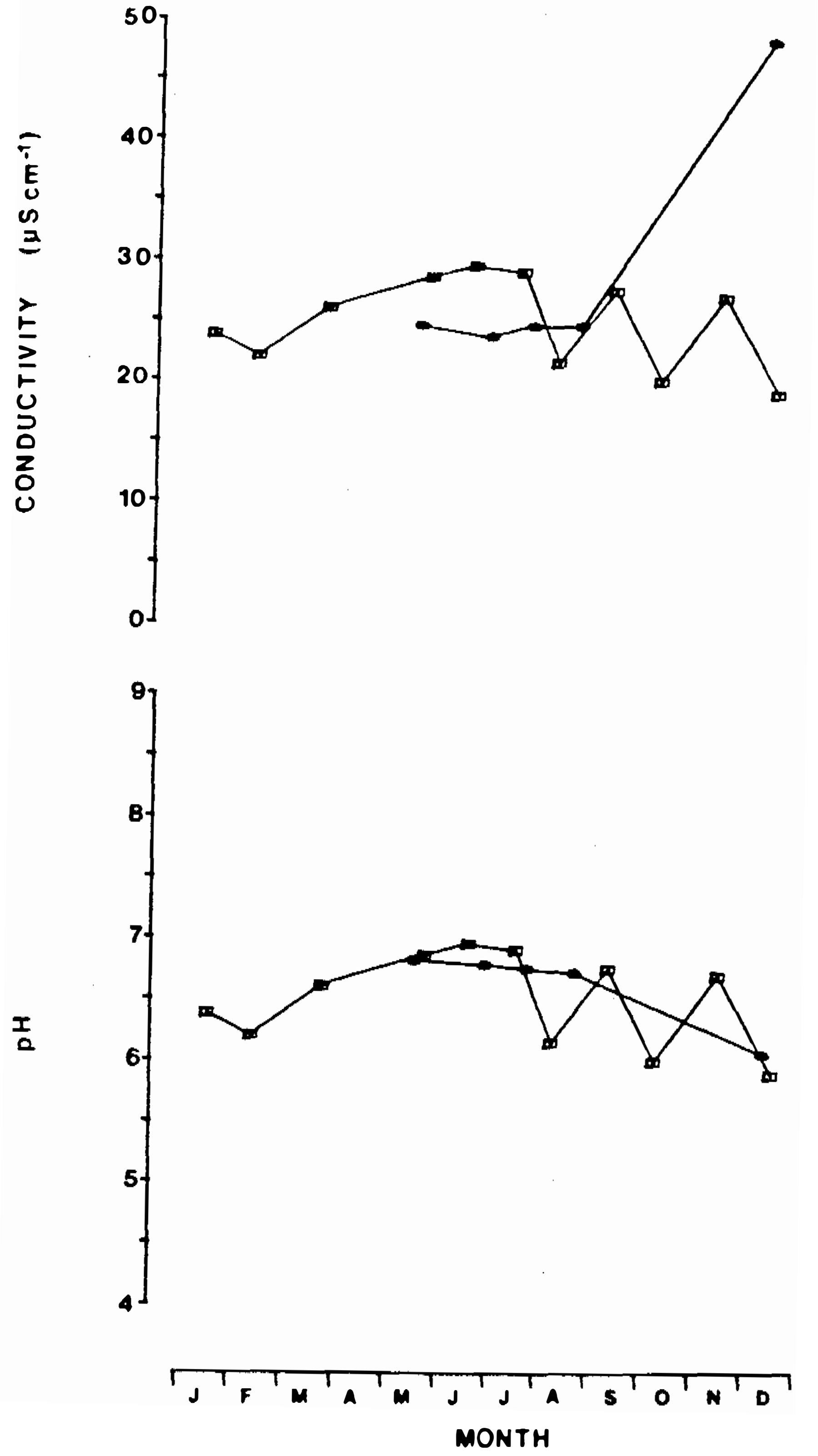


Fig. 3.4.7...Seasonal variations in electrical conductivity (K_{18}) and pH in Naarlanga..billabong during 1979 (*) and 1980 (□).

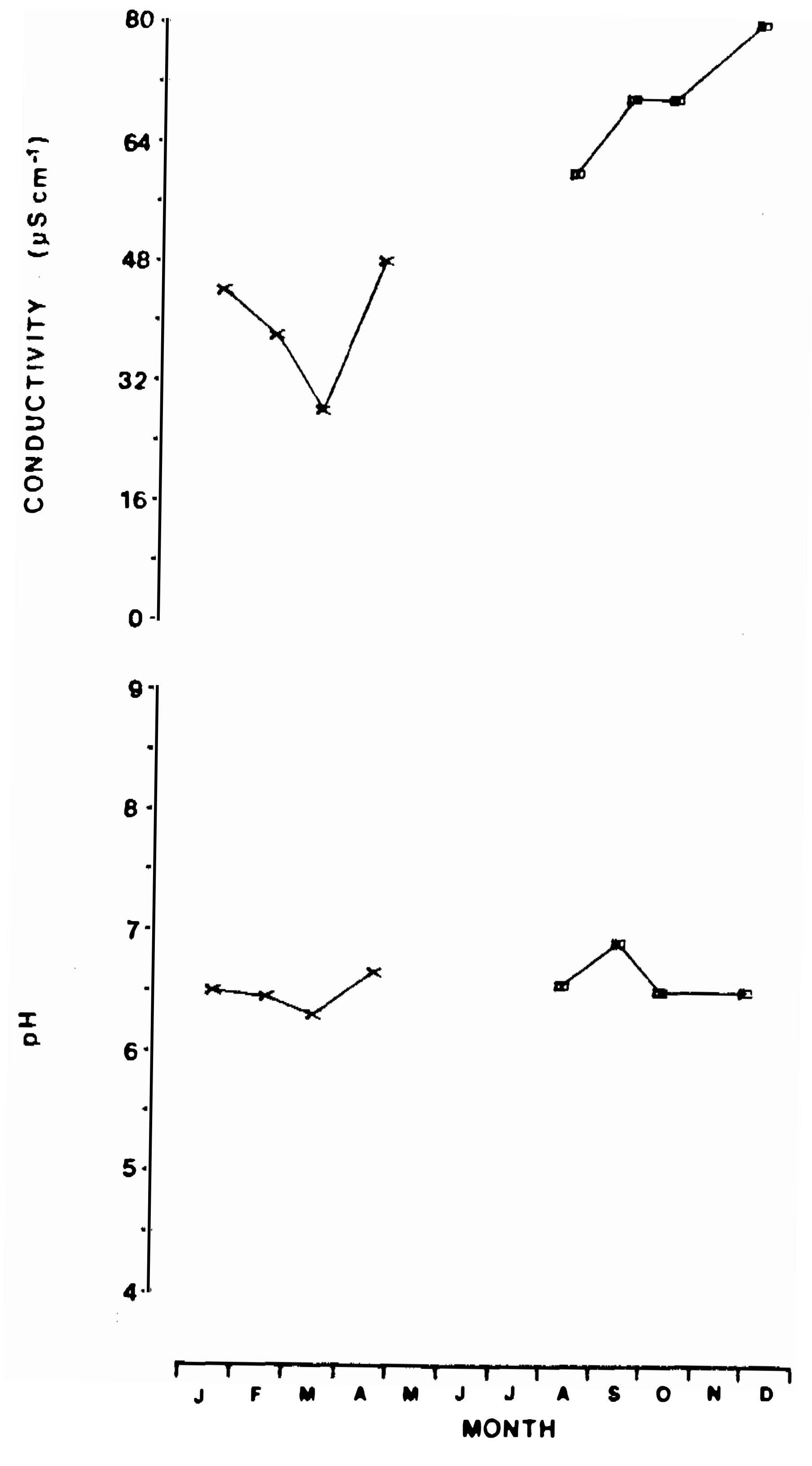


Fig. 3.4.8...Seasonal variations in electrical conductivity (K_{18}) and pH in .Nimbuwah.billabong during 1980 (□) and 1981 (×).

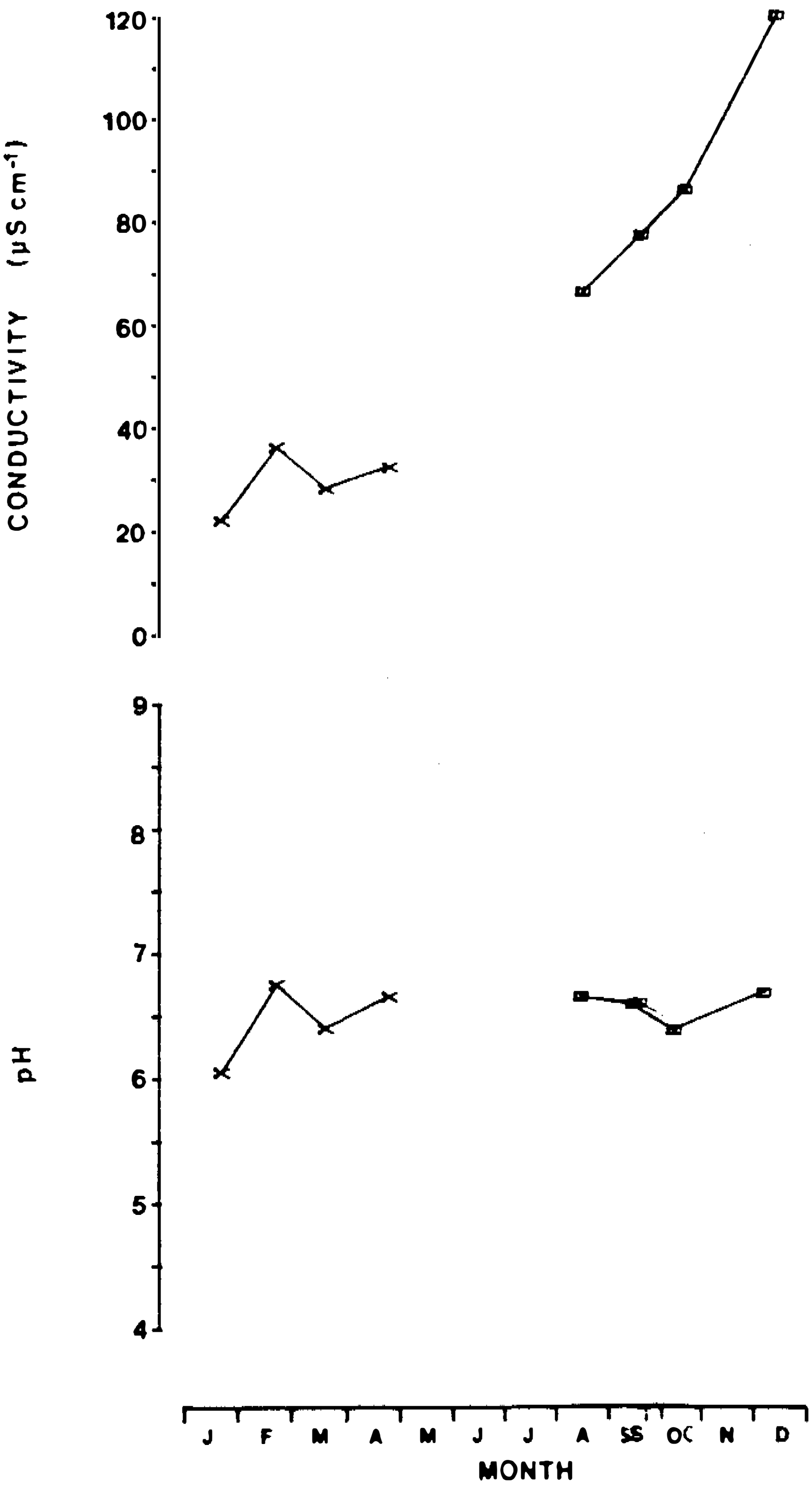


Fig. 3.4.9..Seasonal variations in electrical conductivity (K_{18}) and pH in Mocagnella..billabong during 1980 (□) and 1981 (×).

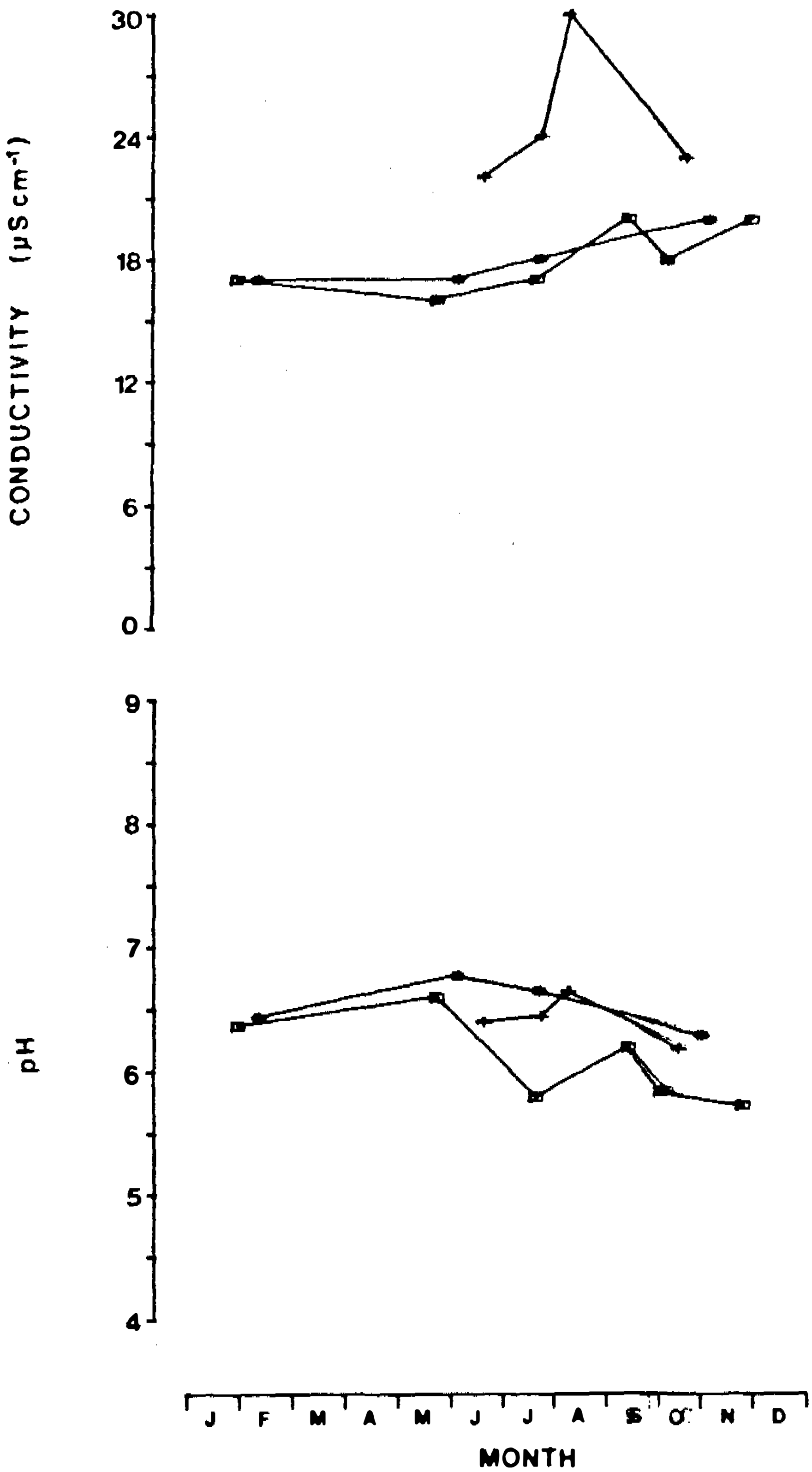


Fig. 3.4.10. Seasonal variations in electrical conductivity (K_{18}) and pH in Bowerbird billabong during 1978 (+), 1979 (*) and 1980 (□).

water chemistry (Figs. 3.4.1,2). The few exceptions to their 'normal' ionic composition came during the rainy months, when seawater-type ionic compositions could occur fleetingly (e.g. Mudginberri on 2/3/79, 17/12/80; Noarlanga on 11/12/79). It was also apparent that the billabong waters in the mid-Wet contained proportionally more SO_4 than during the late Wet and Wet/Dry interchange.

The limited data for Nimbawah and Murganella suggests that there is very little ordered change in equivalent proportions of the various ions throughout the year, despite some Dry season rises in conductivity.

The overall impression of these billabongs is one of chemical stability once the first flush of the Wet has receded. Ionic composition, pH and solute concentrations show little seasonal change. That they remain so dilute and unchanging is probably related to their similar morphometry. All are long, narrow channel billabongs, protected by trees, and with comparatively low surface to volume ratios. All these features are likely to reduce evaporation and the concentration which most other billabongs experience. The observed large drops in water level of Mudginberri and Noarlanga in the early Dry result principally from outflow, not evaporation. Since water chemistry of the billabongs scarcely changes, it is assumed that any incoming groundwater from sandy aquifers would also have retained Wet season chemistry.

3.5 Sodium chloride billabongs

This group, containing all but one (Corndorl) of the backflow billabongs (Georgetown, Coonjimba, Gulungul, Umbungbung), three floodplain billabongs (Leichhardt, Woolwonga and Jingalla), and Buffalo and Kulukuluku, was distinguished by the marked progression of their ionic chemistry toward seawater composition. Buffalo would belong with the other channel billabongs were it not for a distinct progression towards chloride during the Dry (Fig. 3.5.1).

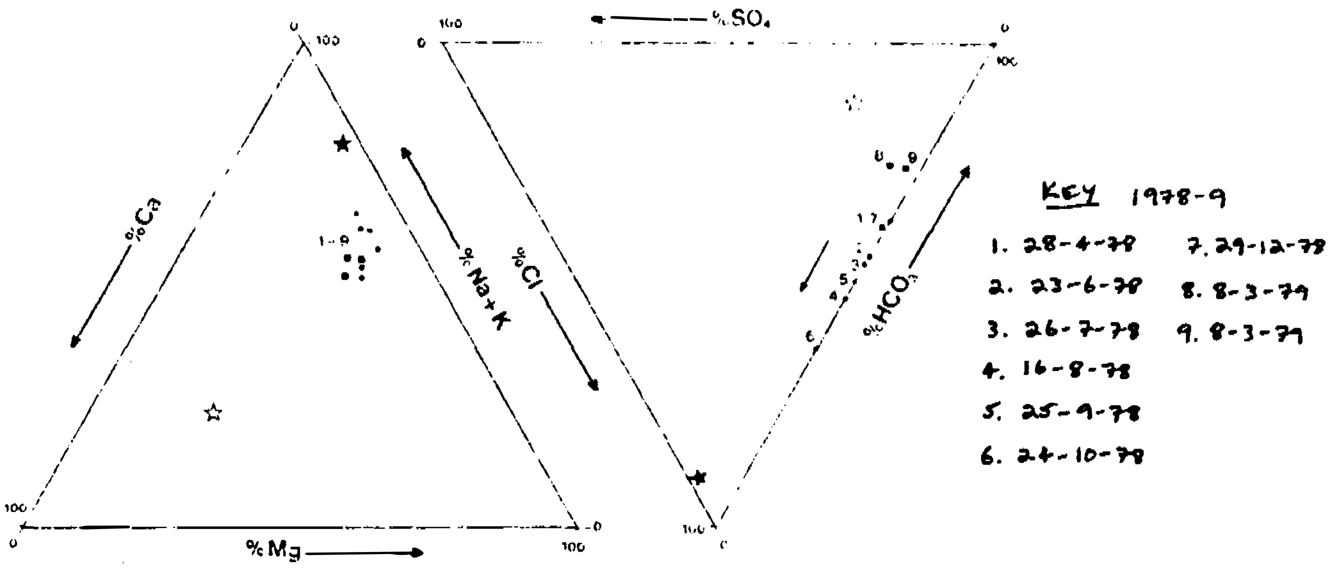


Fig. 3.5.1...Ternary diagrams showing the seasonal pattern of ionic proportions in..Buffalo....billabong. Symbols as for Fig. 3.4-1.

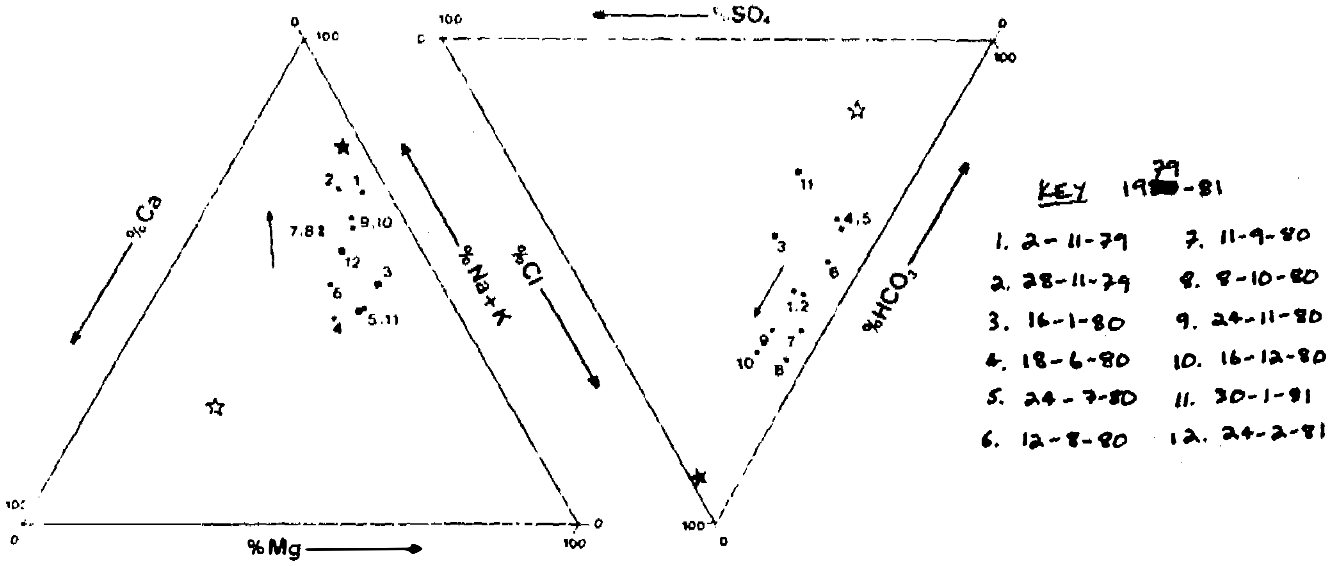


Fig. 3.5.3...Ternary diagrams showing the seasonal pattern of ionic proportions in Kulukuluku...billabong. Symbols as for Fig. 3.4-1.

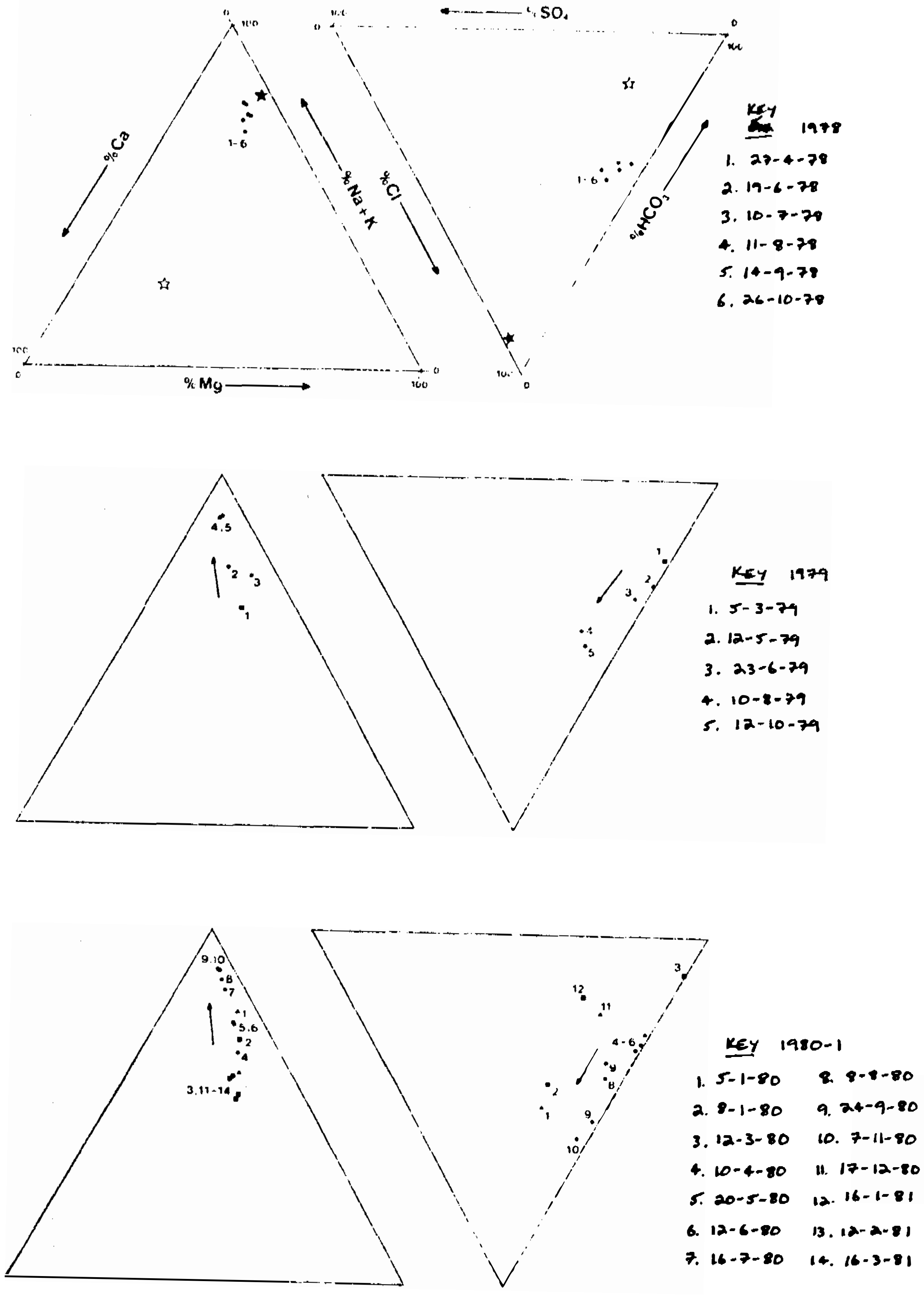


Fig. 3.5.3...Ternary diagrams showing the seasonal pattern of ionic proportions in. Goanna.....billabong. Symbols as for Fig. 3.4-1.

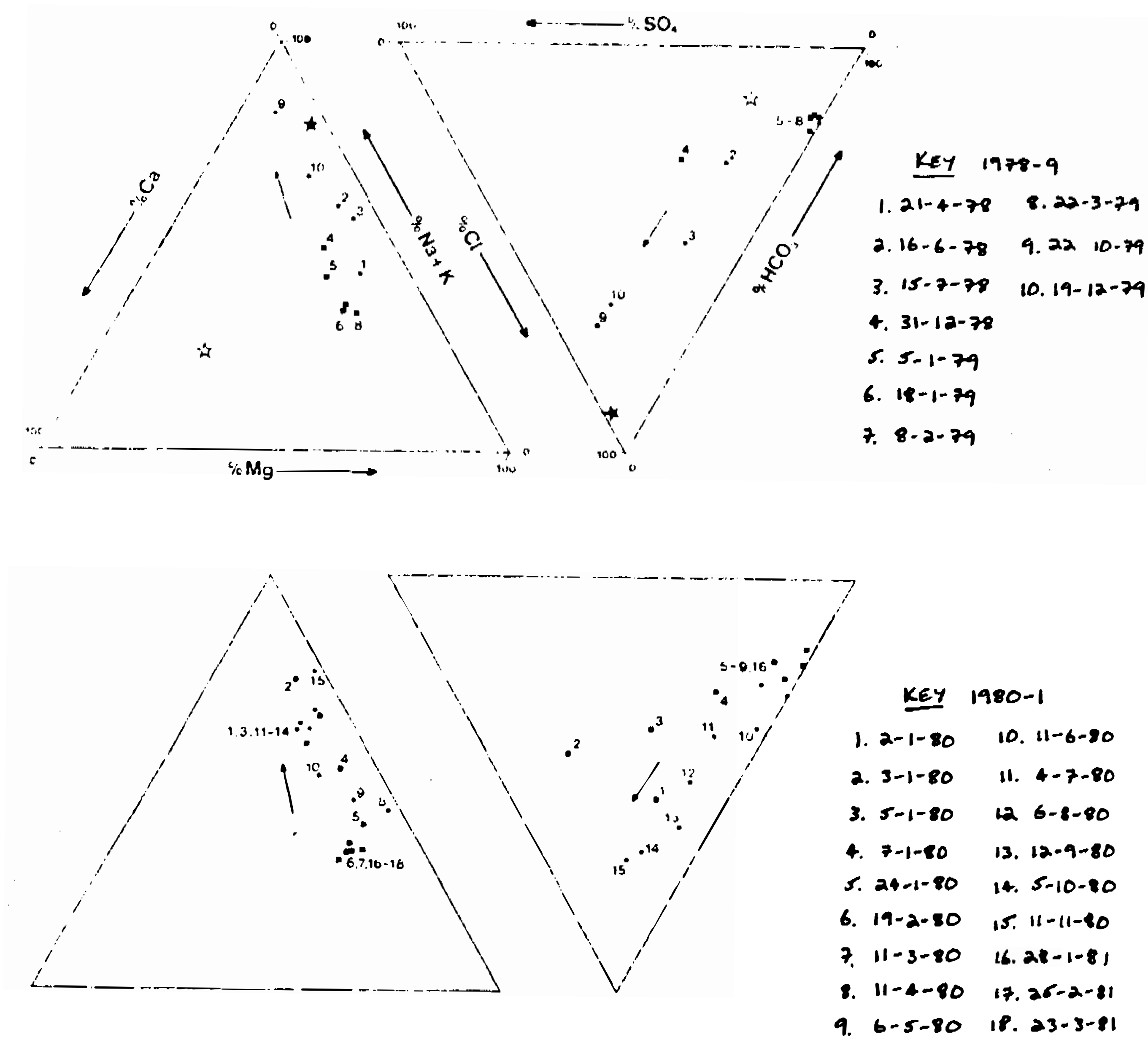


Fig. 3.5.4...Ternary diagrams showing the seasonal pattern of ionic proportions in Georgetown billabong. Symbols as for Fig. 3.4-1.

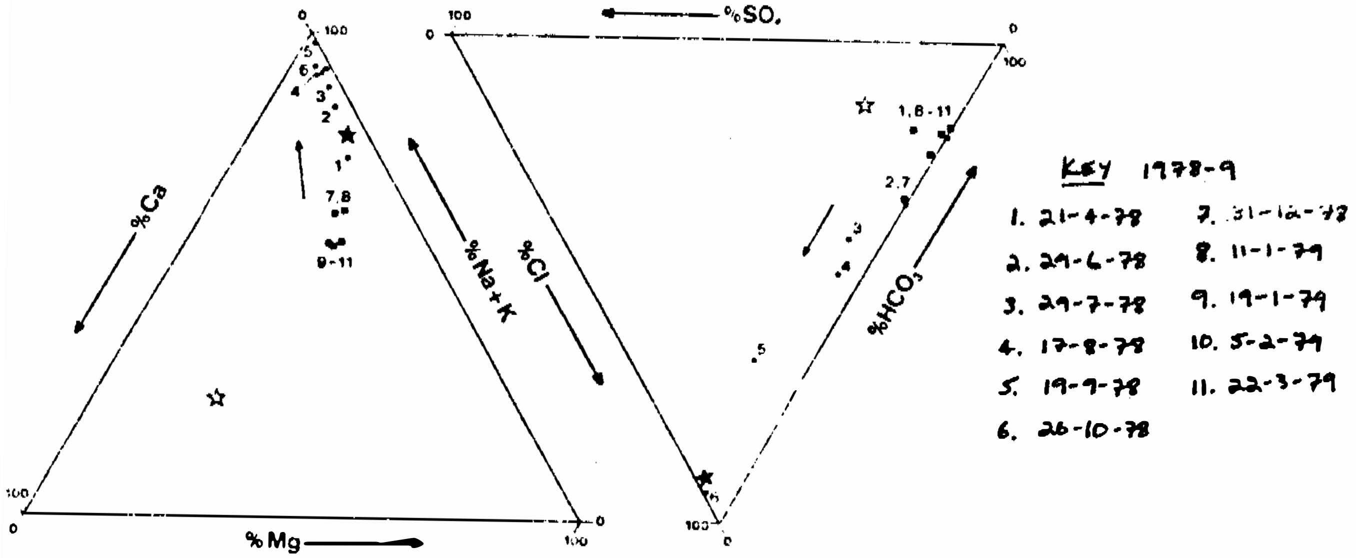


Fig. 3.5.5...Ternary diagrams showing the seasonal pattern of ionic proportions in Coonjimba billabong. Symbols as for Fig. 3.4-1.

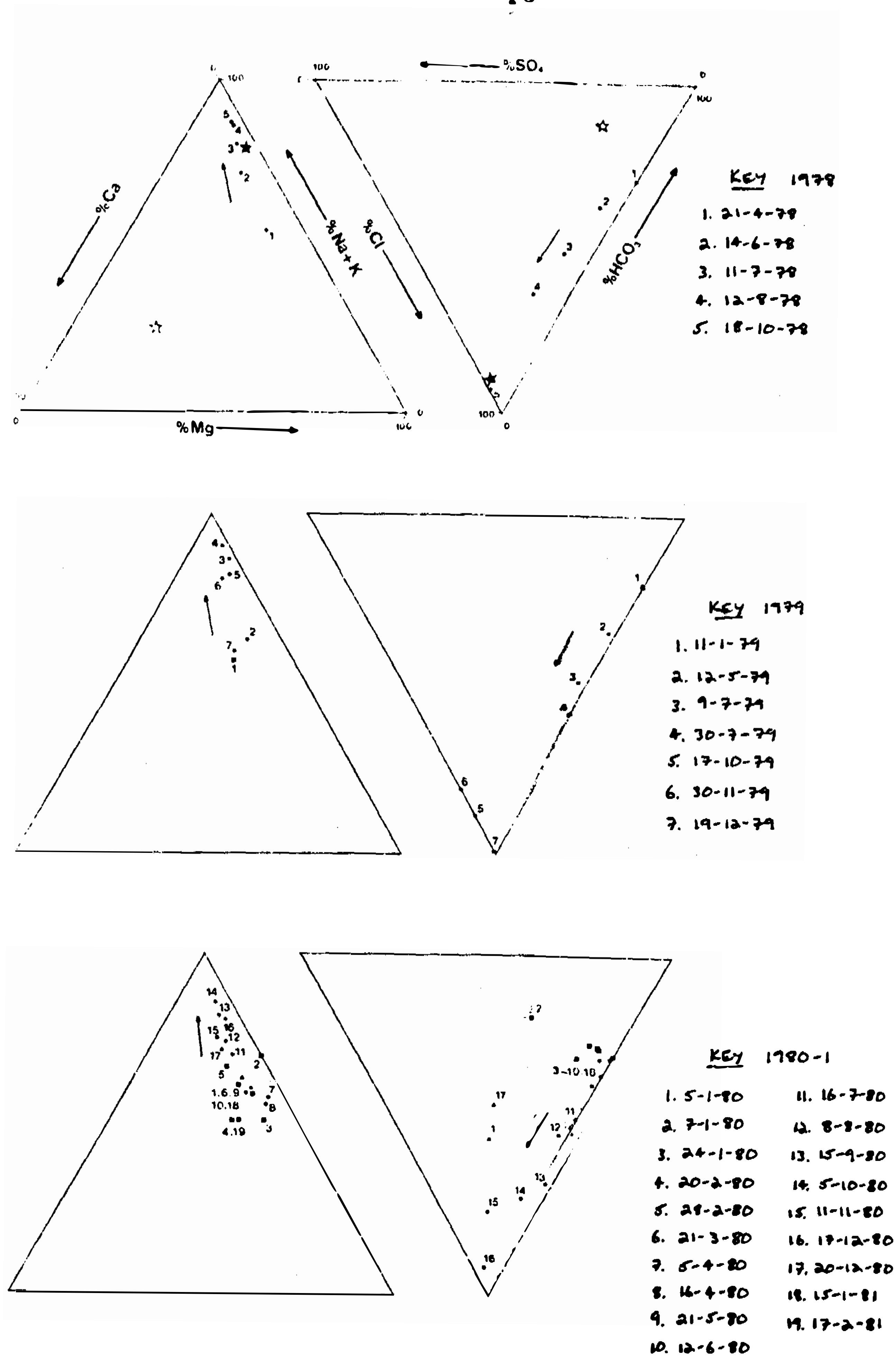


Fig. 3.5.6...Ternary diagrams showing the seasonal pattern of ionic proportions in Gulungul....billabong. Symbols as for Fig. 3.4-1.

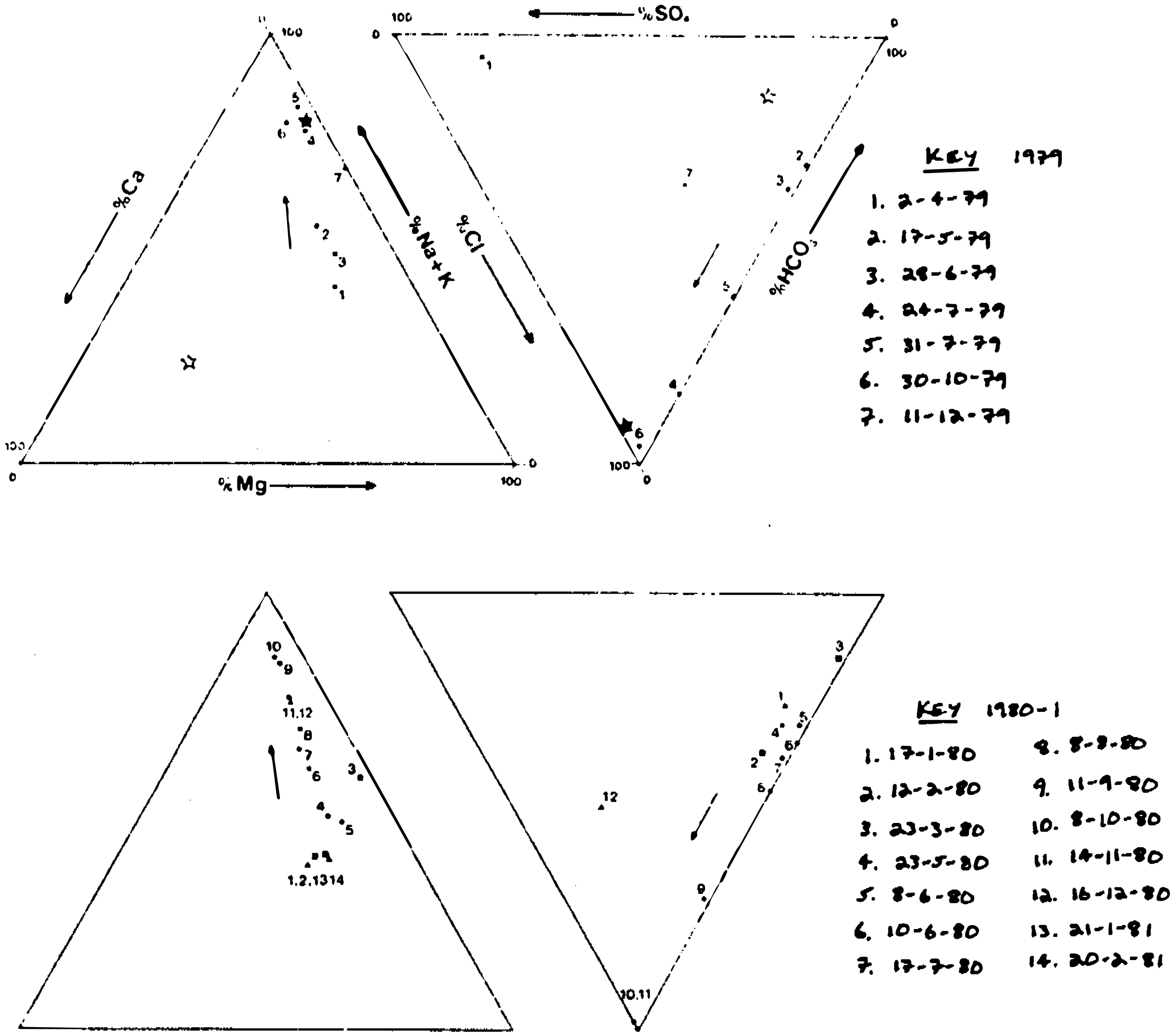


Fig. 3.5.7...Ternary diagrams showing the seasonal pattern of ionic proportions in..[illegible]..billabong. Symbols as for Fig. 3.4-1.

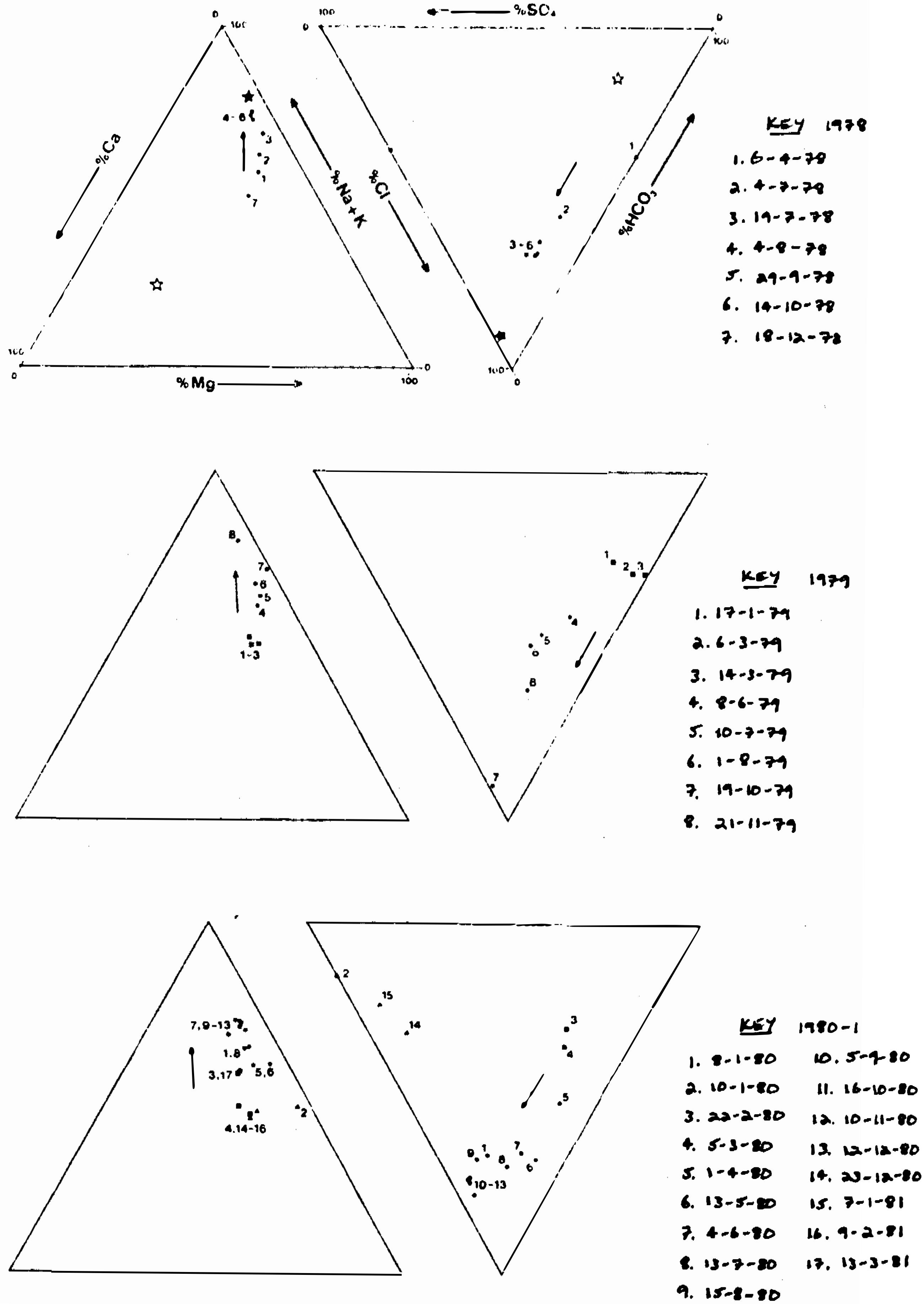


Fig. 3.5.1...Ternary diagrams showing the seasonal pattern of ionic proportions in.Leichhardt..billabong. Symbols as for Fig. 3.4-1.

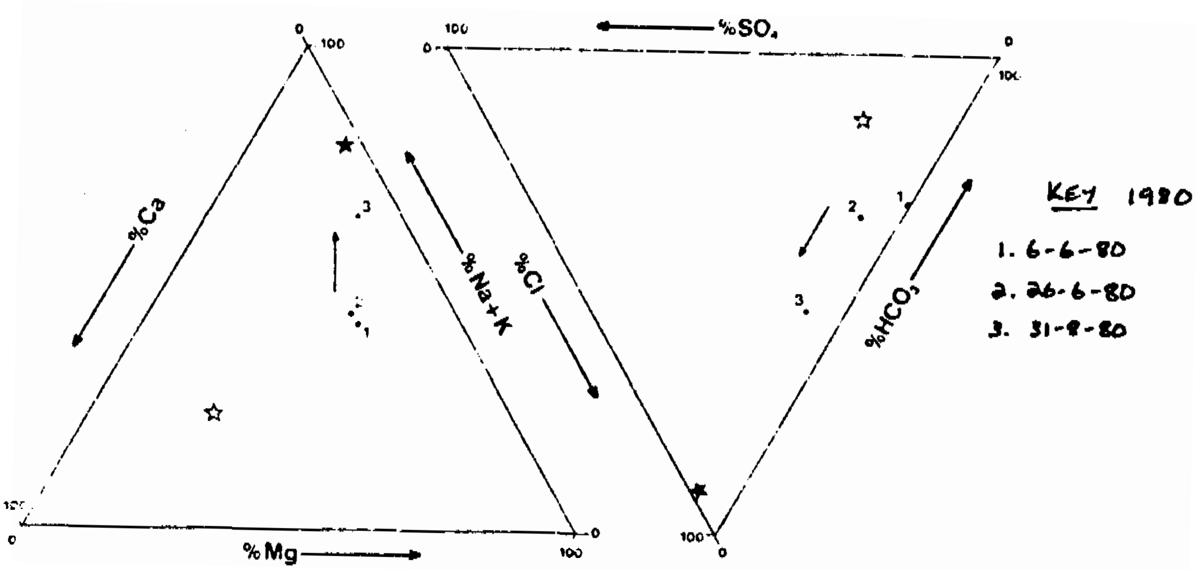


Fig. 3.5.9...Ternary diagrams showing the seasonal pattern of ionic proportions in Woolwonga billabong. Symbols as for Fig. 3.4.1.

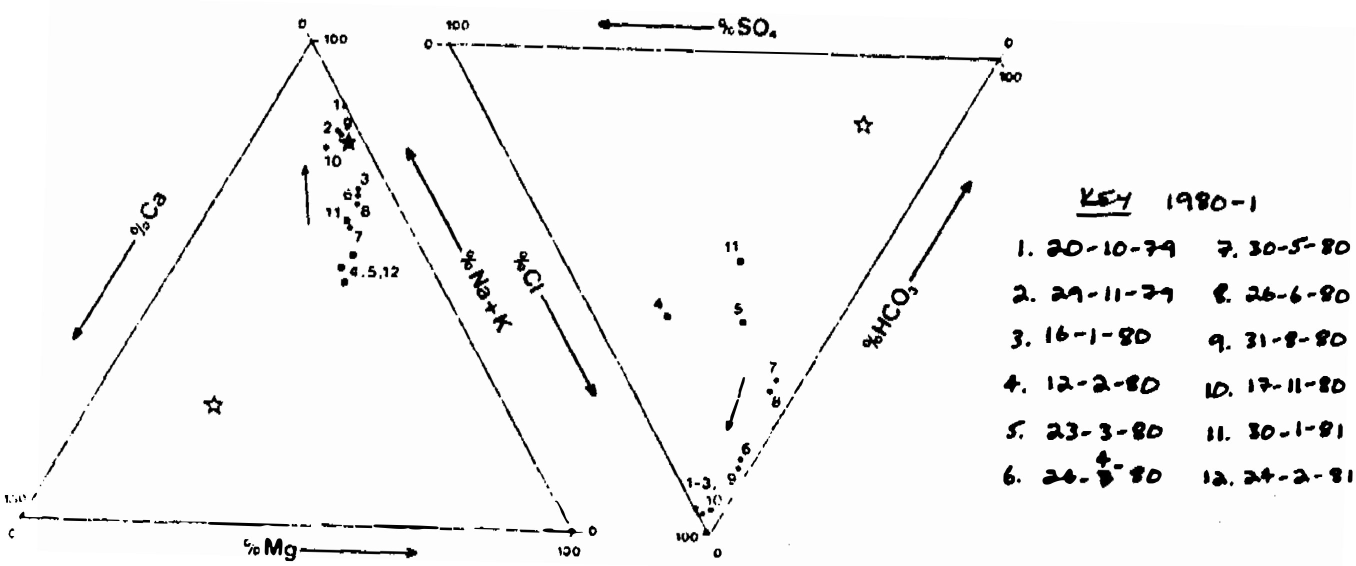


Fig. 3.5.10..Ternary diagrams showing the seasonal pattern of ionic proportions in..Jingalla...billabong. Symbols as for Fig. 3.4-1.

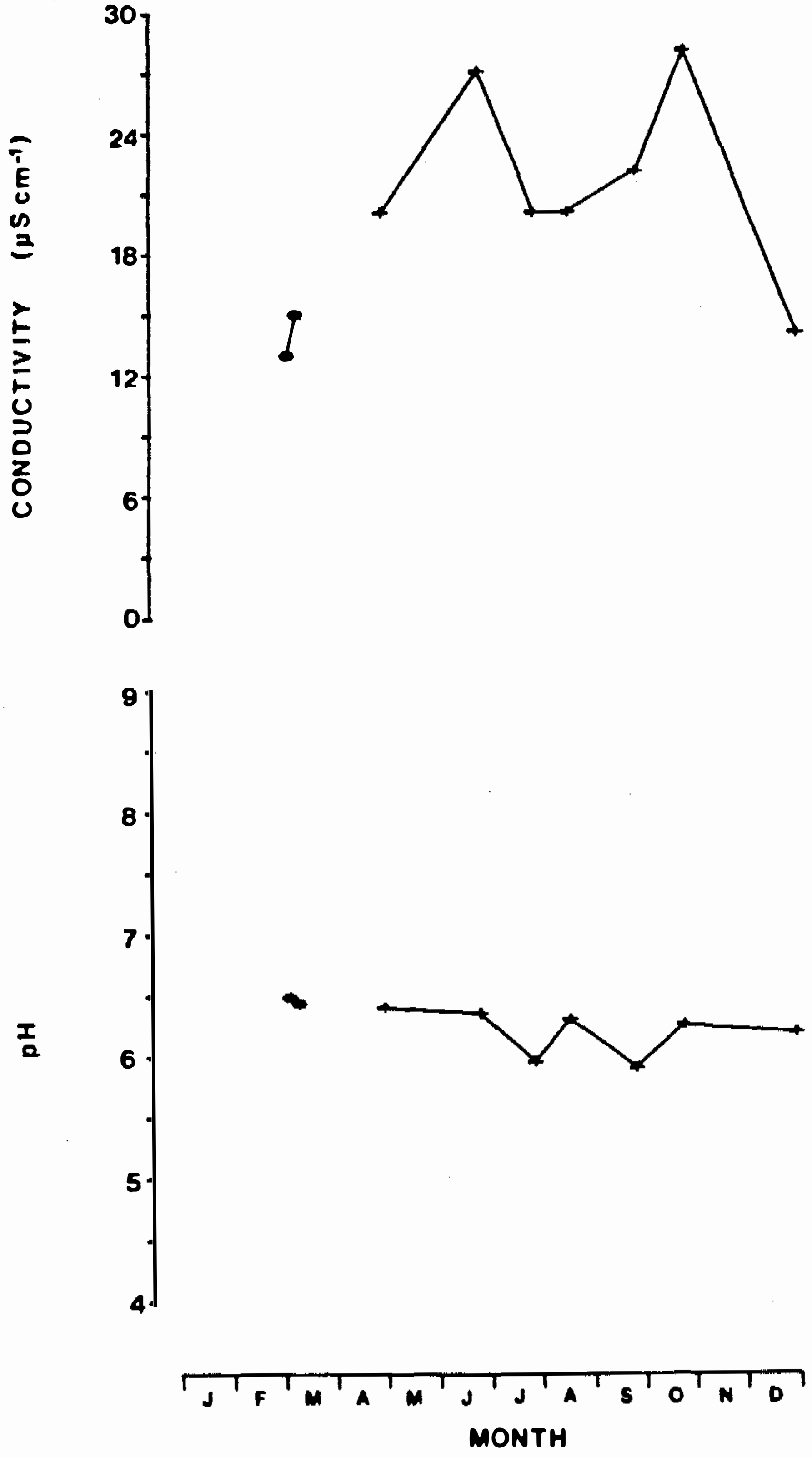


Fig. 3.5.10. Seasonal variations in electrical conductivity (K_{18}) and pH in Buffalo billabong during 1978 (+), 1979 (*) and 1980 (□).

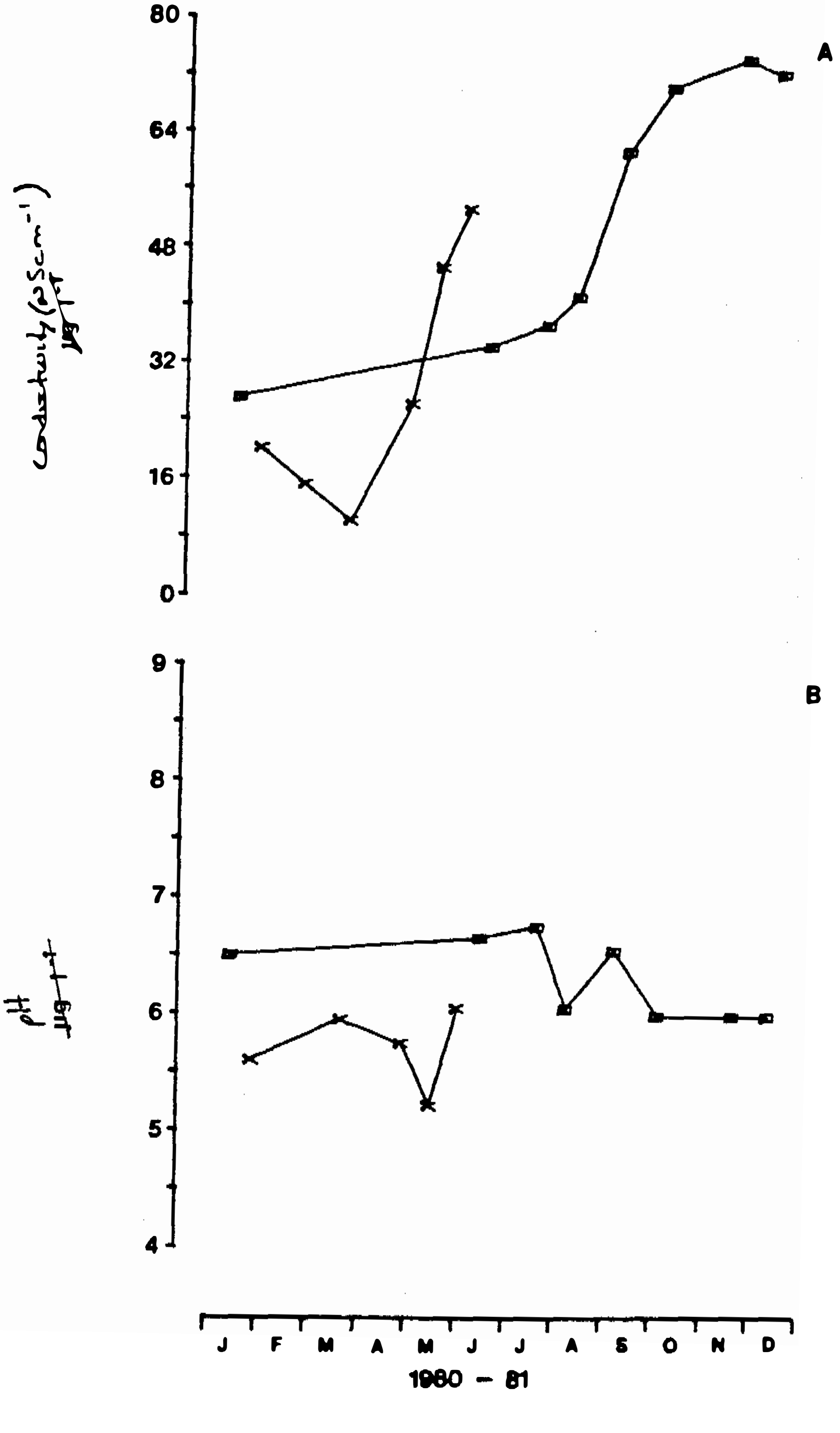


Fig. 3.5.12..Seasonal variations in electrical conductivity (K_{18}) and pH in .Kpkkpldw.billabong during 1980 (□) and 1981 (×).

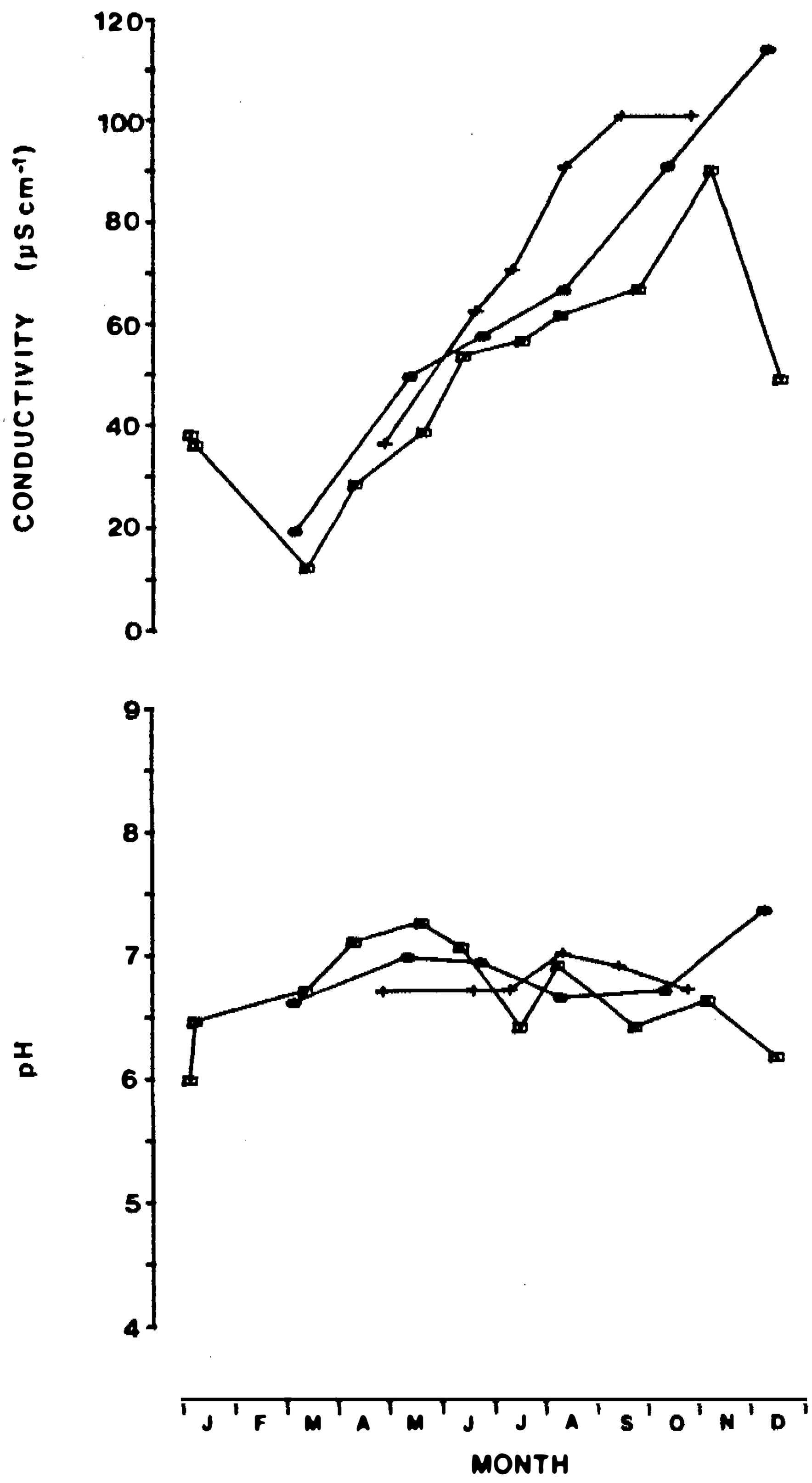


Fig. 3.5.13. Seasonal variations in electrical conductivity (K_{18}) and pH in Georgetown billabong during 1978 (+), 1979 (✱) and 1980 (◻).

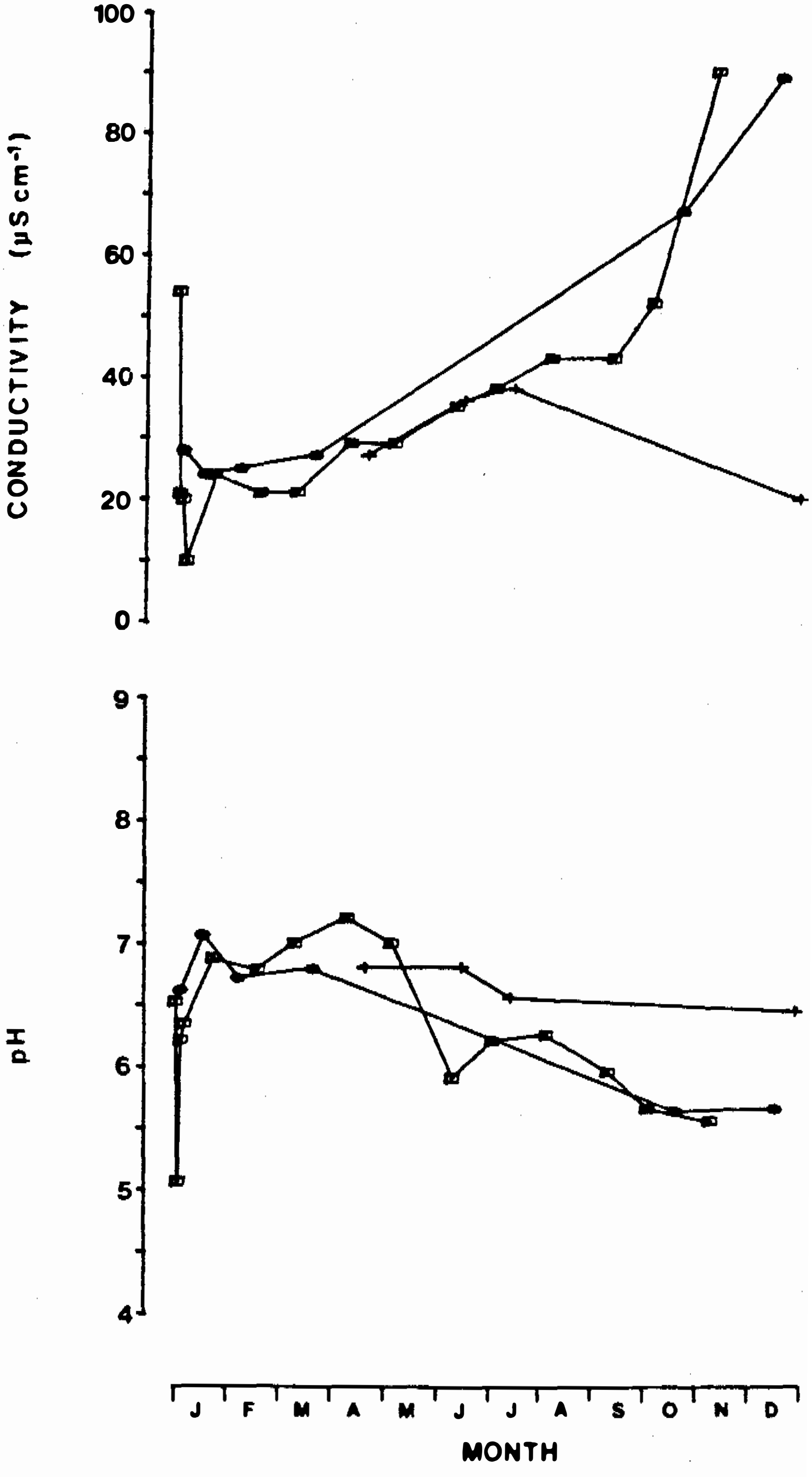


Fig. 3.5.18. Seasonal variations in electrical conductivity (K_{18}) and pH in Georgetown billabong during 1978 (+), 1979 (*) and 1980 (□).

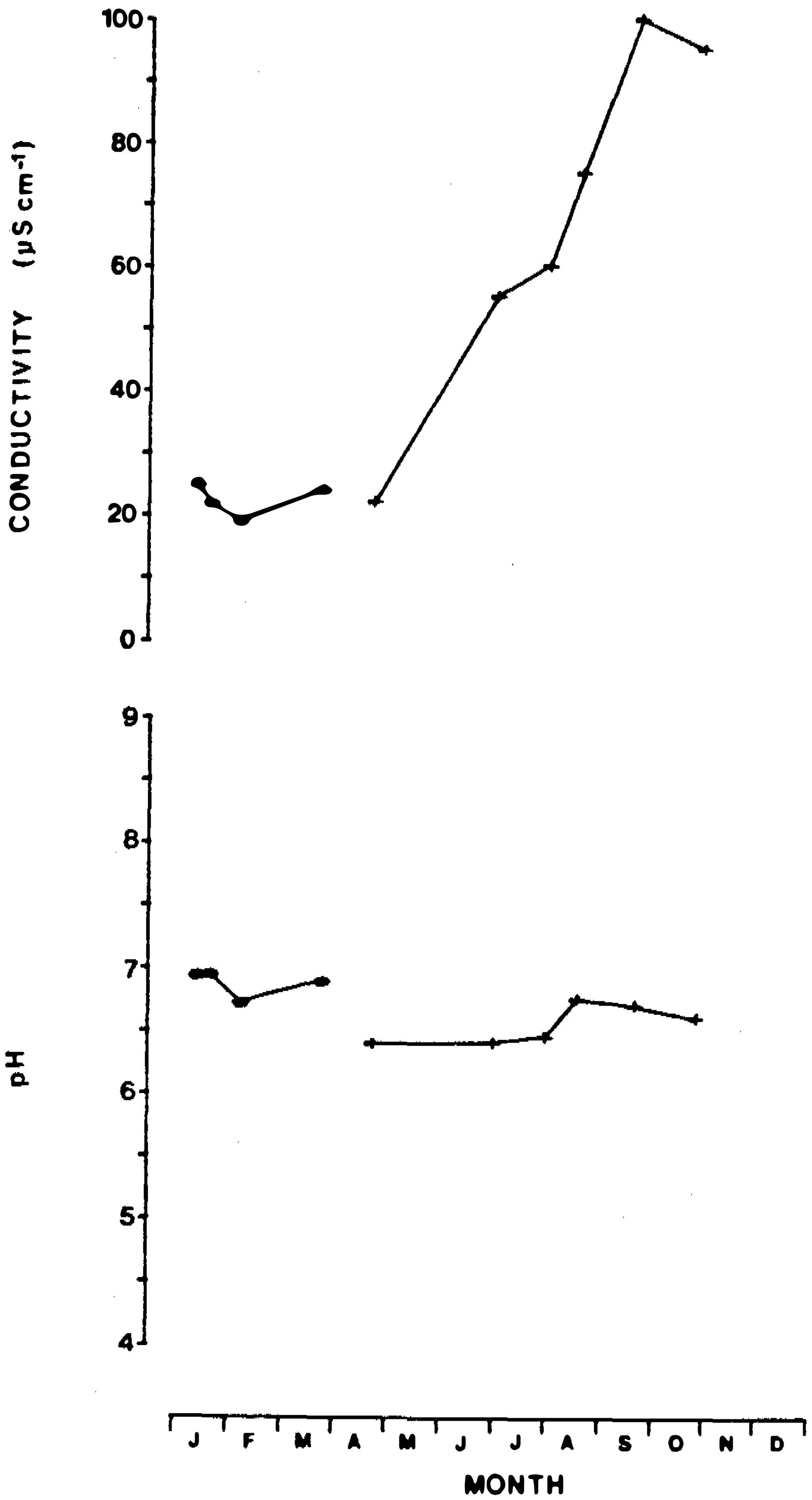


Fig. 3.5.10. Seasonal variations in electrical conductivity (K_{18}) and pH in Coonjimba billabong during 1978 (+), 1979 (✱) and 1980 (□).

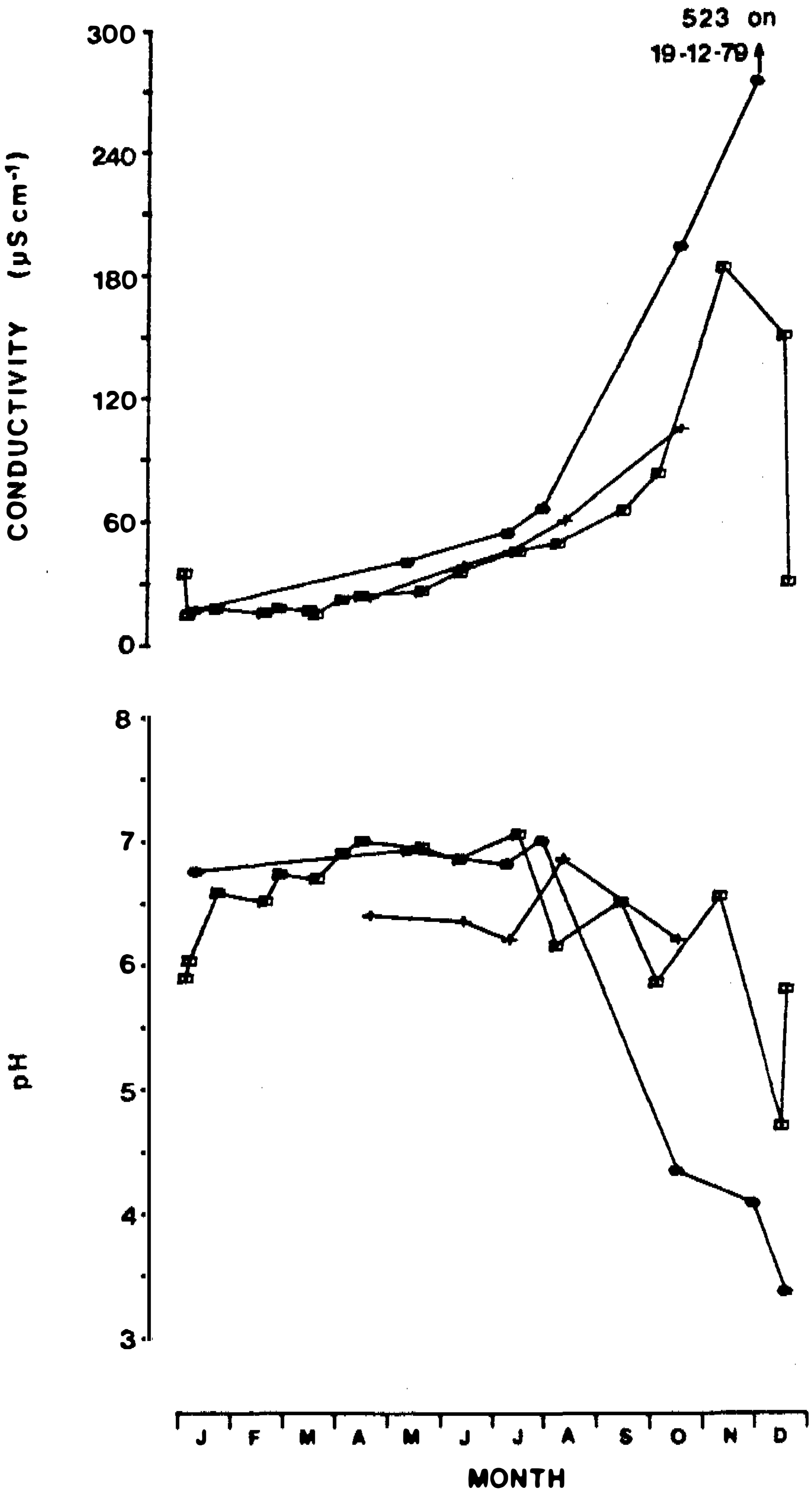


Fig. 3.5.16. Seasonal variations in electrical conductivity (K_{18}) and pH in Gulungul billabong during 1978 (+), 1979 (*) and 1980 (□).

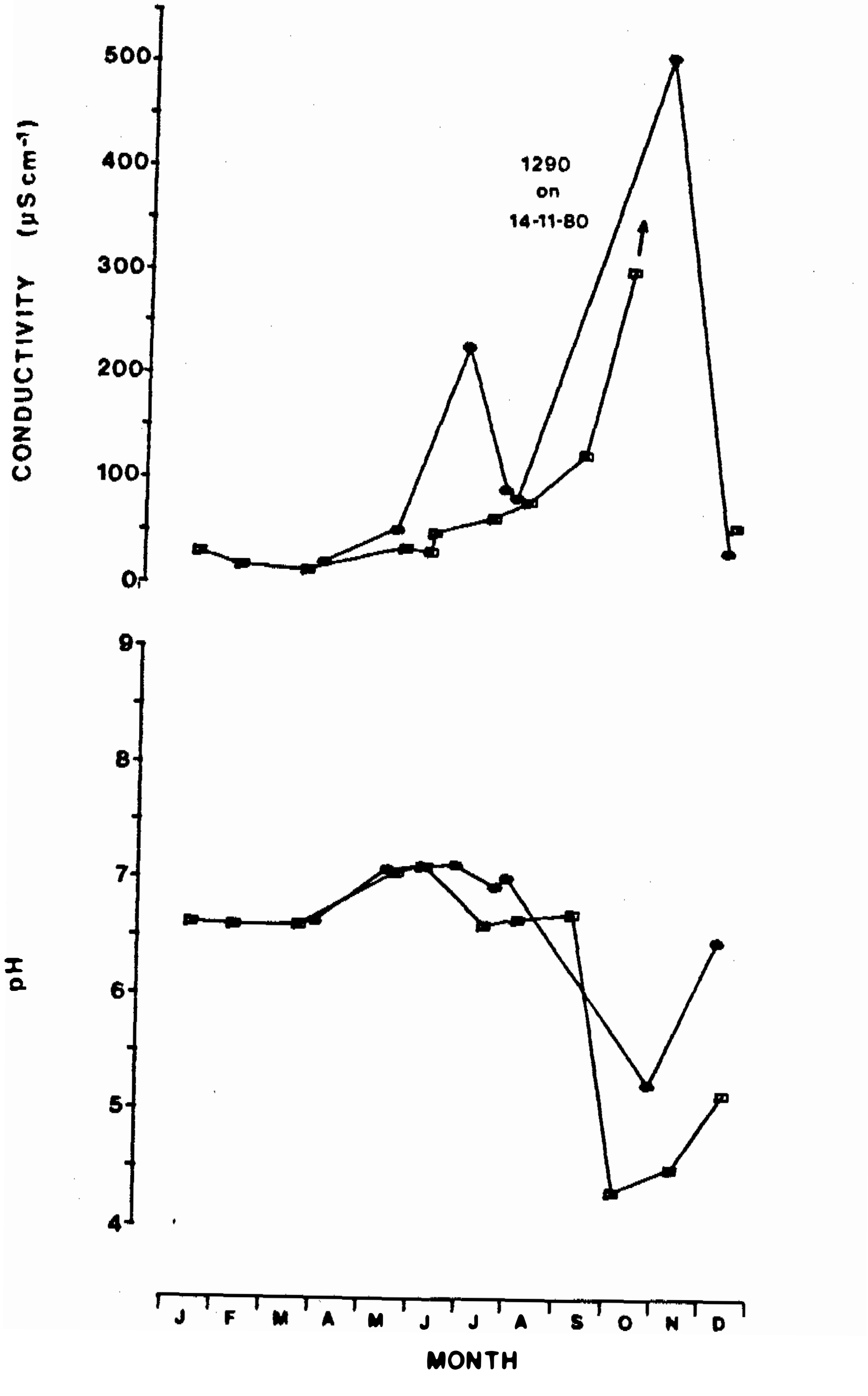


Fig. 3.5.17..Seasonal variations in electrical conductivity (K_{18}) and pH in [illegible] billabong during 1979 (*) and 1980 (□).

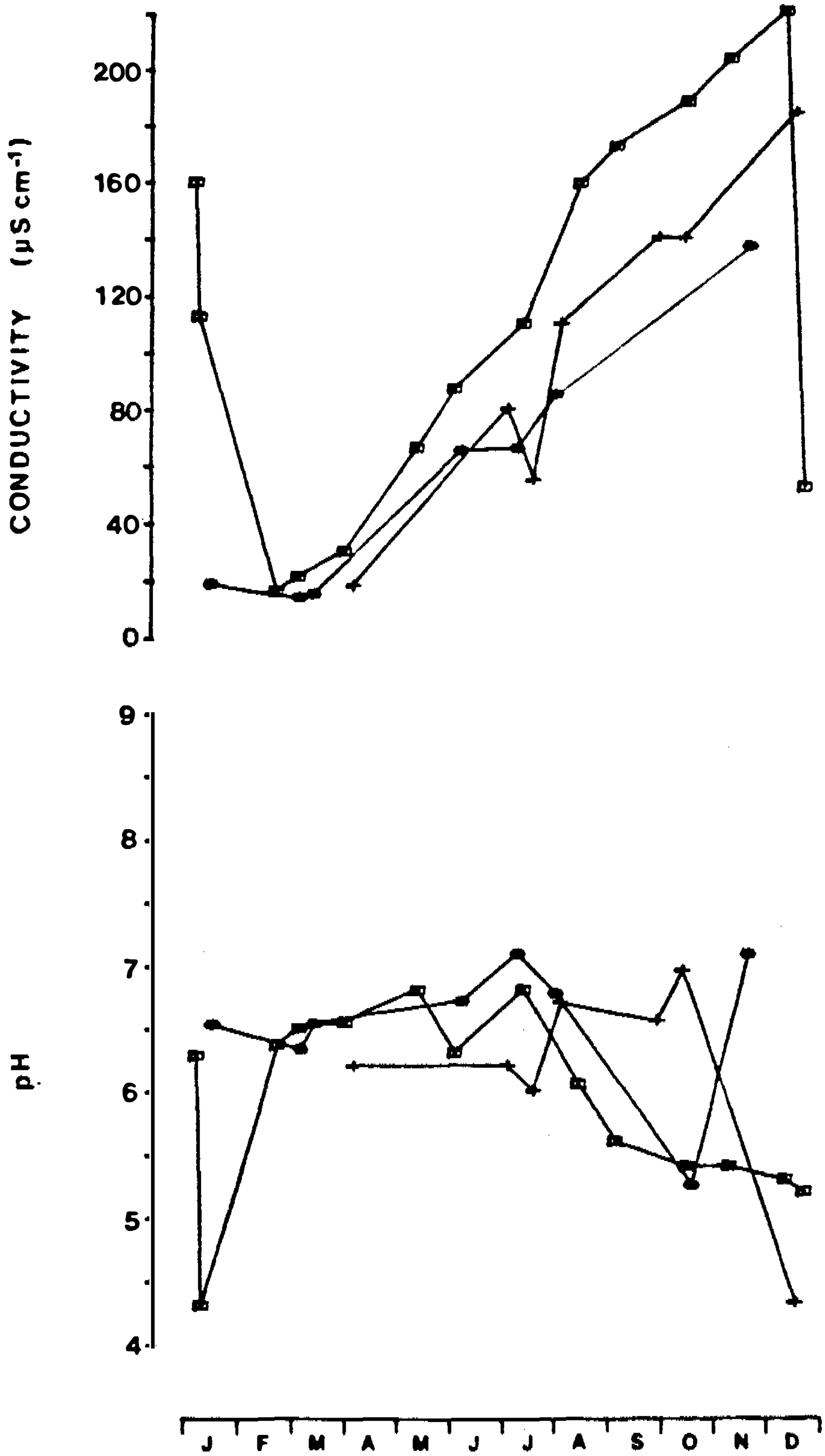


Fig. 3.18. Seasonal variations in electrical conductivity (K_{18}) and pH in Leichhardt billabong during 1978 (+), 1979 (✱) and 1980 (□).

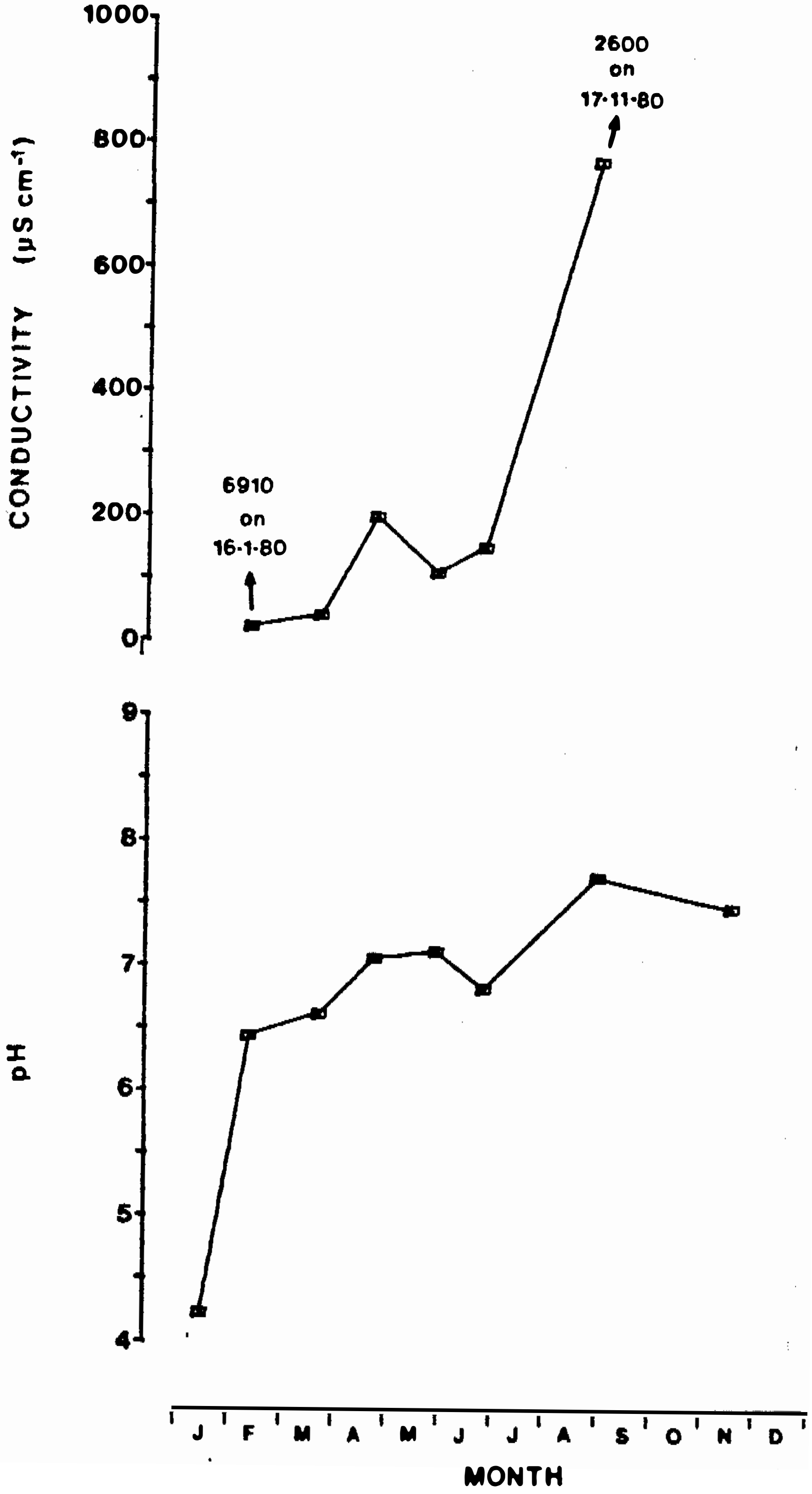


Fig. 3.5.19..Seasonal variations in electrical conductivity (K_{18}) and pH in Jingalla...billabong during 1980 (□).

Apart from Jingalla, conductivities exhibited by this group of billabongs in the late Dry ranged from 30-520μScm^{-1} (Figs. 3.5-~~1-8~~.11-18). The highest values were recorded in the two backflow billabongs, Umbungbung and Gulungul, which, by virtue of the intense evaporation and high surface area to volume ratios, may all but dry up during prolonged dry seasons. The lowest conductivity during the Dry was for Kulukuluku, which is transitional between a channel and a floodplain billabong. Jingalla, where conductivities rose to 2600μScm^{-1} during the 1980 Dry, is reputed to receive saline inflows from either spring tides in the South Alligator estuary, or groundwater seepage from shallow, seawater-contaminated aquifers. In this group of billabongs, pH values generally declined over the Dry (Figs. 3.5-~~1-9~~.11-18), some to as low as 4.0 (e.g. Gulungul).

Increases in electrical conductivity must be expected in all billabongs where evaporative concentration occurs during the Dry, with consequent increases of ionic concentrations. Table 3.5-1 shows that it is sodium and chloride, and in some instances sulphate*, which concentrate at the greatest rate, relative to increases in conductivity. This observation is consistent with the change to sodium chloride dominance through the Dry.

Gulungul in 1978 (Fig. 3.5.6) was, apparently, a rare case, when both cation and anion progression was uninterrupted, and seawater proportions were attained. More often, the changes to sodium chloride dominance were seasonal trends rather than continuous, month by month events. Sometimes the seawater position for cations was overshot e.g. (Figs. 3.5-3,5,6,8), giving monovalent:divalent ratios higher than that for seawater.

Following the first rains, at the Dry-Wet interchange, a reversal of the trend to sodium dominance was evident in some backflow billabongs (Fig. 3.5.5-7). Since at that time they were very shallow remnants, the influence of relatively large inflows of local runoff is not surprising. The seasonal

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* (Table 3.5-1 includes all billabongs in the sodium chloride group plus those in which sulphate becomes important (see below)).

Table 3.5-1. Rate of increase[1], during the 1980 Dry, of concentration of major ions (μeql^{-1}) relative to changes in electrical conductivity for billabongs in the conductivity range 30[2]-300[3] μScm^{-1}, calculated from regression of conductivity upon each ion.

Ion	$\frac{\Delta\ ion}{\Delta K_{25}}$	r	n
Na	4.83	0.9409	98
K	0.84	0.8845	98
Ca	0.93	0.7664	98
Mg	1.15	0.7825	98
SO_4	4.96	0.6200	98
Cl	6.25	0.9505	98

1 Since HCO_3 may fall to zero during the Dry, it could not be included in this analysis.

2 Dry season K_{25} values less than $30\mu Scm^{-1}$ were characteristic of the sodium bicarbonate billabongs, in which composition and concentration change little. These billabongs have been excluded.

3 Since 95% of dry season conductivities were below $300\mu Scm^{-1}$, for statistical reasons the few samples with K_{25} values >300 were excluded from the analysis. The unique Red Lily was also excluded.

cycle for all billabongs is completed when floodwaters enter, dramatically reducing the conductivity (Fig. 3.5-16-18) and restoring the sodium bicarbonate proportions of the Wet.

3.6 Sulphate billabongs

This group is comprised of one backflow billabong (Corndorl), four floodplain billabongs (Ja Ja, Mine Valley, Jabiluka and Nankeen), and Island, which in many of its characteristics is intermediate between channel and floodplain categories. In these billabongs (except Island), there is the same trend as in the sodium chloride grouping, to sodium chloride dominance, as the Dry progresses but, in addition, there is a strong selective concentration of sulphate (Figs. 3.6-2-5; Table 3.6-1). In a few cases, just prior to the first floods of the Wet, sulphate may even displace chloride as the dominant anion (e.g. Island 8/12/80; Ja Ja 5/1/80; Mine Valley 8/1/80, 10/12/80 - see Figs. 3.6-1,3,4).

At the Wet/Dry interchange, water chemistry of these billabongs is similar to that of all others, with pH values near neutrality, low conductivities (<30μScm^{-1}) and sodium bicarbonate dominance. In the floodplain billabongs and in Corndorl there follows a progressive sharp rise in conductivity, accompanied by a drop in pH of 2 units or more (Figs. 3.6-8-12). The very low pH values are characteristic of the floodplain billabongs in the latter part of the Dry. The fall in pH was less in 1978 than in successive years. It appears that the low pH values and the concentration of sulphate are in some way related. At approximately the time when pH falls, sulphate begins to concentrate. In all cases where SO_4 exceeded 10^3μeql^{-1}, pH's approximated, or fell below, 4.0 (e.g. Ja Ja 5/1/80; Mine Valley 13/12/79, 25/9-10/12/80).

Abruptly, early in the Wet, floodwaters restore sodium bicarbonate dominance, reduce the conductivity to <30μScm^{-1}, and bring the pH back to near neutrality (Figs. 3.6-8-12).

Island billabong displays much the same seasonal trends of pH and

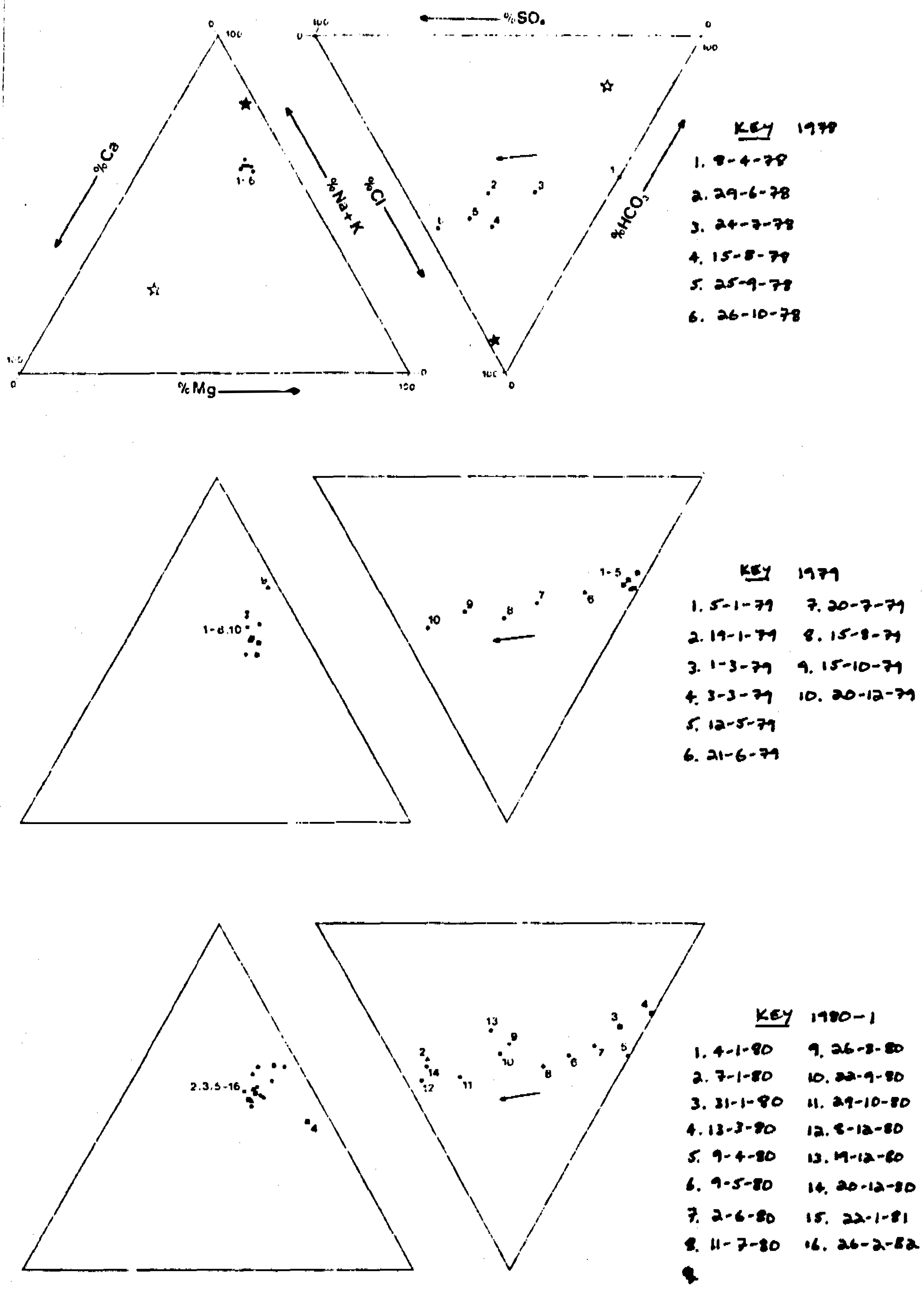

Fig. 3.6.1...Ternary diagrams showing the seasonal pattern of ionic proportions in...Island....billabong. Symbols as for Fig. 3.4.1.

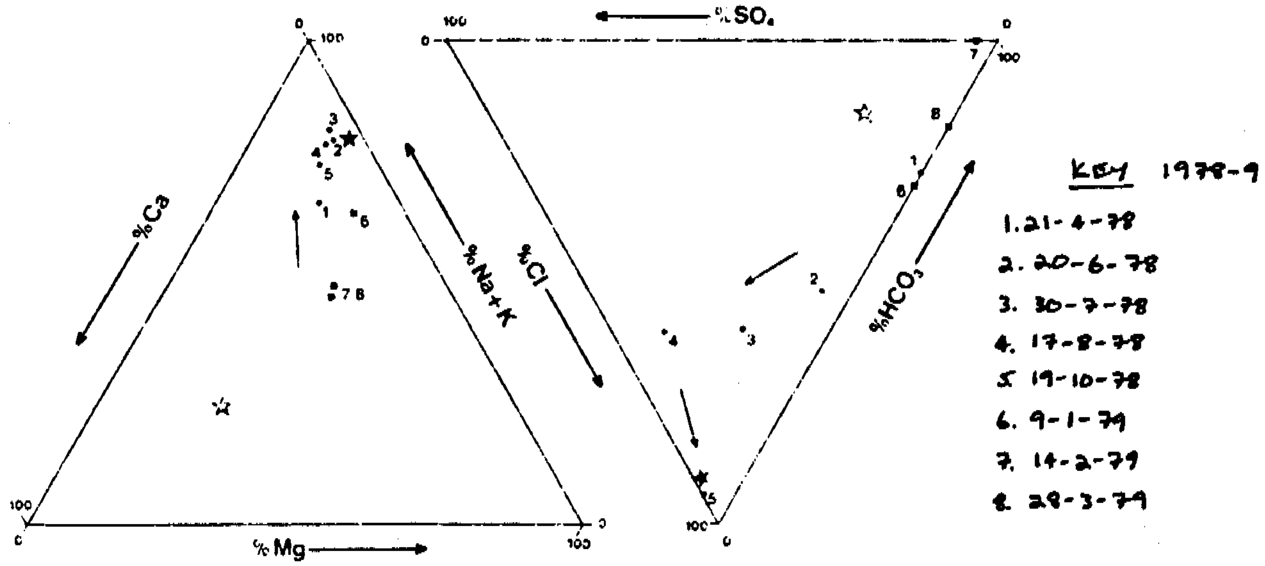

Fig. 3.6.2...Ternary diagrams showing the seasonal pattern of ionic proportions in..Coondal....billabong. Symbols as for Fig. 3.4-1.

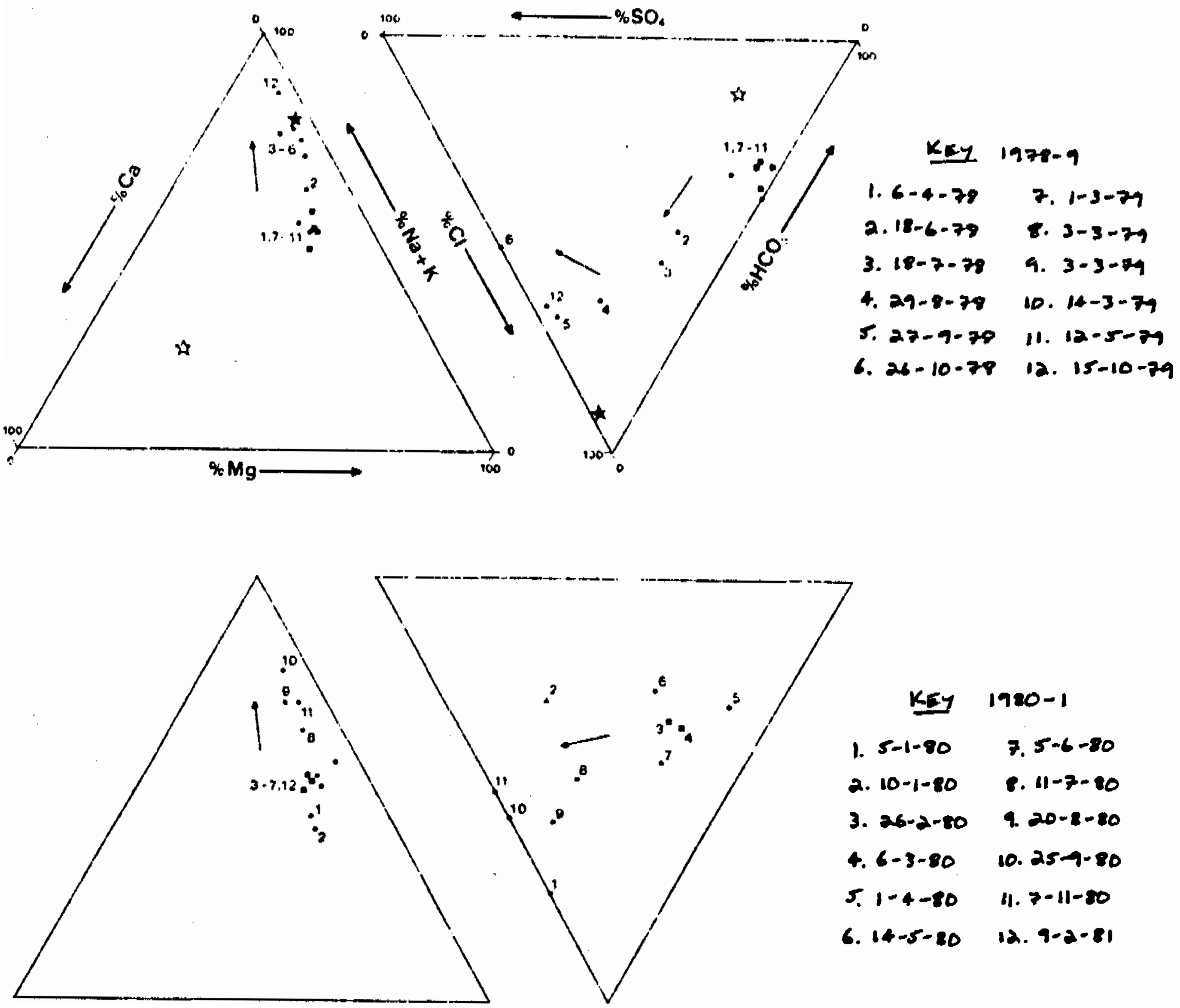

Fig. 3.6.3...Ternary diagrams showing the seasonal pattern of ionic proportions in [illegible]......billabong. Symbols as for Fig. 3.4.1.

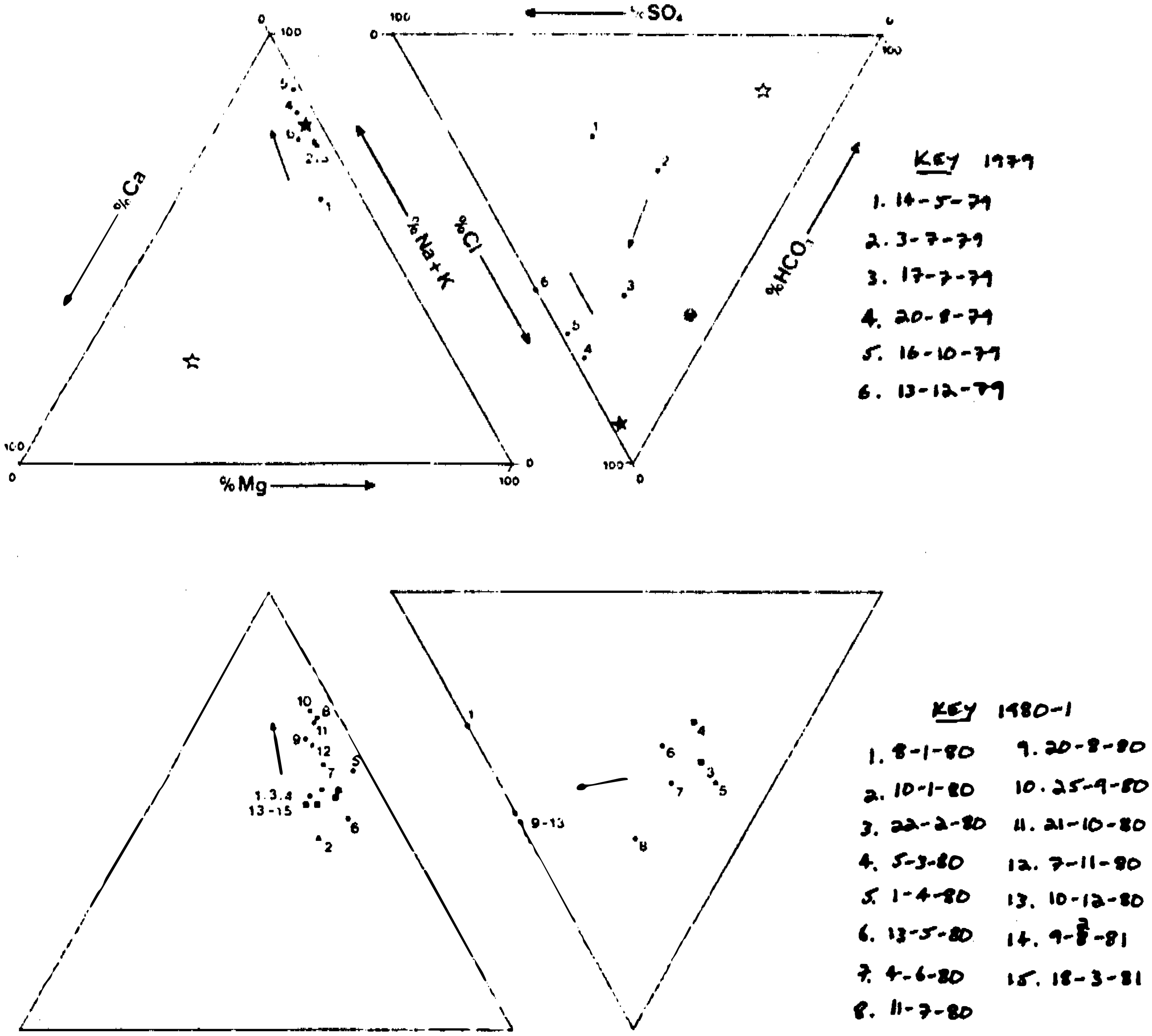

Fig. 3.6.4...Ternary diagrams showing the seasonal pattern of ionic proportions in Mine Valley..billabong. Symbols as for Fig. 3.4-1.

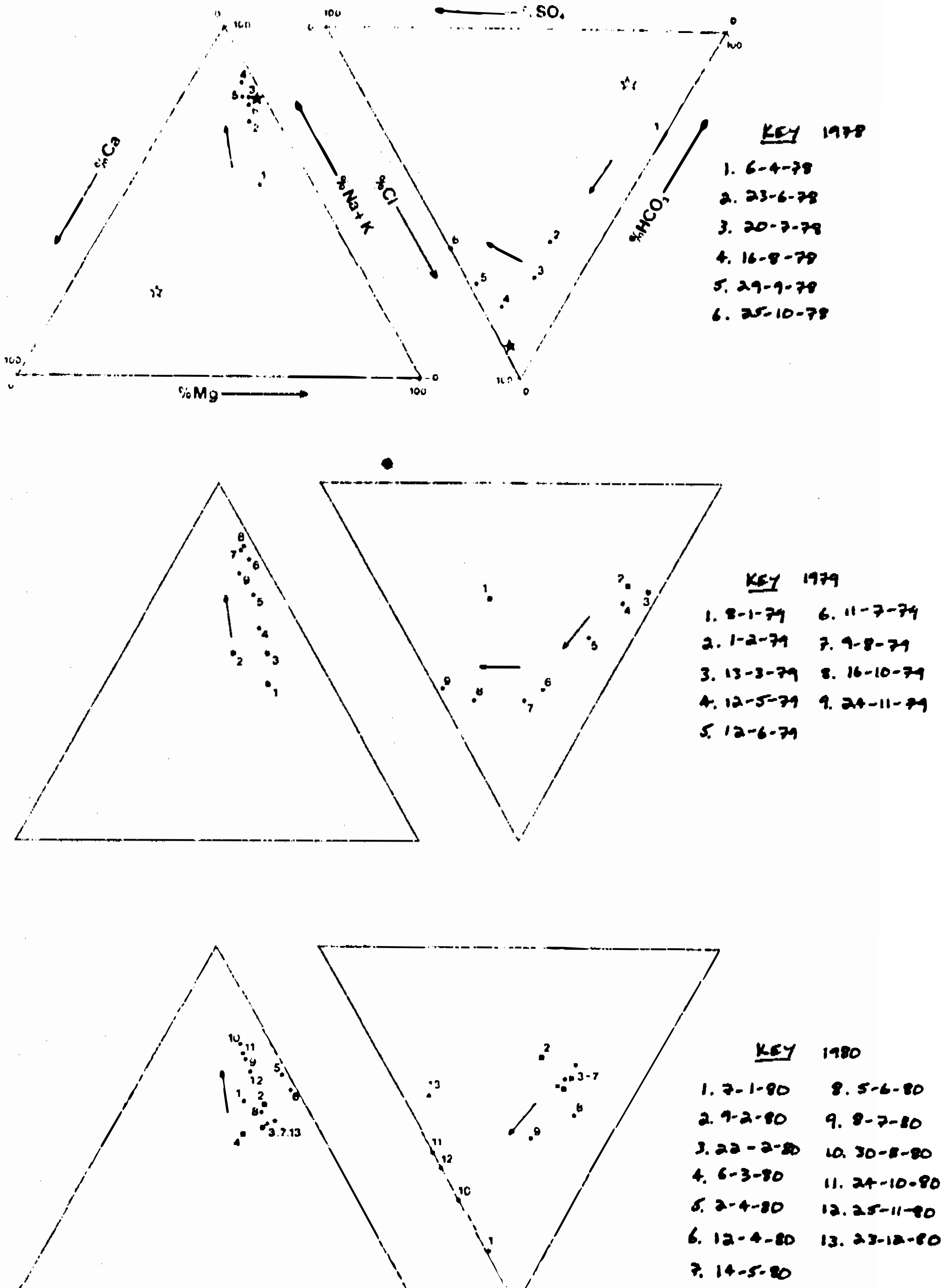

Fig. 3.6.5...Ternary diagrams showing the seasonal pattern of ionic proportions in..Jabiluka....billabong. Symbols as for Fig. 3.4-1.

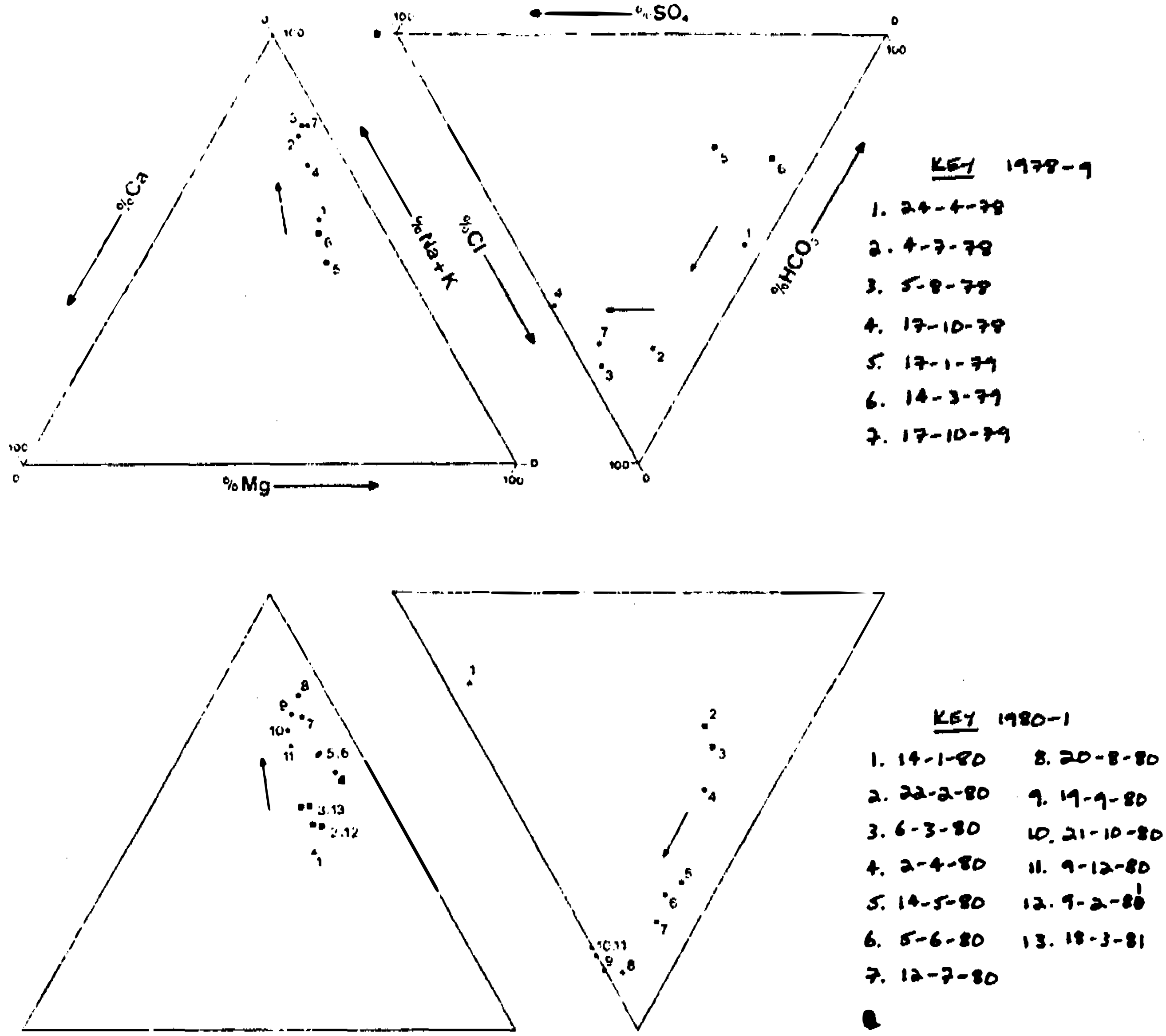

Fig. 3.4.6...Ternary diagrams showing the seasonal pattern of ionic proportions in. Nankeen ...billabong. Symbols as for Fig. 3.4-1.

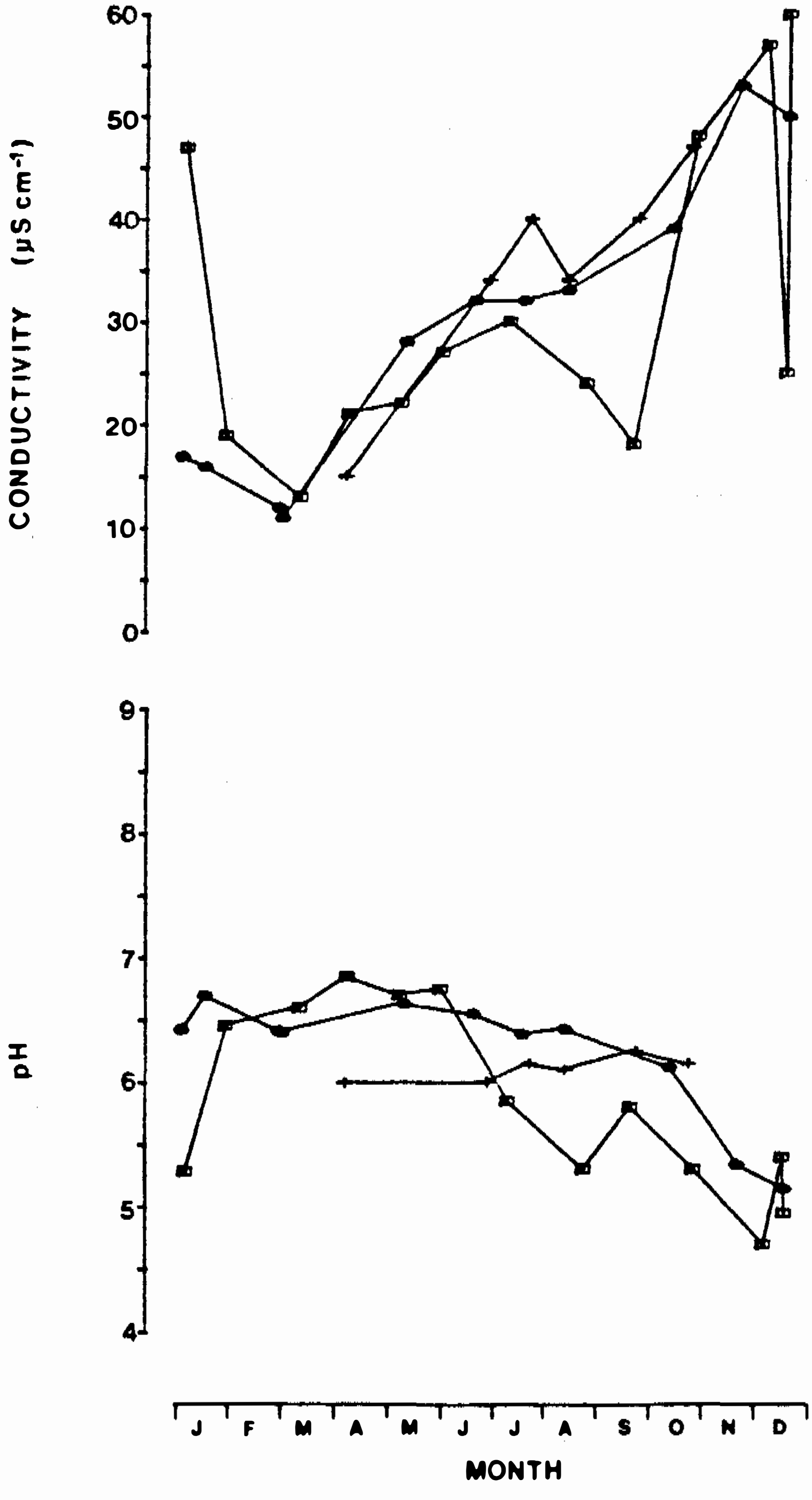

Fig. 3.6.7. Seasonal variations in electrical conductivity (K_{18}) and pH in Island billabong during 1978 (+), 1979 (*) and 1980 (□).

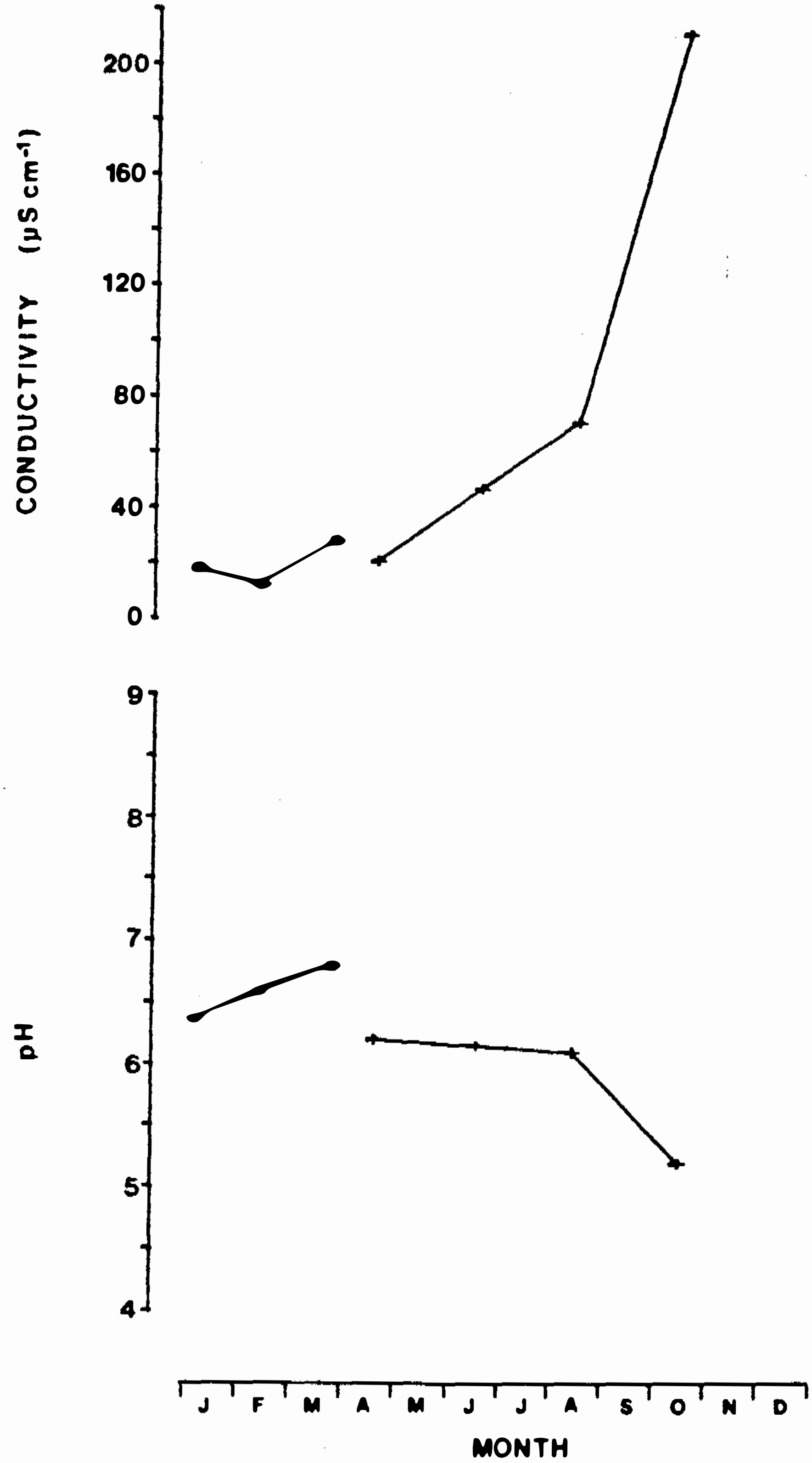

Fig. 3.5.2. Seasonal variations in electrical conductivity (K_{18}) and pH in Corndorl billabong during 1978 (+), 1979 (•).

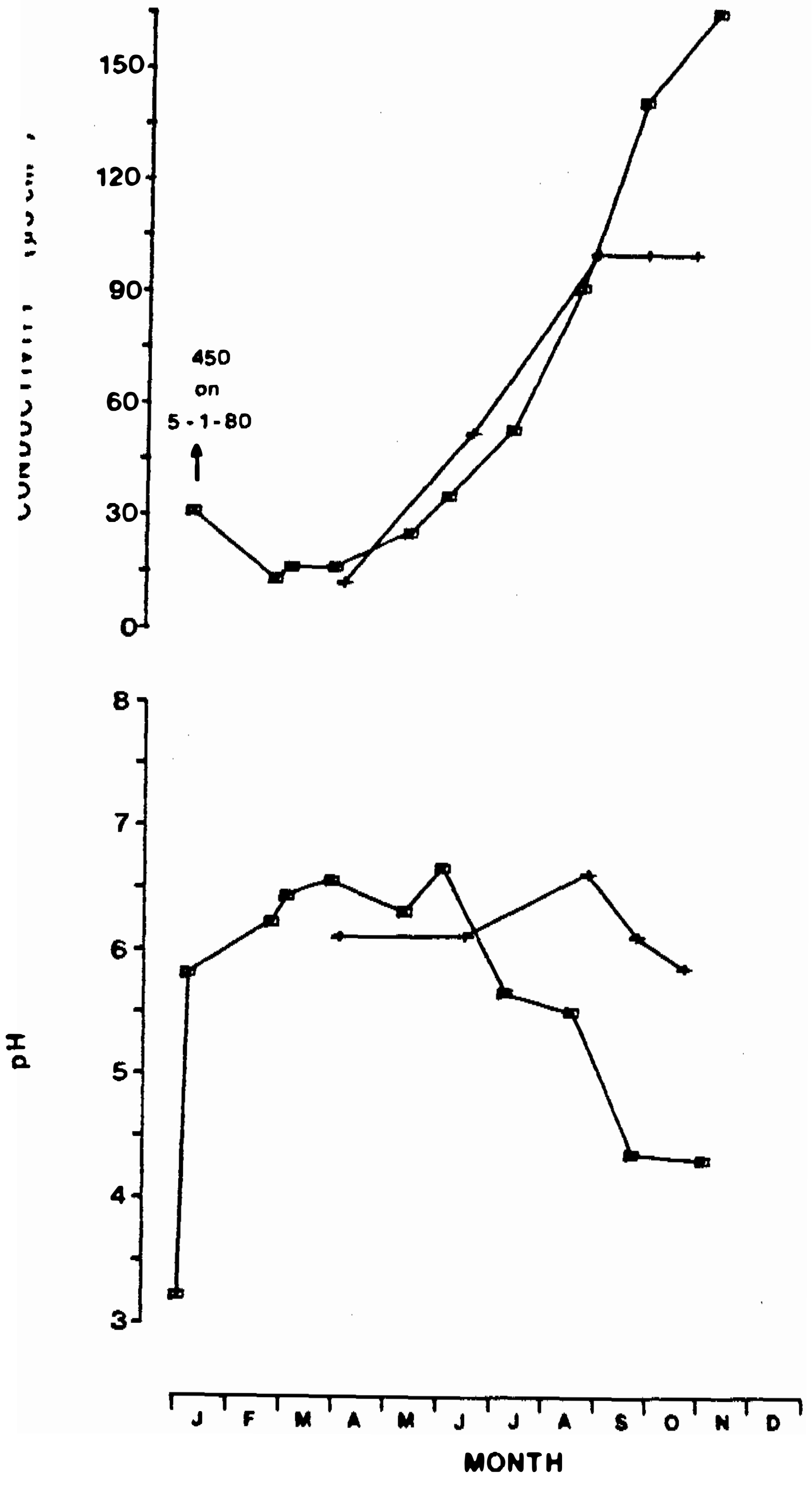

Fig. 3.6.9..Seasonal variations in electrical conductivity (K_{18}) and pH in ..Ja.Ja....billabong during 1979 (*) and 1980 (□).

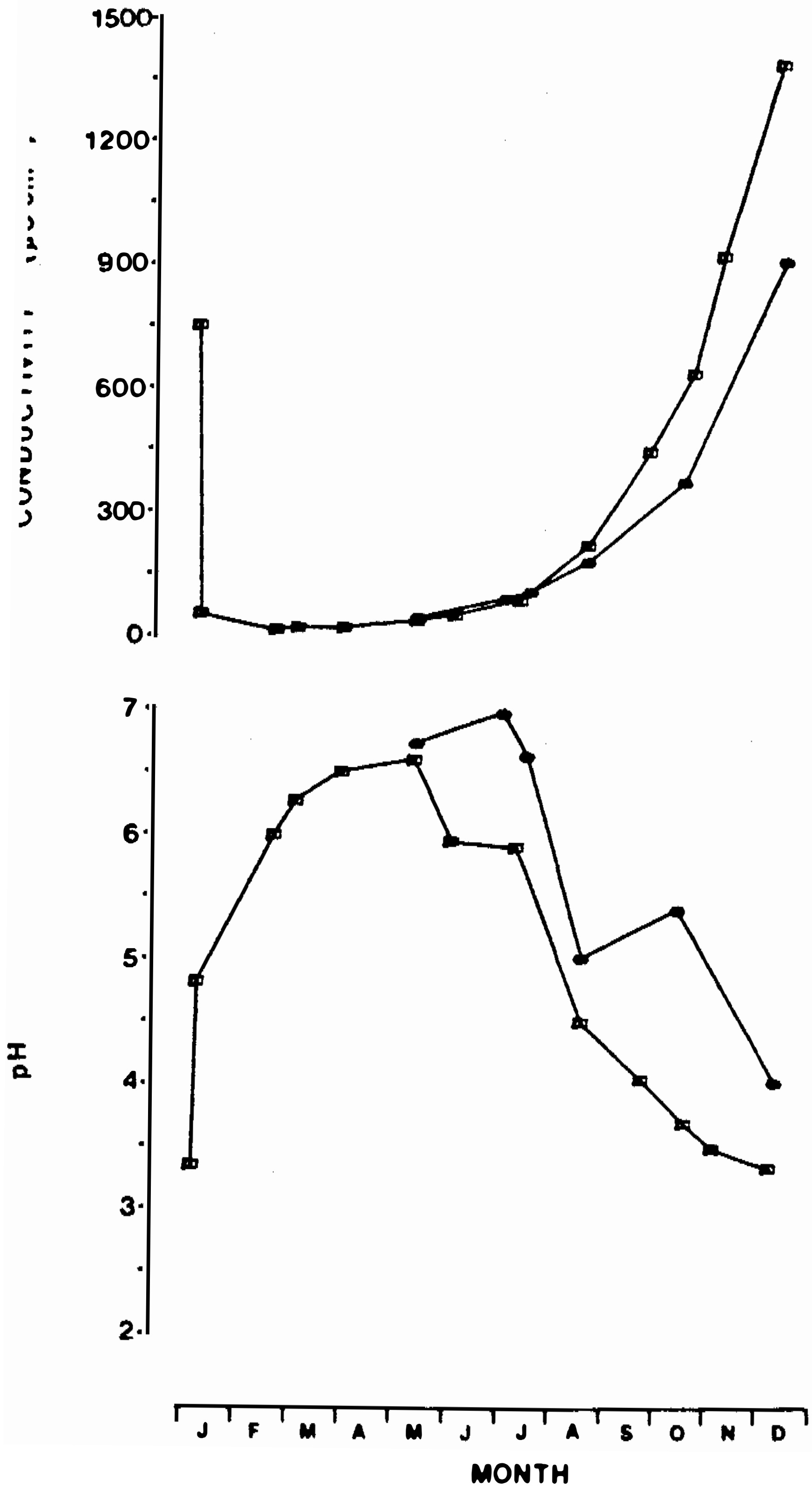

Fig. 3.6.10..Seasonal variations in electrical conductivity (K_{18}) and pH in Mine Valley billabong during 1979 (•) and 1980 (□).

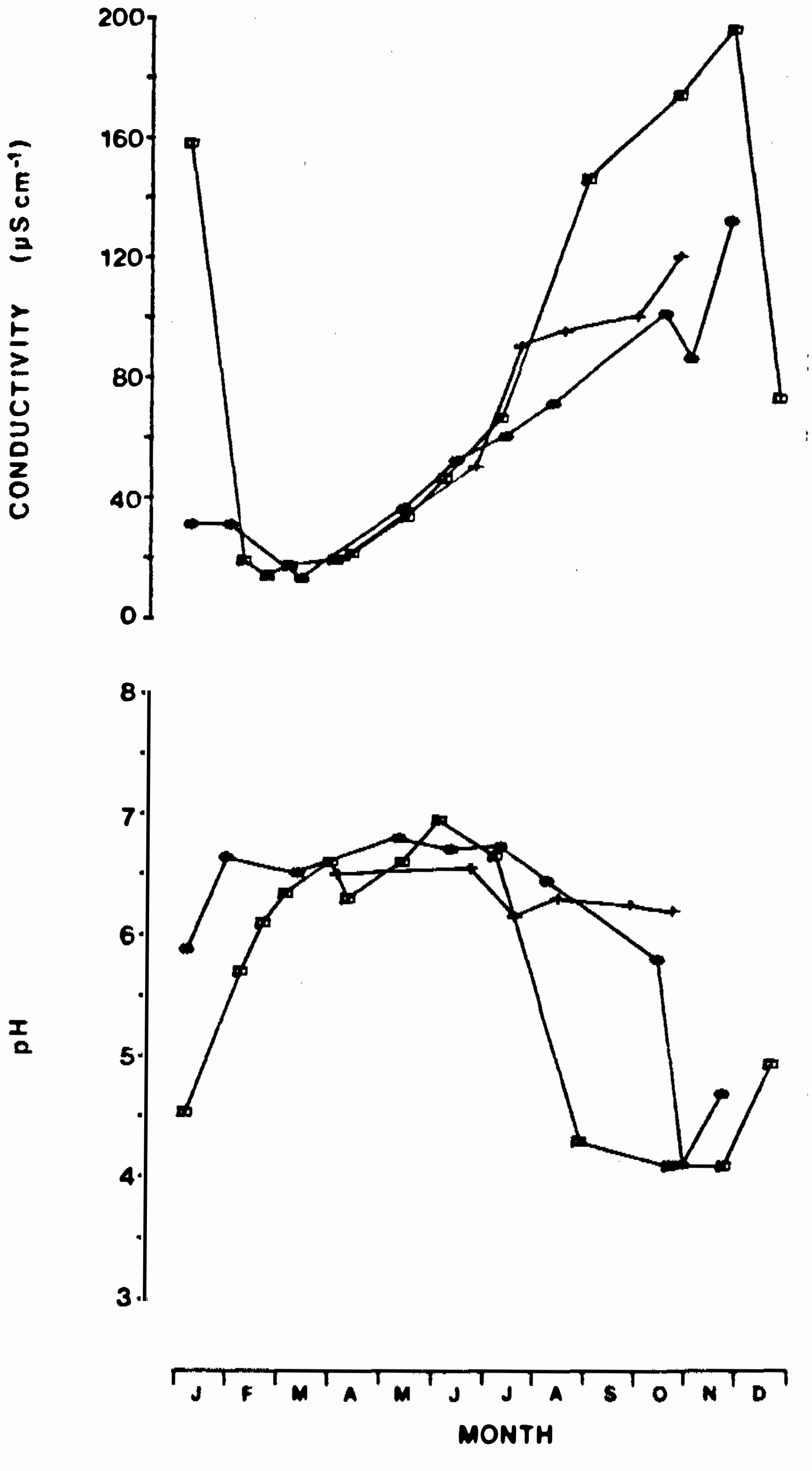

Fig. 3.6.11. Seasonal variations in electrical conductivity (K_{18}) and pH in Jabiluka billabong during 1978 (+), 1979 (*) and 1980 (□).

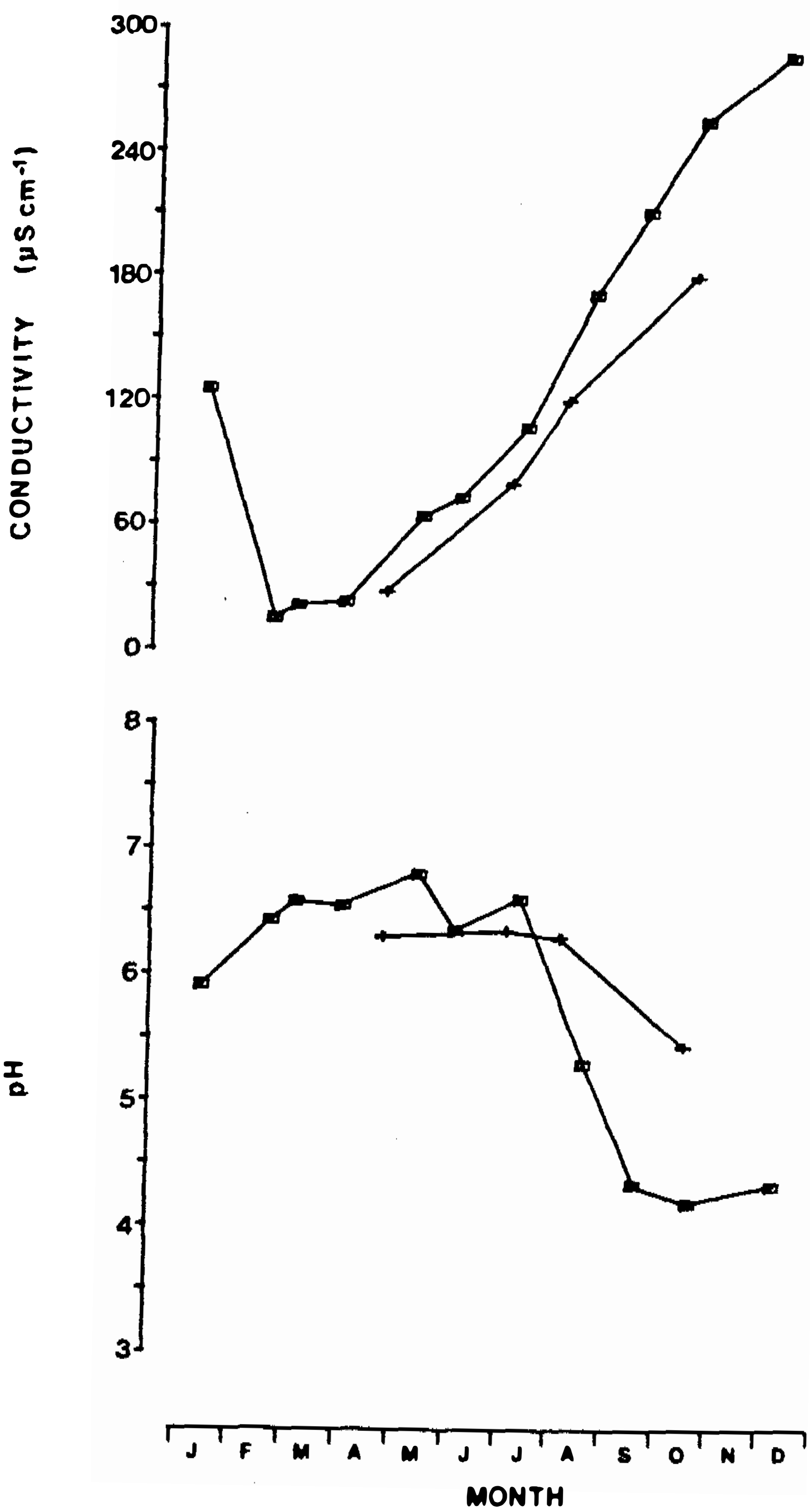

Fig. 3.6.12..Seasonal variations in electrical conductivity (K_{18}) and pH in ..Nankeen..billabong during 1979 (+) and 1980 (□).

Table 3.6-1 Rate of increase of concentration of Na, Cl and SO_4 ions[1] ($\mu eq l^{-1}$) relative to changes in electrical conductivity for sulphate group billabongs in the conductivity range 30-300$\mu S cm^{-1}$, calculated from regression of conductivity upon each ion.

Ion	$\frac{\Delta \text{Ion}}{\Delta K_{25}}$	r	n
Na	4.92	0.9654	32
Cl	6.03	0.9634	32
SO_4[1]	3.37	0.9741	
SO_4	3.53	0.7012	32

1 Only those results where anion Ternary diagrams indicated movement towards sulphate were included in this regression.

conductivity (Fig. 3.6~~-11~~.7) but with much smaller amplitude. Based on the magnitude of these changes, Island belongs more with the channel billabongs, and indeed it does not show the progression to Na or Cl dominance. However, consistent with a character intermediate between channel and floodplain billabongs, it consistently shows an increase in sulphate through the Dry (Fig. 3.6~~-5~~.1).

Sulphate does not figure priminently in most inland waters, the majority of which tend to World Average Freshwater. Where sulphate is present in significant quantities it commonly comes from oxidation of pyrite (Hutchinson 1957), a mineral which is a feature of the geology of the Alligator Rivers Region (Pancontinental Mining Limited 1981).

The weathering of pyrite, iron sulphide, proceeds as follows

$$4\ FeS_2 + 15O_2 + 2H_2O \rightarrow 2\ Fe_2(SO_4)_3 + 2H_2SO_4$$

The production of H_2SO_4 in this reaction is a likely explanation for the low pH values (often <4), coincident with relatively high sulphate levels, witnessed in the floodplain billabongs at the end of the Dry. The other common cause of low pH in natural waters is high concentrations of humic materials (gilvin), and this has been claimed for the Magela region (Fox 1977). However, gilvin values for the Region are considerably lower (Walker, Kirk & Tyler 1982) than those usually associated with low pH. Further, natural gilvin concentrations considerably higher than those found in the billabongs do not depress pH below 4.5 (King & Tyler 1981a, b; 1982; Rai & Hill 1981).

The increase in sulphate in the floodplain billabongs is considerable (e.g. Mine Valley, $22\mu eql^{-1}$ on 25/9/80 to $1310\mu eql^{-1}$ on 25/9/80, prior to the first rains). Though accurate measurements of evaporative concentration rates are unavailable, an external source of sulphate appears probable. The most likely one is the influx of groundwater, introducing sulphates and sulphuric acid from the weathering of pyritic minerals in the catchment. Brown (1979) showed that, late in the Dry, the waters of Mine Valley billabong bore close resemblance to the acid, sulphate-rich, iron-bearing groundwater nearby, and also showed the likelihood of groundwater inflow during the latter part of the Dry. Pancontinental Mining Limited (1981) suggest that the other floodplain billabongs of this group are similarly influenced, and also that groundwater in the vicinity of Island is sulphate-enriched.

As with some billabongs in the NaCl group, the trend to increasing dominance of the monovalent cations may be reversed during the late Dry. Since such reversals in the sulphate billabongs may begin as early as late August (e.g. Corndorl) it is probable that groundwater changed cationic trends as well as introducing sulphate. Later, during the first rains, runoff may be significant in this regard.

In some years, at least some of the floodplain billabongs, including Leichardt, experience a sudden and dramatic increase in sulphate, with an equally sudden decrease in pH, both coincident with the heavy thunderstorms of the Dry/Wet interchange (Table 3.6-2 - Leichardt 18/12/78; Ja Ja 5/1/80) or with the first gentle influx of floodwater (Table 3.6-2 - Leichhardt 10/1/80). This radical water chemistry is short lived, lasting only until the first major flood of the Wet (Table 3.6-2). Pancontinental Mining Limited (1981) sampled Ja Ja at frequent intervals during one of these unusual happenings, alerted to some untoward event by a major fish kill on 3/1/80. Fish deaths had also been recorded in Leichardt in 1978 (Table 3.6-2). Oxygen concentrations in Ja Ja and Leichardt on these occasions were higher than many in which fish in these and other billabongs survive, so that death must be attributed to some other factor of the changed chemistry. Pancontinental Mining Limited (1981) found that the runoff into Ja Ja on 3/1/80 was sulphate-rich and very acidic, and sought explanation in the crystalline crust which forms on the black soils of the floodplain. When dissolved in billabong water, this crust had the same effect as the runoff had had on 3/1/80. Pancontinental Mining Limited (1981) suggest that

Table 3.6-2 Some chemical characteristics of selected floodplain billabongs at the Dry/Wet interchange (DW) and during the early Wet (W), with ranges of values for preceding or following Dry (D), for comparison.

	Leichhardt							Ja Ja			
	4-11/78 (D)	18/12/78 (DW)	17/1/78 (W)	3-11/79 (D)	8/1/80 (DW)	10/1/80 (DW)	22/2/80 (W)	5-10/79 (D)	5/1/80 (DW)	10/1/80 (DW)	26/2/80 (W)
K_{25} (µScm^{-1})	20-140	184	19	15-137	160	113	12	32-117	450	31	13
pH	6.2-7.0	4.3	6.5	6.5-7.1	6.3	4.3	6.0	6.6-5.0	3.2	5.8	6.2
SO_4 (µeql^{-1})	0-120	770	23	2-157	220	879	23	30-273	1228	115	30
Fish kill?	-	Yes	-	-	-	No	-	-	Yes	-	-

the crust comes from groundwater which seeps to the surface and evaporates, and identified aluminium as a possible toxic constituent. This sudden change in water chemistry, while involving sulphate, should be distinguished from the regular seasonal accretion of sulphate in the sulphate group of billabongs. In the latter case, gradual influx of groundwater is envisaged, in the former, a sudden influx of mineral-rich water from surface runoff, which may or may not occur in a given year. When it does occur, it may affect a billabong such as Leichardt, which normally does not witness a seasonal increase in sulphate.

3.7 Calcium bicarbonate billabongs

Red Lily was the only billabong in this group, and the only billabong ever to approach World Average Freshwater in ionic proportions for both cations and anions (Fig. 3.7-1).

Red Lily receives water from both the East Alligator River, and a local catchment including a number of escarpment outliers, one of which forms part of the southern bank of the billabong. The composition of neither inflow is known, but whatever it may be, in the middle Wet the billabong differs from all others investigated in being unequivocally calcium bicarbonate dominated. Solute concentration (indicated by conductivity - Fig. 3.7-2) was three times the Wet season values for the Magela. Contact with limestone is suspected.

In common with floodplain and backflow billabongs, conductivity values rose steeply during the Dry. In contrast, pH scarcely varied through the year, and, unlike other billabongs, was always above 7.0 (Fig. 3.7-2). This is probably a reflection of the strong bicarbonate dominance throughout the year. However, though bicarbonate remained dominant, there was a trend towards chloride through the Dry, matched by a trend from calcium towards sodium (Fig. 3.7-1). In this, Red Lily shows the same seasonal traits as all but the channel billabongs, but differs in the initial preponderance of calcium, and its retention of bicarbonate dominance. Surprisingly, calcium

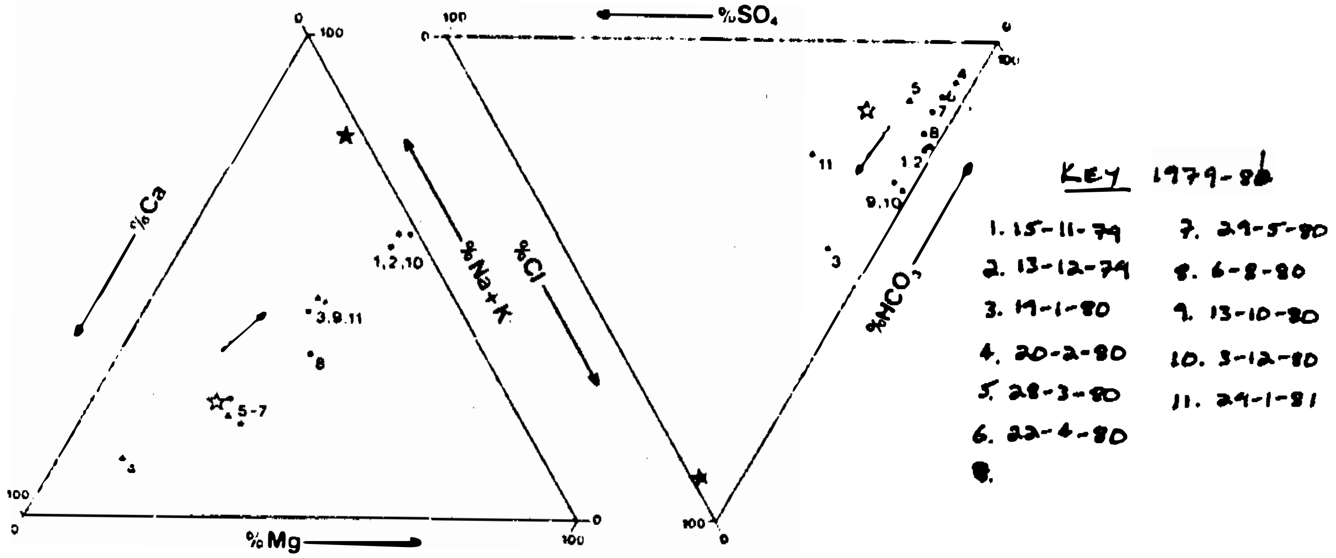

Fig. 3.7.1...Ternary diagrams showing the seasonal pattern of ionic proportions in..Red Lily...billabong. Symbols as for Fig. 3.4-1.

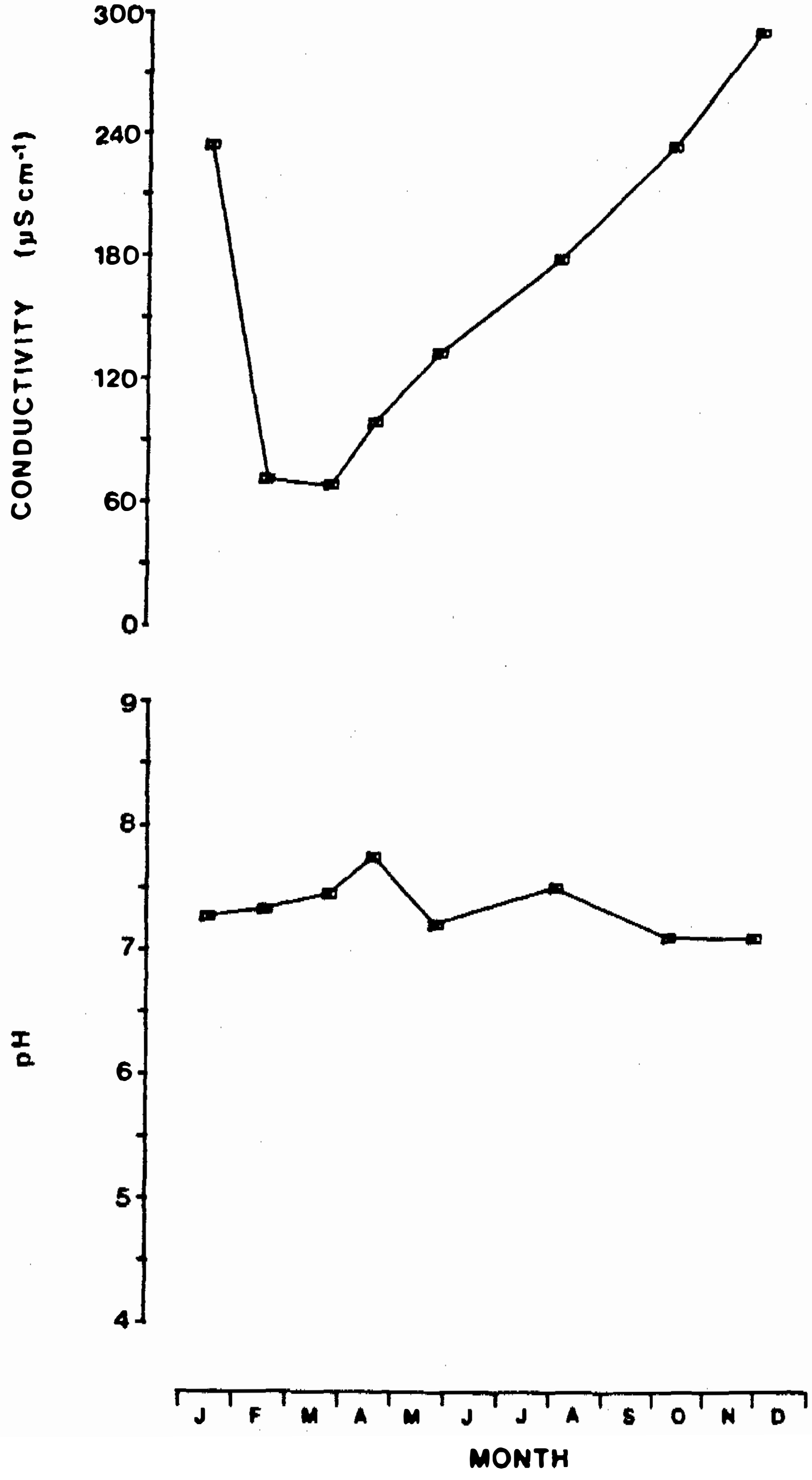

Fig. 3.7.2...Seasonal variations in electrical conductivity (K_{18}) and pH in .Red Lily...billabong during 1980 (□).

did not concentrate during the Dry, but fluctuated capriciously about $500 \mu eq l^{-1}$ until late in the Dry when it dropped to $120 \mu eq l^{-1}$. The latter event may have been caused by photosynthetic precipitation of $CaCO_3$ at the time of maximum macrophyte biomass (Walker, Waterhouse & Tyler 1982) in the billabong.

3.8 Electrical conductivity and ionic solutes

The electrical conductivity of natural waters provides a rapid, vicarious measure of salinity. For samples from all billabongs during 1980, in the conductivity range $K_{25} = 30\text{-}300 \mu S cm^{-1}$, the following relationships were found.

$$K_{25} = 2.06\ (\Sigma^{+} + \Sigma^{-}) - 9.66 \qquad (mg l^{-1},\ r = 0.9399,\ n = 113)$$

$$K_{25} = 0.07\ (\Sigma^{+} + \Sigma^{-}) - 4.64 \qquad (meq l^{-1},\ r = 0.9800,\ n = 113)$$

Values outside this range were excluded for statistical reasons (see Table 3.5-1).

4. RESULTS - INFLUENCE OF GROUNDWATER

Enrichment of the floodplain billabongs with sulphate, during the latter half of the Dry, suggested influx of a sulphate-rich groundwater. Pancontinental Mining Limited (1981) reported sulphate-rich groundwater near several billabongs, and suspected that it affected billabong chemistry. For this reason, the possibility of groundwater influence on Jabiluka was investigated. The usual method for obtaining groundwater - surface water interactions, that of siting observation bores near the shores and measuring the distribution of hydraulic head and permeability (Lee 1977), was adopted. An attempt was made to identify possible surface aquifers feeding Jabiluka. Ten bores were established (Fig. 4.1) early in November 1980, in addition to those of Pancontinental Mining Limited which were also monitored.

Whilst establishing the boreholes, large differences in soil type at different points on the shoreline were noted. Table 4.1 shows that most sites had clays, of various colours and textures, extending throughout the profile. Bores 8-10, at the southern end, had a highly organic layer below 1.5 m. The layer in bore 10 contained large pieces of wood. Hart (pers. comm.) also found intact wood, at a similar depth, on the floodplain between Mudginberri and Island. At the north-east end of the billabong there were sandy soils. At bore 1, pure sand overlay a comparatively dry, brown-grey clay. Further south (bores 2-4) a few centimetres of brown, sandy soil overlay a light grey sand-clay mixture.

The lithology of the bores appeared to determine the permeability and discharge capacity of the aquifers which they tapped. The bores in the clay soils yielded water very slowly, whereas bores in the sandy region filled almost instantaneously. This suggests that there is a permeable corridor of sandy soil along the north-eastern shoreline.

Table 4.2 shows that only in the sandy region was the watertable hydraulically higher than the billabong surface. Further, in that region,

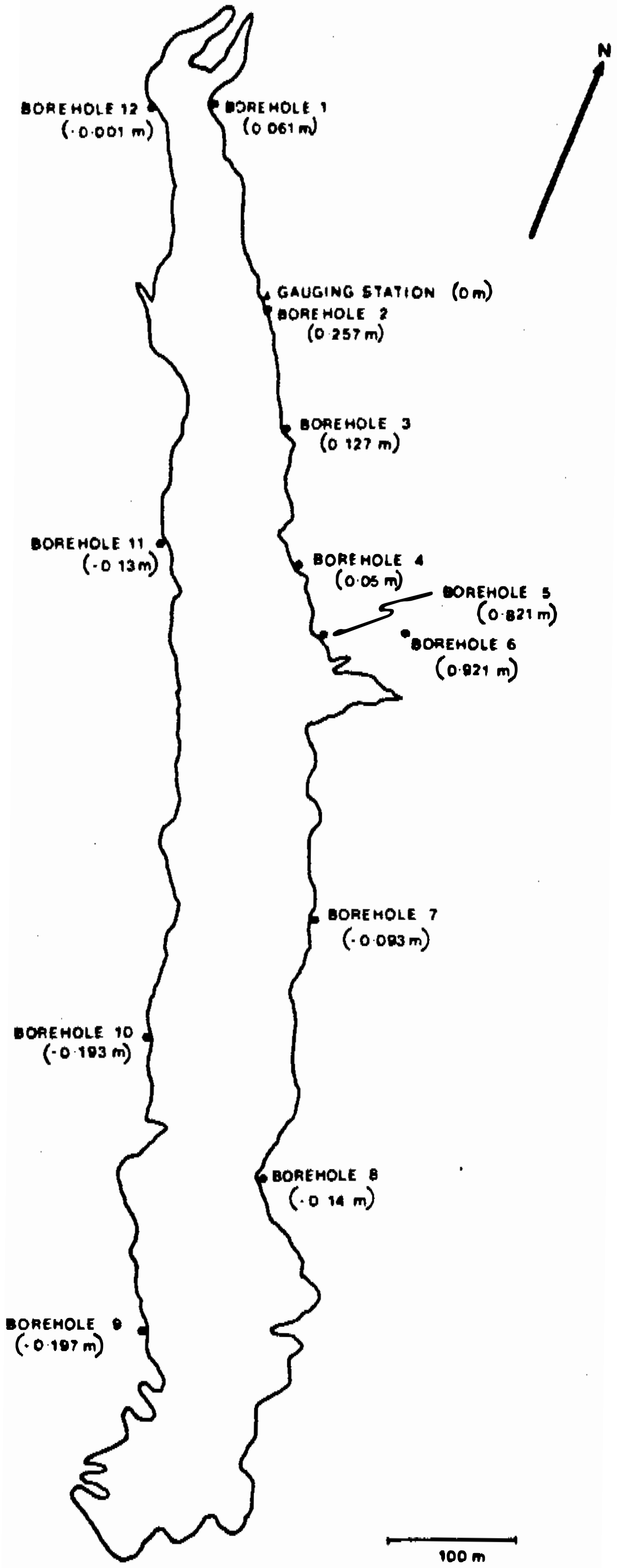

Fig. 4.1 Outline map of Jabiluka billabong showing location of boreholes. The rim height of each cased borehole above 0m level on the gauge board at the gauging station is shown. Boreholes 4 and 5 were installed by Pancontinental Mining Limited.

Table 4.1 Some characteristics of boreholes at Jabiluka billabong

Borehole	Horizon	Description	Yield
1	A	White sand	Seepage
	B	Brown-grey clay	
2	A	Brown sandy soil	Good flow
	B	Light grey sand-clay mixture	
3	A	Brown sandy soil	Good flow
	B	Dark grey sand-clay mixture	
	C	Light grey sand-clay mixture	
4	A	Brown sandy soil	High flow
	B	Orange sand-clay mixture	
5		(Pancontinental Mining Limited)	
6		(Pancontinental Mining Limited)	
7		No data	
8	A	Brown-black clay soil	Seepage
	B	Grey clay	
	C	Brown-black, sulphurous organic clay[1]	
9	A	Brown-black clay soil	Seepage
	B	Grey clay	
	C	Dark brown organic clay[2]	
10	A	Brown-black clay soil	Seepage
	B	Grey clay	
	C	Brown clay	
	D	Highly organic layer including pieces of wood	
11	A	Brown-black clay soil	Seepage
	B	Grey-brown clay	
12	A	Grey-brown clay	Seepage
	B	Dark grey clay	
	C	Grey-brown clay	

1 When left to dry, a coating of sulphur formed on the surface.

2 When left to dry, a coating of white crystals ($CaCO_3$?) formed on the surface.

Table 4.2 Hydraulic head in boreholes, relative to billabong water surface, and change in this head relative to a fixed arbitrary gauge board datum between 5/11/80 and 26/11/80. The boreholes marked with an asterisk are in sandy soil. For Panconinental Mining Limited's bores (5 and 8) lithology is not known, but from their proximity to 4 a sandy profile is presumed.

	Hydraulic head (m) relative to billabong surface			Change in hydraulic head (m)
Borehole	5/11/80	11/11/80	26/11/80	
1	-0.144	-0.056	-0.307	-0.263
2*	-0.007	+0.006	-0.003	-0.096
3*	+0.075	+0.089	+0.075	-0.100
4*	+0.047	+0.052	+0.175	+0.028
5*	-0.174	-0.159	-0.157	-0.083
6*	+0.423	+0.351	+0.437	-0.086
7	-0.355	-0.181	-0.249	-
8	-0.480	-0.710	-	-
9	-0.171	-0.201	-0.383	-0.312
10	-0.341	-0.343	-0.319	-0.140
11	-0.148	-0.222	-0.409	-0.361
12	-0.353	-0.298	-0.495	-0.242

water levels in the boreholes dropped much less than elsewhere over the three week period of investigation, indicating significant groundwater recharge. At site 4, the level actually increased. These data indicate that groundwater is likely to enter the billabong in this region.

Flow paths of groundwater, indicated by relative water levels, are difficult to determine from the small number of bores. However, the levels in bores 1-6 do suggest a north-westerly flow along the gradient from high to lower water levels, within the sandy sediments of the north-eastern bank.

Chemical analyses of bore waters on 6/11/80 showed considerable variation from bore to bore (Table 4.3). It is clear that conductivity values are very much less in the sandy region than in the clay soils, and are of the same order as in the billabong. This, together with the hydraulic data, suggests that groundwater is flowing in the sandy soil but residing for long periods in the clay where conductivity values are very much higher than ever achieved in the billabong. Further, with the exception of bores 8 and 10, the clay boreholes were alkaline, whereas the sandy ones were acid, like the billabong. The reason for the high acidity in bores 8 and 10, the two with organic layers, is not known. All of the sandy bores, and half of the clay bores, had sulphate dominance (Table 4.3; Fig. 4.2); in the billabong, sulphate was a close second to chloride.

All the above evidence points to the influx of groundwater, rich in sulphate, from a sandy aquifer. This would account for the enrichment of sulphate in billabong waters through the Dry, and also contribute to the increase in conductivity.

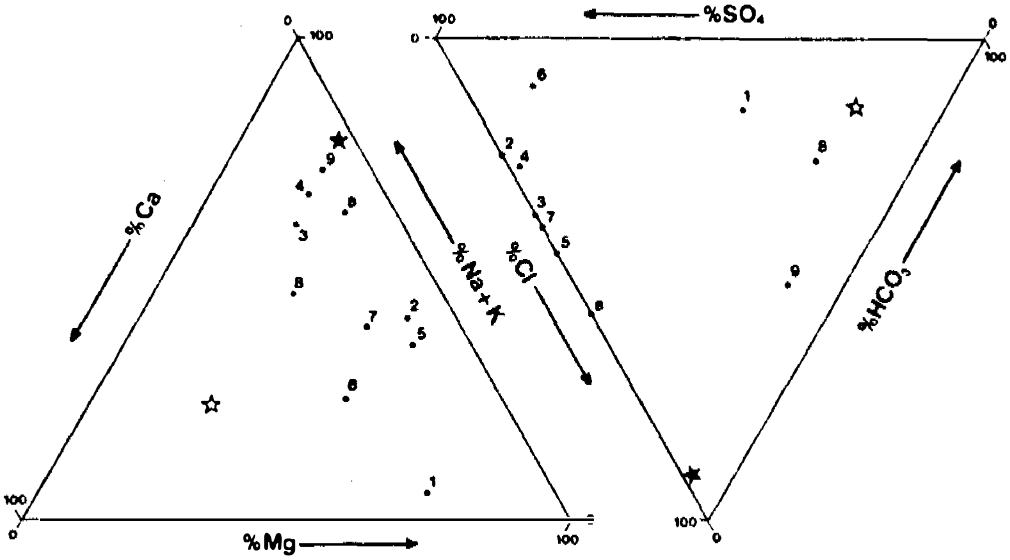

Fig. 4.2 Ternary diagrams showing ionic proportions of borehole waters, in comparison with Jabiluka billabong water, on 6/11/1980.

Table 4.3 Chemical characteristics of boreholes, sampled on 6/11/80. Bores in sandy locations are marked with an asterisk.

PARAMETER	Borehole 1	2*	3*	4*	8	9	10	11	12	Jabiluka billabong
Laboratory pH	7.45	3.60	4.00	5.10	2.65	7.40	3.05	7.35	8.45	4.30
Conductivity at 18°C (μScm^{-1})	2010	405	94	210	4630	5930	1060	1440	3700	177
Sodium										
(mgl^{-1})	128.1	16.6	4.0	19.9	289.8	420.2	43.9	151.1	565.8	17.0
(μeq %)	24.7	34.4	49.0	61.0	32.7	23.2	33.2	45.3	71.3	59.2
Potassium										
(mgl^{-1})	17.0	6.2	1.7	3.8	52.5	42.9	15.2	9.0	22.8	4.8
(μeq %)	1.9	7.6	12.4	6.9	3.5	1.4	6.8	1.6	1.7	9.9
Calcium										
(mgl^{-1})	81.2	3.7	1.4	3.8	79.6	449.0	19.6	78.0	59.9	2.5
(μeq %)	18.0	8.8	19.4	13.5	10.3	28.5	17.0	26.9	8.7	9.9
Magnesium										
(mgl^{-1})	152.8	12.6	0.8	3.2	251.3	452.4	30.1	46.4	77.4	3.2
(μeq %)	55.4	49.2	19.2	18.5	53.4	46.9	43.0	26.2	18.3	21.0
Chloride										
(mgl^{-1})	100.1	17.5	6.5	16.1	887.5	213.7	63.2	142.7	391.9	27.1
(μeq %)	14.7	24.0	36.4	26.4	44.5	9.7	39.3	24.9	51.0	57.2
Sulphate										
(mgl^{-1})	247.4	56.1	11.3	43.7	1108.7	1700.1	97.6	103.3	77.7	20.3
(μeq %)	36.3	76.0	63.6	71.4	55.5	77.3	60.7	18.0	10.1	42.8
Bicarbonate										
(mgl^{-1})	575.2	0	0	2.3	0	492.9	0	562.4	513.6	0
(μeq %)	49.0	0	0	0.2	0	13.0	0	57.1	38.9	0

5. RESULTS - NUTRIENT STATUS

5.1 Preamble

Nitrogen and phosphorus compounds are essential cellular components of all organisms. Unlike most other cellular constituents such as carbon, iron and sulphur, nitrogen, and especially phosphorus, are often in short supply. They are the two nutrients most likely to limit biological productivity in terrestrial and aquatic ecosystems. Unlike the major ions, nitrogen and phosphorus are non-conservative, being rapidly cycled in the biosphere.

The chemical form in which these two elements occurs is critical for identification and quantification of nutrient sources and cycles in freshwaters, and analytical strategies seek to separate phosphorus and nitrogen into various fractions. The first fractionation separates dissolved and sestonic forms, by filtration or centrifugation. The seston is the living (plankton) and non-living (tripton) suspended, particulate matter. A number of techniques have been proposed for further fractionation (Olsen 1967). The likely forms in which phosphorus and nitrogen occur in freshwaters are shown in Table 5.1-1.

Considerable controversy surrounds the fractionation of total phosphorus. There is uncertainty as to the specificity and accuracy of many of the analytical techniques; there are doubts that the fractions defined analytically correspond closely with forms in nature (Burton 1973, Olsen 1967, Rigler 1964). For example, filtration purports to separate dissolved and particulate fractions. In reality much of the colloidal phosphorus may be retained by the filter (Rigler 1964). Orthophosphate concentrations are probably overestimated because of hydrolysis of some labile organic phosphorus compounds during analysis (Wetzel and Likens 1979). The oxidative acid digestion, frequently employed in determination of 'total phosphorus', frees all the phosphorus except that in resistant

Table 5.1-1 Likely forms of phosphorus and nitrogen in freshwaters (after Vollenweider 1968).

Dissolved P		Sestonic P		
Orthophosphate PO_4-P (dissolved inorganic P)	As organic colloids and/or combined with an adsorptive colloid	As mineral particles (e.g. apatite) and/or adsorbed on inorganic complexes such as clays, carbonates and $Fe(OH)_3$	Organisms	Adsorbed on detritus and/or present in organic compounds

Gaseous N	Dissolved N		Sestonic N	
N_2, N_2O, NO	Inorganic compounds (NH_3, NO_2, NO_3)	Organic compounds such as amino acids peptides and polypeptides Dissolved albumin and other organic compounds	Organisms	Organic detritus and/or inorganic and organic compounds adsorbed on particles

minerals such as feldspars and ilmenite (Burton 1973). It is usual to refer to the numerical difference between this 'total phosphorus' and orthophosphate-phosphorus as 'organic phosphorus', but this quantity may include a significant inorganic particulate component, such as orthophosphate adsorbed on clay particles (see Table 5.1-1).

The elucidation of nutrient cycles in freshwaters has attracted much attention in recent years. For both phosphorus and nitrogen, cycling is complex and largely biochemical. The cycling of phosphorus is particularly rapid, resulting in very low concentrations of orthophosphate (<5%; Wetzel 1975) in most natural waters. Most phosphorus is contained within the living seston, primarily algae. In the open water a rapid, metabolic cycle begins with the secretion of highly labile, low molecular weight phosphorus compounds from the plankton. This is taken up by the high molecular weight, dissolved colloidal fraction, and subsequently released as soluble orthophosphate which is, in turn, rapidly assimilated by the biota (Lean 1973).

Phosphorus is added to this system by the inflows, and lost from it in the outflow and by loss to the sediments (Fig. 5.1-1). In many cases the trophic status of waterbodies is determined by the size of this external phosphorus loading together with any internal loading that may occur. An extensive littoral zone, especially if colonised by dense macrophyte beds, may influence considerably the internal loading (Wetzel 1975).

The nitrogen cycle is basically microbial in nature, in which bacterial oxidation and reduction of nitrogen compounds are coupled with photosynthetic assimilation and utilization by algae and macrophytes (Wetzel 1975). The cycle involves the biochemical processes of nitrogen assimilation, ammonification, nitrification, and denitrification (Brezonik 1973) (Fig. 5.1-2). Assimilation of inorganic nitrogen into organisms predominately involves uptake of ammonia, and to a lesser extent nitrate.

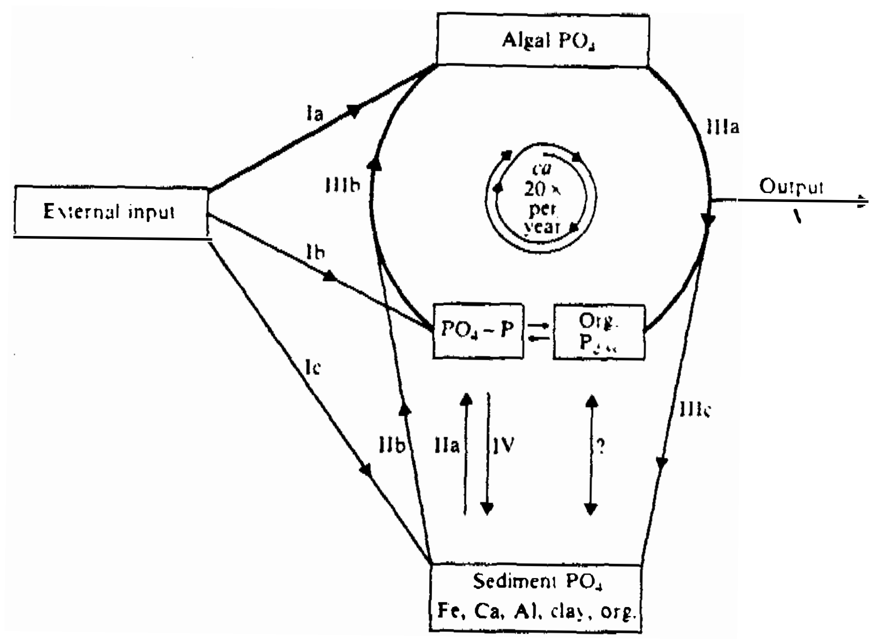

Fig. 5.1-1 The phosphorus cycle for an open freshwater system (after Golterman 1975).

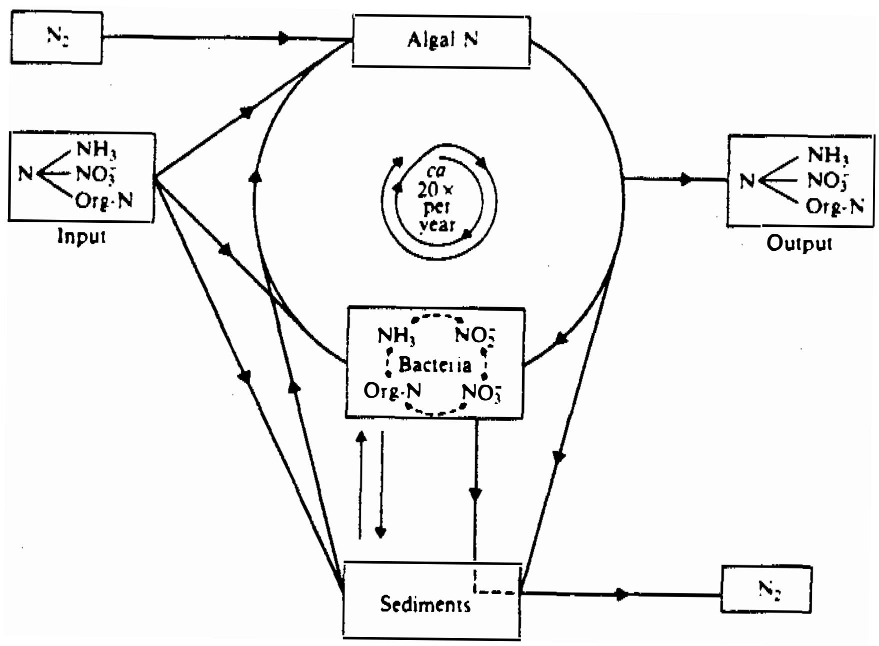

Fig. 5.1-2 The nitrogen cycle for an open freshwater system (after Golterman 1975).

The reverse, whereby organic nitrogen is returned to the inorganic nitrogen pool as ammonia, is termed ammonification; aerobic autotrophic bacteria oxidise ammonia to nitrite and nitrate during nitrification, whilst the process of denitrification reduces nitrate to molecular nitrogen.

Much of the attention paid to plant nutrients in freshwaters in recent years, stems from alarm at the rapid deterioration of water quality consequent upon enrichment by phosphorus and nitrogen. This process of eutrophication involves qualitative and quantitative changes in littoral, benthic and planktonic fauna and flora, decreases in transparency, reduction in dissolved oxygen, and general impairment of water utility (~~Anon~~ onal Academy of Sciences 1969; Barabas 1981a,b).

Since nitrogen, and, particularly, phosphorus, are heavily implicated in the eutrophication process, attempts have been made to determine yard-sticks for defining critical concentrations of these nutrients, and for classifying lake trophic levels. The trophic classification of Vollen-weider (1968) (Table 5.1-2) has gained wide acceptance.

Vollenweider's trophic scheme is based on total phosphorus rather than orthophosphate, but on dissolved inorganic nitrogen rather than total nitrogen. Total phosphorus is a more representative measure of the phosphate pool than is orthophosphate-P, because of the rapid kinetics of the phosphorus cycle (Wetzel 1975). By contrast, much organic nitrogen occurs in forms resistant to rapid bacterial degradation (Cole 1975; Wetzel 1975), limiting nitrogen regeneration from this source. This, coupled with the preference for ammonia and nitrate in nitrogen uptake by organisms (Brezonik 1973), implies that the combined concentrations of these two fractions are representative of the pool of biologically-available nitrogen. Although the word eutrophication refers, literally, to nutrient enrichment, the process is frequently recognized more by its effects, particularly that of greatly enhanced primary production. Accordingly, a number of biological indices of trophic status, such as chlorophyll concentrations and annual

Table 5.1-2 A classification of trophic status based on nutrient concentrations (after Vollenweider 1968).

Trophic status	Total-P ($\mu g l^{-1}$)	Inorganic-N ($\mu g l^{-1}$)
1. Ultra-oligotrophic	<5	<200
2. Oligo-mesotrophic	5-10	200-400
3. Meso-eutrophic	10-30	300-650
4. Eutrophic	30-100	500-1500
5. Hypereutrophic	>100	>1500

production, have been used (Sakamoto 1966; Vollenweider 1968; Walmsley et al. and Butty 1980) in addition to nutrient concentrations.

Although nitrogen, and sometimes trace elements, may limit productivity, phosphorus is the one element most likely to increase production if added alone to a waterbody. As such, it is the element most frequently implicated in eutrophication (Vallentyne 1974), and the one on which abatement programmes are centred.

5.2 Analytical technique

The preferred method for fractionation of phosphorus species involves an initial filtration through 0.45 μm membranes, ideally carried out in the field, or very soon after sampling (Burton 1973; Olsen 1967). Many laboratories employ cheaper and coarser glass fibre filters.

Many of the billabongs become so turbid that filtration through membranes is difficult, and the sediments so finely divided that 0.45 μm membranes remove only a portion of the suspended material. To be sure of removing most solids, sequential filtration, culminating in 0.1 μm membranes (Walker, Kirk and Tyler 1982), with frequent changes of filter, is required. This is time consuming and expensive. For these reasons, samples could not be filtered before freezing for transport. It is possible that this has led to overestimation of orthophosphate-P (PO_4-P), through rupture of phytoplankton on freezing and extraction, release of phosphorus from readily-hydrolyzable organic material, and release of phosphorus adsorbed on clay particles (A. McComb, pers. comm). However, it is considered that any overestimation is slight, since the ratio of PO_4-P to total P is essentially the same for turbid and non-turbid waters. Further, any overestimation represents phosphorus which is readily hydrolyzable and, therefore, probably available to algae. The term "reactive phosphorus" may be preferred to PO_4-P. As a measure of phosphorus availability, this "reactive phosphorus" fraction may be more realistic than that of PO_4-P strictly in the dissolved. Because the overestimation is likely to be small, the term PO_4-P is retained.

Orthophosphate-P generally accounts for less than 5% of total phosphorus in natural surface waters (Wetzel 1975), and in highly productive tropical waters, orthophosphate may be virtually undetectable (e.g. Lake George, Uganda (Ganf and Viner 1973). However, exceptions to this general statement, including many in the tropics, are legion. In Lago do Casthano, Amazonia, PO_4-P accounts for 0-65% of total phosphorus, depending upon season (Schmidt 1973). Orthophosphate is usually between about 20% and 60% of the total phosphorus in the African lakes Victoria (Talling 1966) and Mutanda (Talling and Talling 1965), while in Lakes Albert (Talling 1963) and Mulehe (Talling and Talling 1965) PO_4-P constitutes practically all the total phosphorus. Thus, the finding in the present study that in the Region's billabongs PO_4-P commonly accounted for 20-40%, and at times in excess of 70%, of the total phosphorus, is entirely feasible.

5.3 Temporal characteristics

As for major ions, during the Wet (February) nutrient concentrations were at a minimum and relatively constant over the range of billabongs in the Region (Table 5.3-1). In general, the mid-Wet is characterised by total-P (TP) concentrations of below $45 \mu g l^{-1}$, inorganic-N (IN) below 35 $\mu g l^{-1}$, and total-N (TN) $<1200 \mu g l^{-1}$. These nutrient levels place the billabongs, at this time of high flow and rapid flushing, in the meso-eutrophic or eupolytrophic classifications of Vollenweider (1968) based on total-P, and in the ultra-oligotrophic level based on inorganic-N. The IN:PO_4-P ratios were generally less than 10, often considerably so. As with major ion chemistry, Red Lily was a renegade, with total-P levels considerably higher than all other billabongs.

Table 5.3-1 Concentrations of total phosphorus (TP), orthophosphate-P (PO_4-P), inorganic nitrogen (IN = NH_4+NO_3) and total nitrogen (TN), and the IN:PO_4-P ratios (by weight) during the middle Wet (February).

Billabong	Nutrients ($\mu g l^{-1}$)						
	TP		PO_4-P	IN	TN		IN:PO_4-P
	1980	1980	1980 (1981)	1980 (1981)	1980	1981	1980 (1981)
Bowerbird		20	(6)	(7)		299	(1.2)
Georgetown	20	33	3	17	987	436	5.7
Gulungul	16	30	1	18	969	259	18.0
Goanna	31	26	7	31	451	177	4.4
Mudginberri	13	20	1	34	618	1023	34.0
Island		19	(7)	(10)	433	304	(1.4)
Ja Ja	15	16	4	34	993	378	8.5
Mine Valley	13	20	1	12	885	418	12
Leichhardt	5		5	17	969		3.4
Jabiluka	14	42	2	17	919	778	8.5
Nankeen	11	23	3	24	1036	177	8.0
Noarlanga	14	21	2	18	943	720	9.0
Umbungbung	13	33	2	18	615	519	9.0
Kulukuluku		15	(4)	(6)	-	358	(1.5)
Jingalla	16	22	1	13	952	337	13.0
Nimbawah		24	(15)	(14)	-	521	(0.9)
Murganella	-	-	-	-	-	-	-
Red Lily	51	108	15	14	1136	552	0.9

By July, the mid-point of the Dry, the homogeneity in nutrient levels characteristic of the Wet had disappeared, and two groupings of billabongs could be distinguished, both on the basis of total-P and total-N concentrations (Table 5.3-2,3). The first group, predominantly channel billabongs, had changed little since the Wet. Again, IN:PO_4-P ratios were low. In Red Lily, total-P values had declined since the Wet, to those of other billabongs in this group. In the second group, all nutrient species showed increases over the Wet values.

By the late Dry (October/November), differentiation into three main groups of billabongs on the basis of total-P levels was obvious (Tables 5.3-4,5). A similar situation has already been noted with regard to major ion chemistry (Section 3.3). However, in contrast to the latter, the three nutrient groups corresponded fully with the morphometric classification of billabongs (Table 5.3-5). In its nutrient characteristics, Red Lily resembled the channel billabongs. Inorganic-N and total-N levels appeared to be less diagnostic than total-P levels, except for channel billabongs, which were clearly differentiated from all others by all three nutrient parameters. Levels of both phosphorus and nitrogen in the channel billabongs suggest little change in trophic status during the Dry, whereas rises in total-P concentrations of more than an order of magnitude characterise the floodplain and backflow billabongs (Table 5.3-1,5). Thus, with few exceptions, the waters of these latter billabong types fall within the hypereutrophic category of Vollenweider for total-P. The response of inorganic-N concentrations to the passing Dry is more variable, with trophic status on this basis varying from meso-eutrophic to hypereutrophic.

With the exception of Jingalla, all floodplain billabongs now had relatively high IN:PO_4-P ratios (>18); all others remained below the value of 12. The classification of billabongs into 3 groups on the basis of total-P, perhaps somewhat arbitrary, conforms with the historical morphometric and hydrologic classification as channel, backflow and floodplain billabongs (Table 1.1), and they will be discussed under these headings.

Table 5.3-2 Concentrations of total phosphorus (TP), orthophosphate-P (PO_4-P), inorganic nitrogen (IN = NH_4+NO_3) and total nitrogen (TN), and the IN:PO_4-P ratios (by weight) during the middle Dry (July).

Billabong	Nutrients (µgl^{-1})						
	TP		PO_4-P	IN	TN		IN:PO_4-P
	1979	1980	1980	1980	1979	1980	1980
Bowerbird	10	16	3	9	361	389	3.0
Georgetown	-	142	73	349	-	995	4.8
Gulungul	185	81	38	5	1570	758	0.1
Goanna	-	102	78	268	-	872	3.4
Mudginberri	-	30	13	18	-	589	1.4
Island	33	38	9	13	800	759	1.4
Ja Ja	-	64	29	252	-	865	8.7
Mine Valley	42	67	40	480	1783	1988	12.0
Leichhardt	43	48	13	24	1797	1159	1.8
Jabiluka	-	83	22	150	-	781	6.8
Nankeen	-	53	19	329	-	994	17.3
Noarlanga	20	21	6	5	463	591	0.8
Umbungbung	99	29	21	17	1823	988	0.8
Kulukuluku	-	29	8	14	-	696	1.8
Jingalla	-	30	16	20	-	374	1.3
Nimbawah	-	35	16	91	-	454	5.7
Murganella	-	30	10	43	-	486	4.3
Red Lily	-	24	22	23	-	513	1.0

Table 5.3-3 A grouping of billabongs based on TP and TN concentrations in the mid-Dry (July) of 1979 and 1980. (Data of Table 5.3-2).

Group	Morphometric classification	Billabong	TP ($\mu g l^{-1}$)	TN ($\mu g l^{-1}$)	IN:PO_4-P
1	Channel	Mudginberri	20-35	454-591	0.8-5.7
		Noarlanga			
		Nimbawah			
TP<40		Murganella			
TN<80	" /Escarpment rockpool	Bowerbird	10-16	361-389	3.0
	" /Floodplain	Island	29-38	696-800	1.4-1.8
		Kulukuluku			
	Floodplain	Jingalla	24-30	374-513	1.0-1.3
		Red Lily			
2	Backflow	Georgetown	29[1]-185	758[1]-1823	0.1-4.8
		Gulungul			
TP>40		Umbungbung			
TN>800	Channel/Backflow	Goanna	102	872	3.4
	Floodplain	Ja Ja	42-67	865-1988	1.8-17.3
		Mine Valley			
		Leichhardt			
		Jabiluka			
		Nankeen			

1. The TP value for Umbungbung in 1980 ($29 \mu g l^{-1}$) is more in common with those of Group 1 but the TN value in 1980 ($1823 \mu g l^{-1}$) and the 1979 values for TP ($99 \mu g l^{-1}$) and TN ($988 \mu g l^{-1}$) place Umbungbung clearly in Group 2. Likewise, Gulungul in 1980 had a comparatively low TN value ($758 \mu g l^{-1}$) but in all other cases belonged to Group 2.

Table 5.3-4 Concentrations of total phosphorus (TP), orthophosphate-P (PO_4-P), inorganic nitrogen (IN = NH_4+NO_3) and total nitrogen (TN), and the IN:PO_4-P ratios (by weight) during the late Dry (October/November).

Billabong	Nutrients ($\mu g l^{-1}$)						
	TP		PO_4-P	IN	TN		IN:PO_4-P
	1979	1980	1980	1980	1979	1980	1980
Bowerbird	14	33	7	33	450	524	4.7
Georgetown	-	559	69	367	5310	3147	5.3
Gulungul	440	978	76	920	848	11397	12.1
Goanna	453	458	147	297	4592	2070	2.0
Mudginberri	45	34	16	7	697	603	0.4
Island	43	30	20	12	647	633	0.6
Ja Ja	-	270	99	2379	-	5113	24.0
Mine Valley	178	129	22	2575	-	11246	117.0
Leichhardt	155	106	35	636	2103	1989	18.2
Jabiluka	197	129	20	991	1784	1745	49.6
Nankeen	-	119	25	1699	-	3301	68.0
Noarlanga	20	32	12	19	608	655	1.6
Umbungbung	714	1182	304	2723	26115	4595	9.0
Kulukuluku	49	54	16	69	883	585	4.3
Jingalla	-	116	99	44	1755	1806	0.4
Nimbawah	-	31	22	89	-	635	4.0
Murganella	-	41	11	94	-	517	8.5
Red Lily	70	64	33	41	1224	914	1.2

Table 5.3-5 A grouping of billabongs based on TP concentrations in the late Dry (October/November) of 1979 and 1980. (Data of Table 5.3-4).

Group	Morphometric classification	Billabong	TP ($\mu g l^{-1}$)	TN ($\mu g l^{-1}$)	IN:PO_4-P
1	Channel	Mudginberri	20-45	517-697	0.4-8.5
		Noarlanga			
TP<70		Nimbawah			
		Murganella			
	" /Escarpment rockpool	Bowerbird	14-33	450-524	4.7
	" /Floodplain	Island	30-54	633-883	0.6-4.3
		Kulukuluku			
	Floodplain	Red Lily	64-70	914-1224	1.2
2	Floodplain	Ja Ja	106-270	1175-11246	18.2-117.0[1]
TP 100-300		Mine Valley			
		Leichhardt			
		Jabiluka			
		Nankeen			
		Jingalla			0.4
3	Backflow	Georgetown	440-1182	848-26115	5.3-12.1
TP>400		Gulungul			
		Umbungbung			
	Channel/Backflow	Goanna	453-8	2070-4592	2.0

1 Excluding the value for Jingalla which is shown separately.

5.4 Channel billabongs

The channel billabongs are characterised by relatively constant nutrient levels through the year (Figs. 5.4.1-8), the lowest concentrations for the Region (Table 5.3-5). However, whilst these are regionally low, TP levels are, on a world-wide scale, very high, corresponding to meso-eutrophic to hypereutrophic status. By contrast, concentrations of inorganic nitrogen remain at levels indicative of ultra-oligotrophy.

Fractionation of the total phosphorus indicates that orthophosphate-P commonly accounts for 20-40% of the total, and may even exceed the level of particulate phosphorus on occasions. This proportion is considerably higher than that routinely found elsewhere (PO_4-P≈5% TP; Wetzel 1975).

The combined concentrations of ammonia and nitrate, constituting the bulk of biologically-available inorganic nitrogen, amounts to only 5-10% of the total nitrogen; the remainder is regarded as organic nitrogen. Thus, in the channel billabongs there appears to be a surfeit of biologically-available phosphorus (PO_4-P), and a paucity of biologically-available nitrogen.

Whilst total nutrient levels may fluctuate widely within the narrow range characteristic of this group, some seasonal trends are evident. First, TP values were at a minimum in the Wet. Surprisingly, TN was sometimes at a maximum at this time (e.g. Noarlanga and Mudginberri, Figs. 5.4-1,2). Generally, TN minima occurred at the Wet/Dry interchange. Minima of both TP and TN occurred in the mid-Dry (Figs. 5.4.1-8). There was little or no seasonal change in the very low inorganic nitrogen levels whereas PO_4-P concentrations rose through the Dry, apparently unaffected by fluctuations in TP.

It is apparent that all the channel billabongs are regionally low in nutrients, and change little with season.

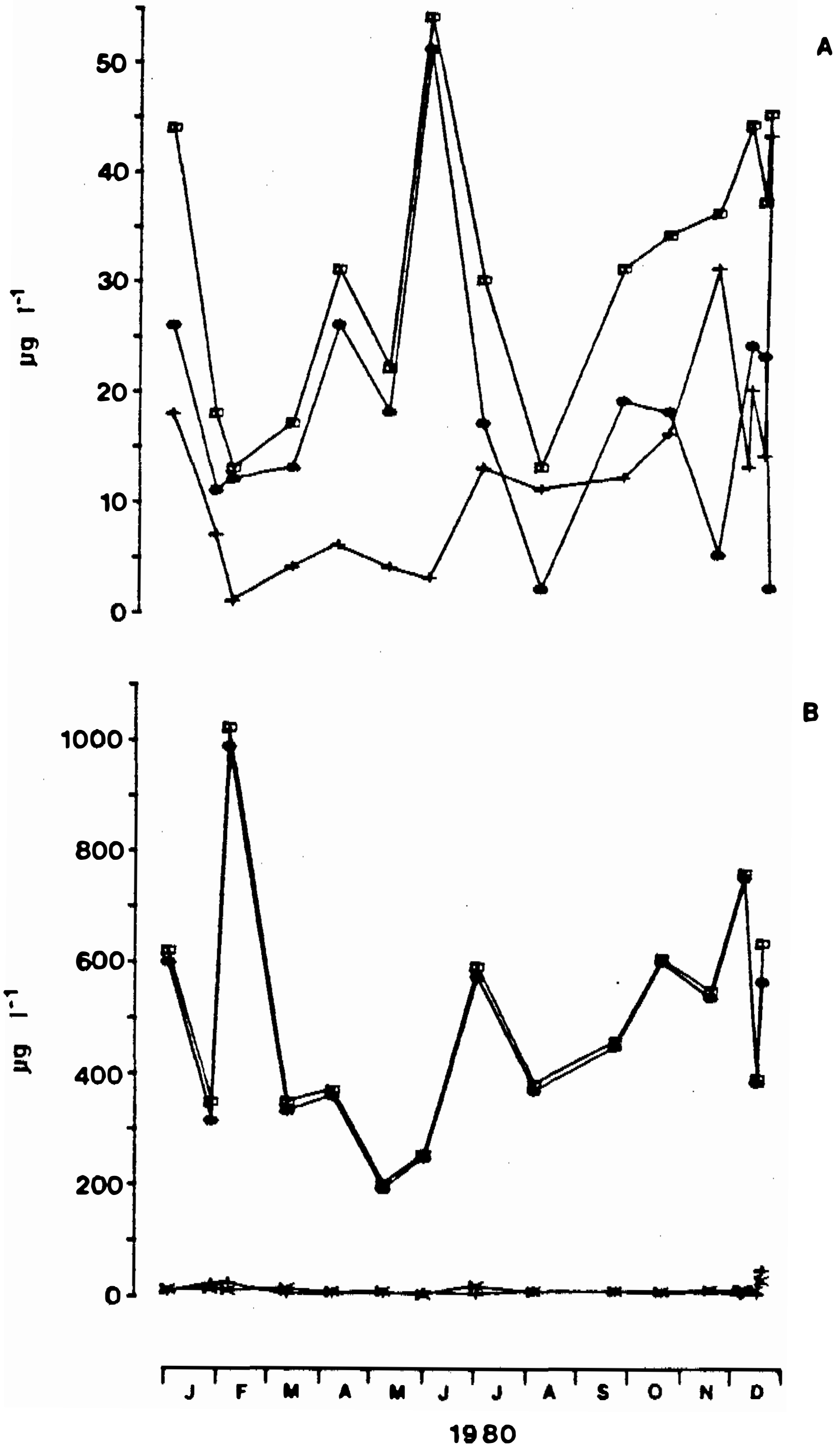

Fig. 5.4-1 Seasonal variations in nutrient concentrations in Mudginberri billabong during 1980.

A. Total phosphorus (□), 'organic' phosphorus (✱), and orthophosphate-phosphorus (+).

B. Total nitrogen (□), organic nitrogen (✱), ammonia (×) and nitrate (+).

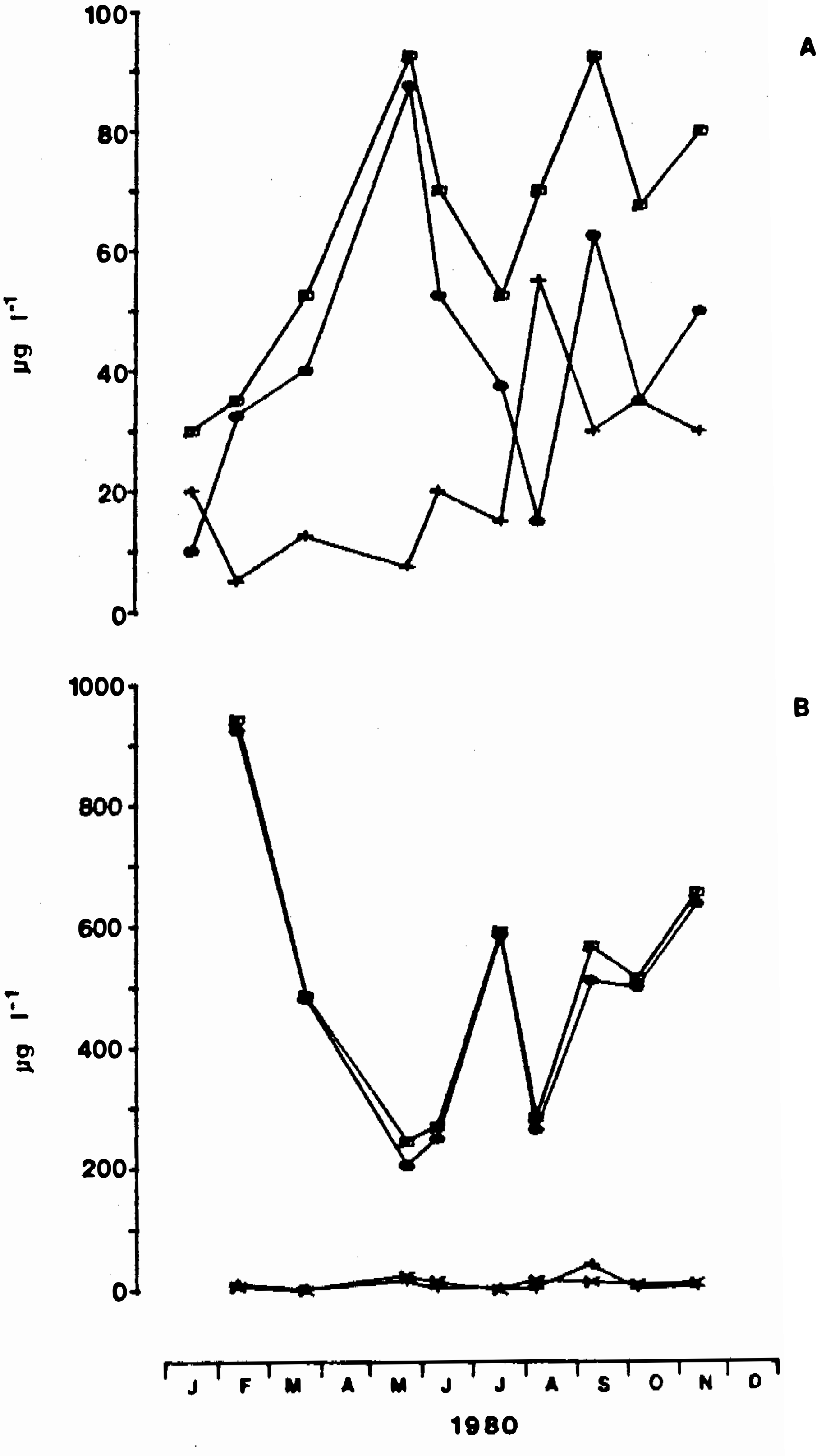

Fig. 5.4.2..Seasonal variations in nutrient concentrations in Nourlangie billabong during 1980. Symbols as for Fig. 5.4.1.

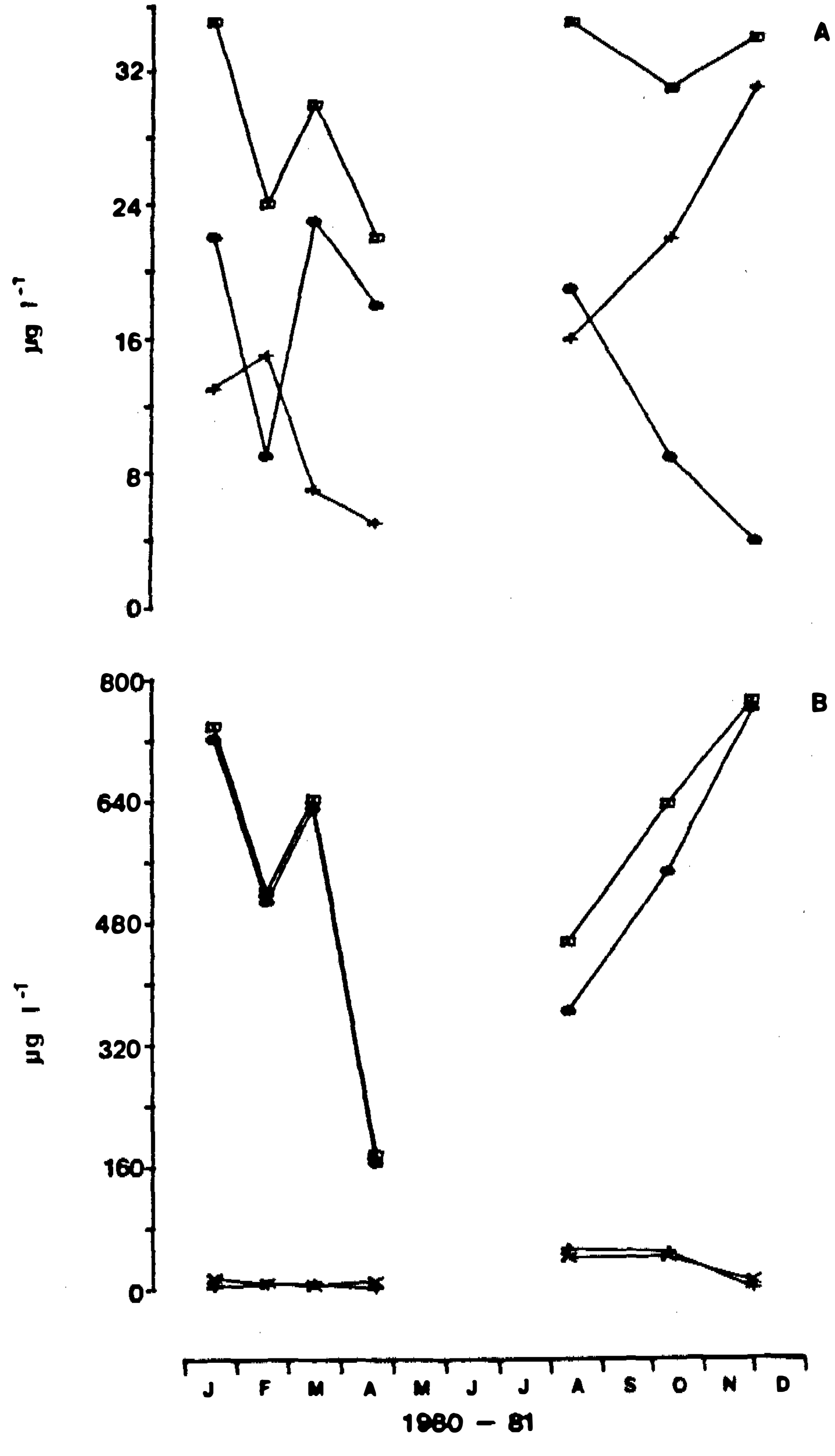

Fig. 5.4.3...Seasonal variations in nutrient concentrations in Nankeen billabong during 1980. Symbols as for Fig. 5.4.1.

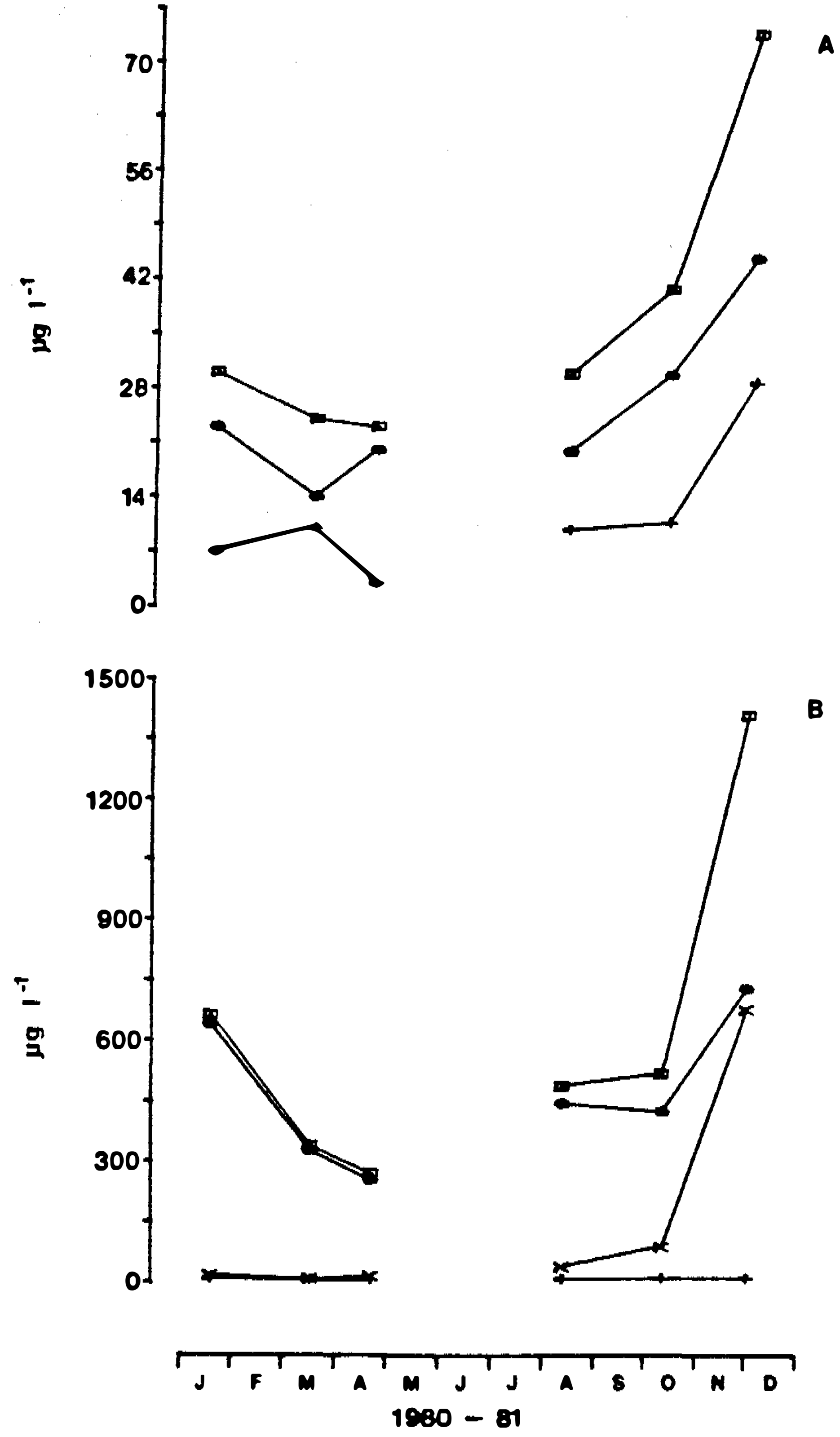

Fig. 5.4.4. Seasonal variations in nutrient concentrations in Murgenella billabong during 1980-1. Symbols as for Fig. 5.4.1.

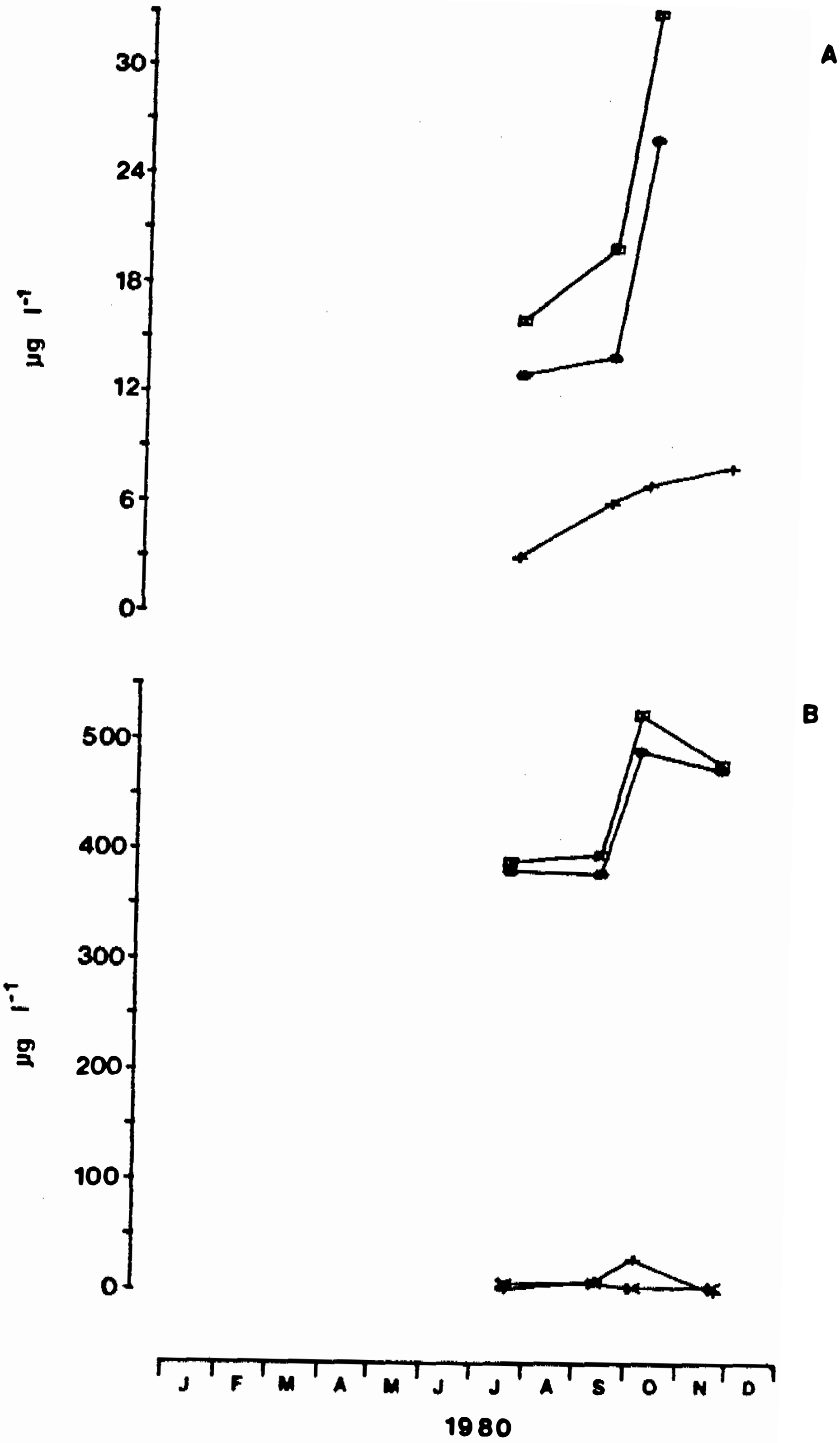

Fig. 5.4.5. Seasonal variations in nutrient concentrations in Bowerbird billabong during 1980. Symbols as for Fig. 5.4-1.

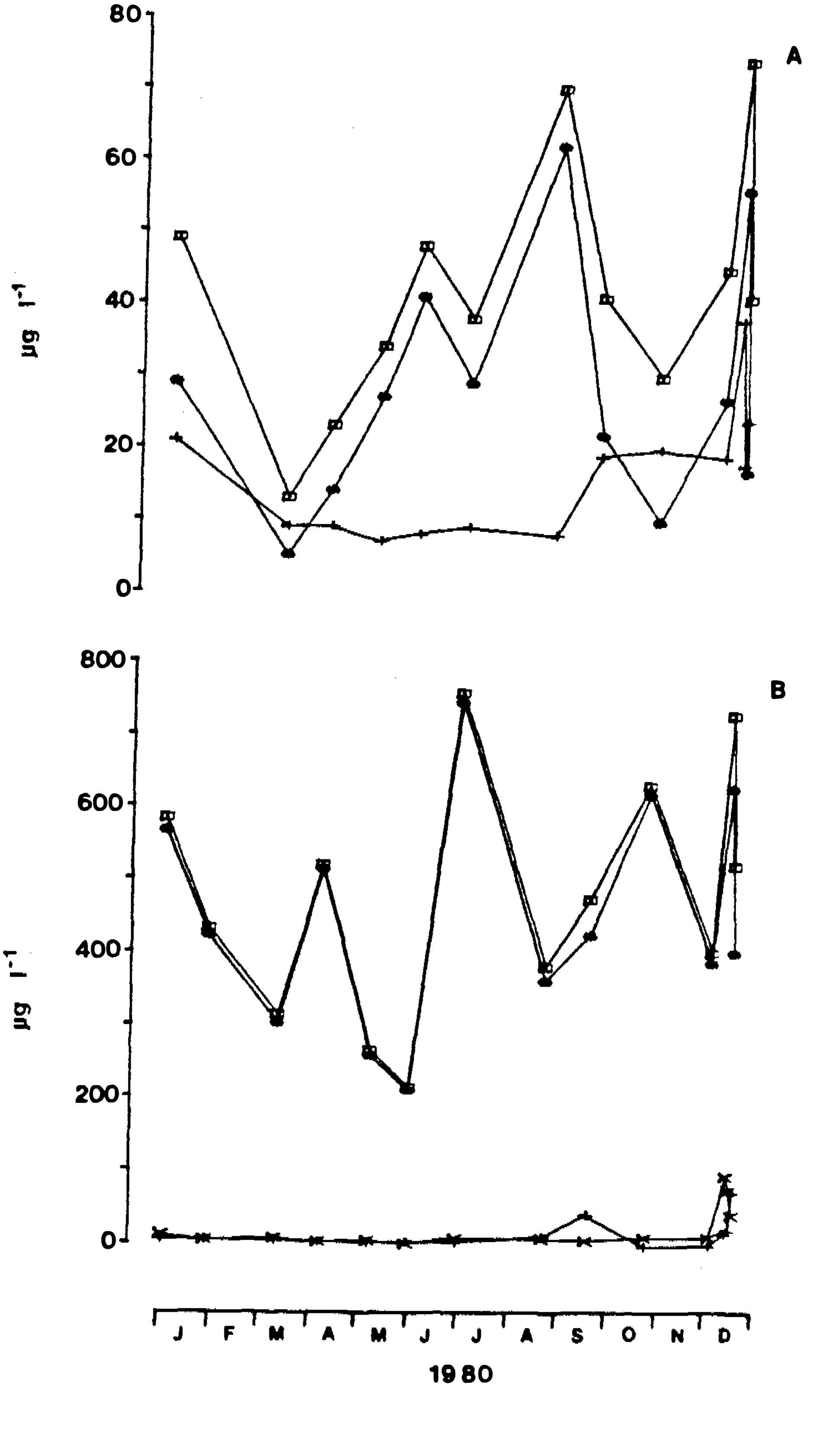

Fig. 5.4.6. Seasonal variations in nutrient concentrations in Island billabong during 1980. Symbols as for Fig. 5.4.1.

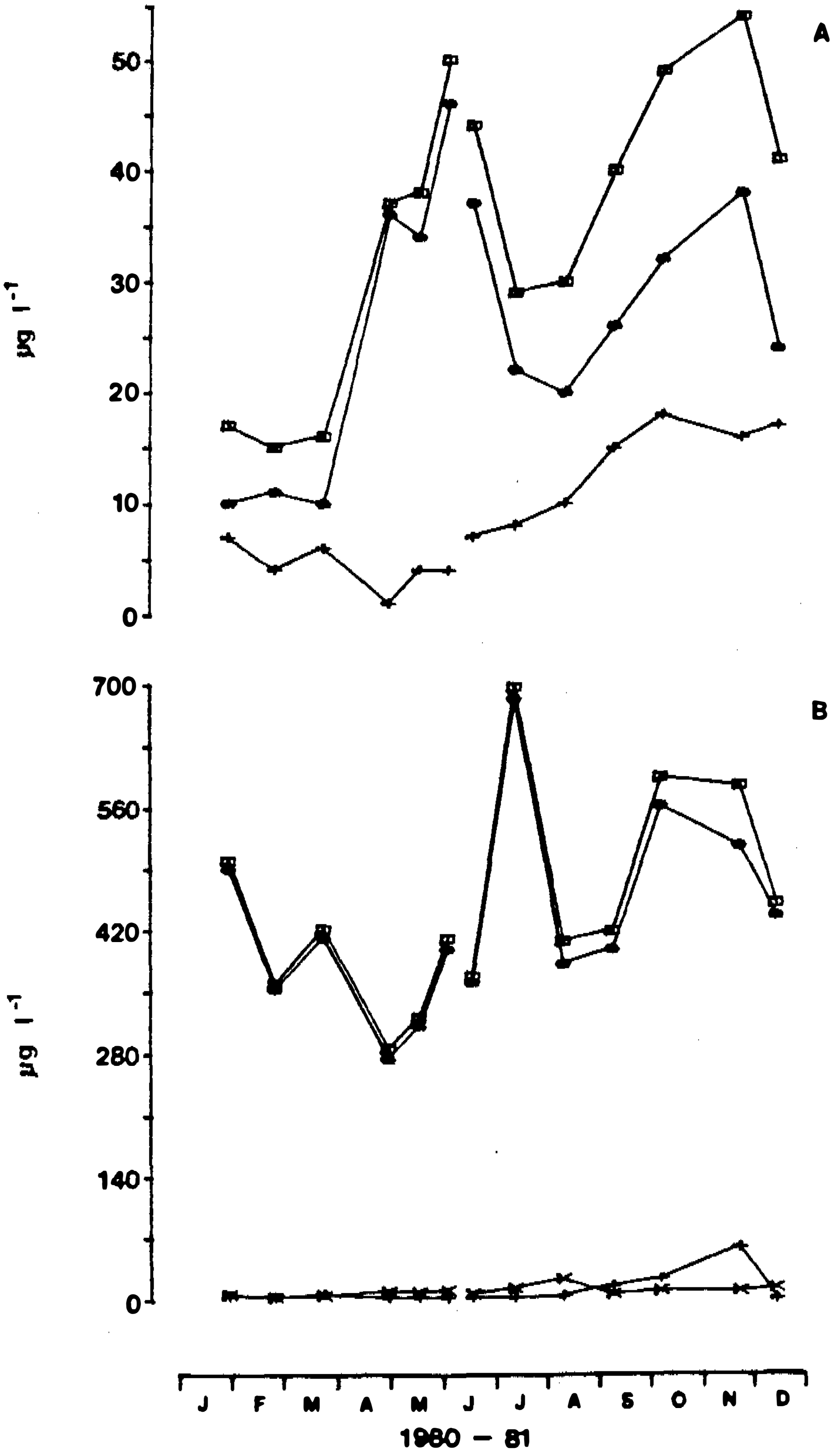

Fig. 5.4.7..Seasonal variations in nutrient concentrations in. Kulukuluku billabong during 1980. Symbols as for Fig. 5.4.1.

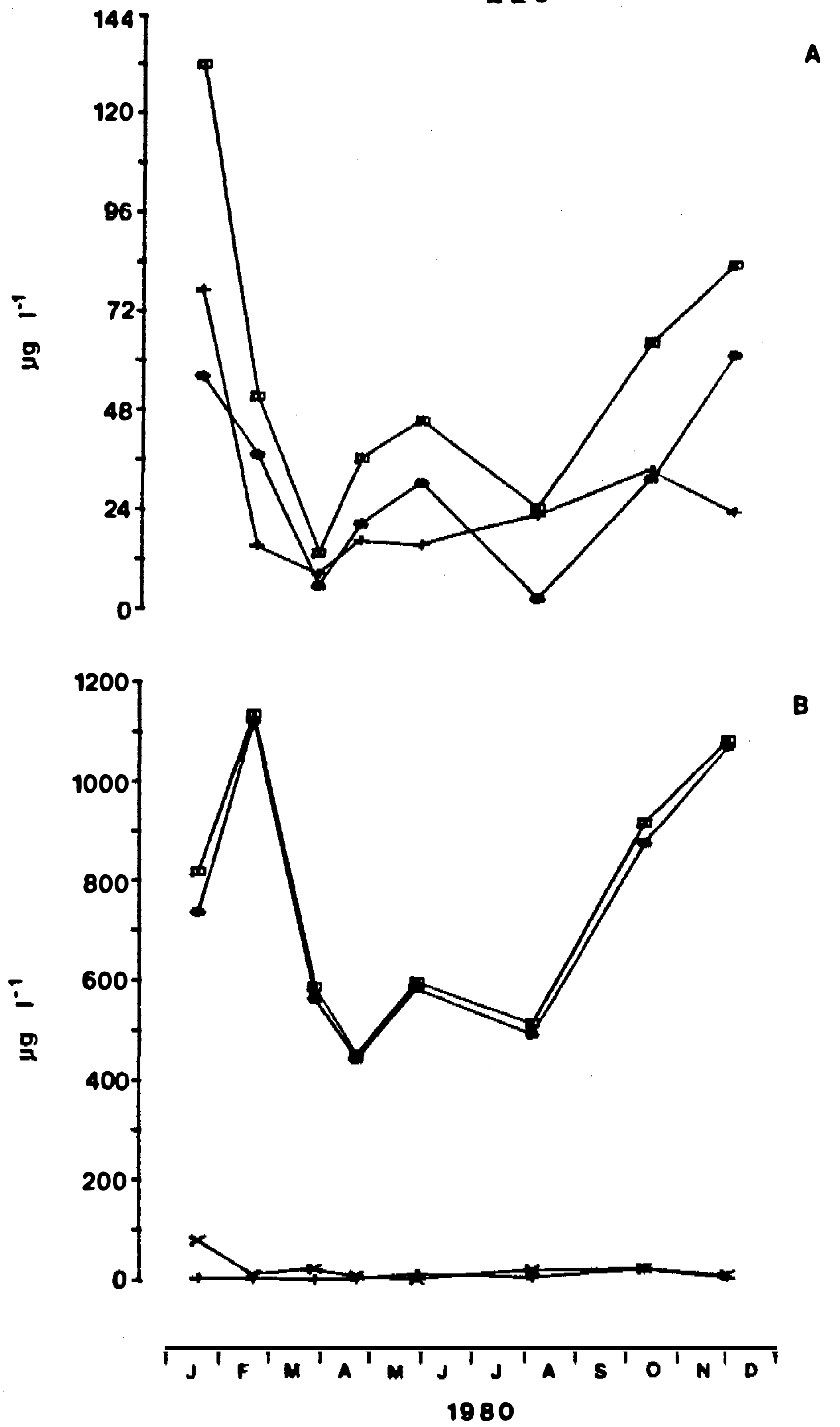

Fig. 5.4.8. Seasonal variations in nutrient concentrations in Red Lily billabong during 1980. Symbols as for Fig. 5.4.1.

5.5 Floodplain billabongs

From the comparatively low values common to all billabongs during February (Table 5.3-1), nutrient concentrations in the floodplain billabongs (except Red Lily) increase markedly through the Dry (Figs. 5.5~~-1-7~~.1-6). By the late Dry most are hypereutrophic in terms of both TP and IN. Figures 5.5-2-7 show that nutrient concentrations rose almost exponentially, sooner in some billabongs than in others. In most, TP reached a maximum earlier in the Dry than did TN. In Mine Valley, for example, (Fig. 5.5~~-3~~.2), TP peaked in late September whilst TN did not reach its yearly maximum until December. Nutrient levels declined dramatically following dilution and flushing by the incoming floodwaters of the Wet.

As with the channel billabongs, PO_4-P generally constituted 20-40% of total-P, the only exception being Jabiluka (Fig. 5.5~~-5~~.4), where it remained constant from June until December whilst total-P increased five-fold. With respect to nutrient fractions, the big difference between floodplain and channel billabongs was that inorganic-N often constituted in excess of 40% of total-N during the latter half of the Dry (for all except Jingalla). Consequently, whereas IN:PO_4-P ratios for the channel billabongs were generally less than 5 in October, for the floodplain billabongs (except Jingalla) the ratio exceeded 18 (Table 5.3-5). The dominant inorganic-nitrogen compound was ammonia, the preferred nitrogen source for most biota, and in Leichhardt, Jabiluka and Nankeen, maximum or near maximum ammonia concentrations occurred by late August. However, nitrate could predominate at the very end of the Dry (e.g. Nankeen, Jabiluka).

The general situation, then, of nutrient conditions in the floodplain billabongs is one of comparatively low concentrations during the Wet, and rapidly rising nutrient levels during the mid-Dry, which result in hypereutrophic status by the late Dry.

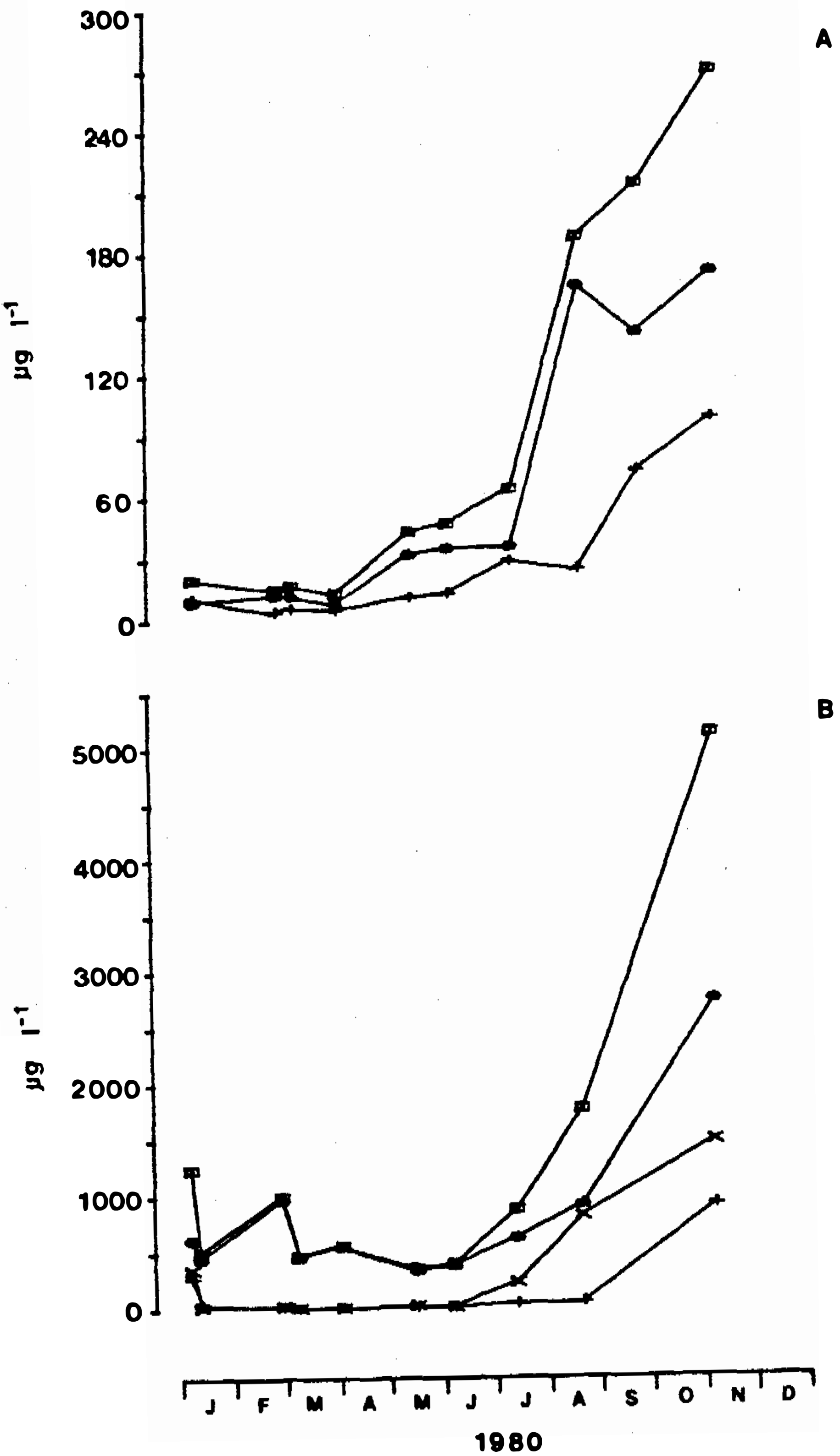

Fig. 5.5.1...Seasonal variations in nutrient concentrations in..Ja Ja...
billabong during 1980. Symbols as for Fig. 5.4.1.

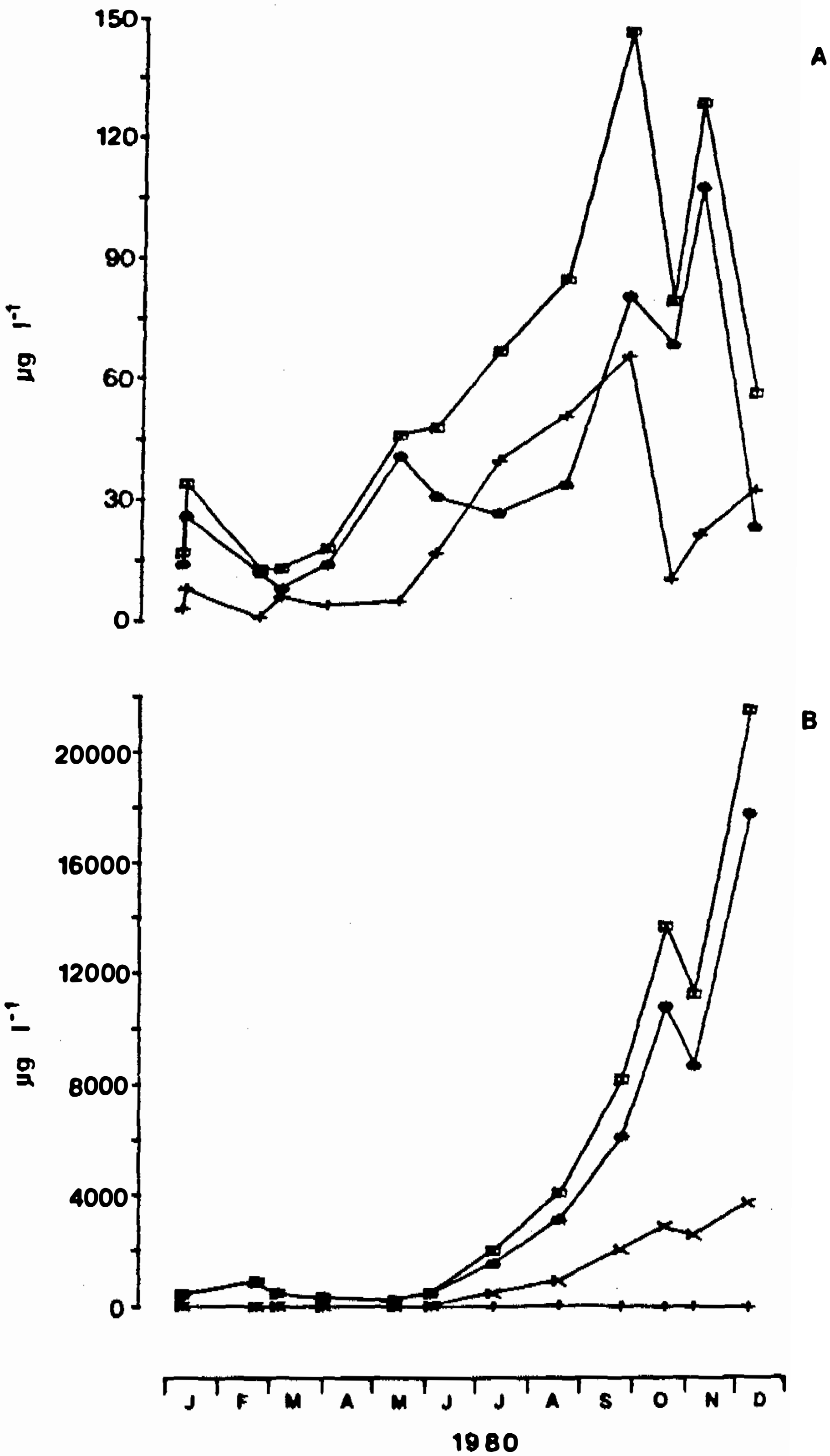

Fig. 5.5.2..Seasonal variations in nutrient concentrations in.Mine Valley billabong during 1980. Symbols as for Fig. 5.4.1.

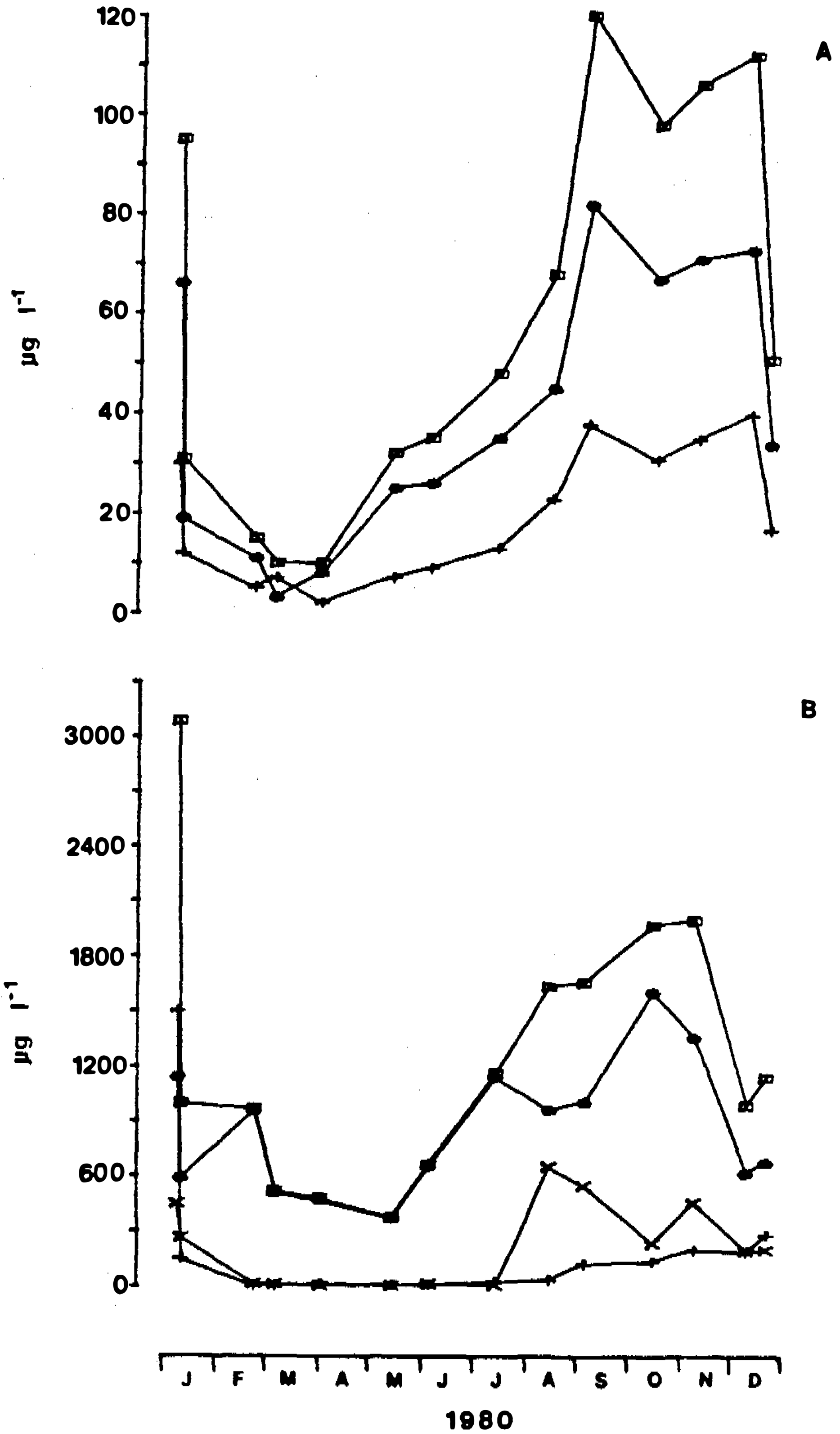

Fig. 5.5.3. Seasonal variations in nutrient concentrations in Leichhardt billabong during 1980. Symbols as for Fig. 5.4.1.

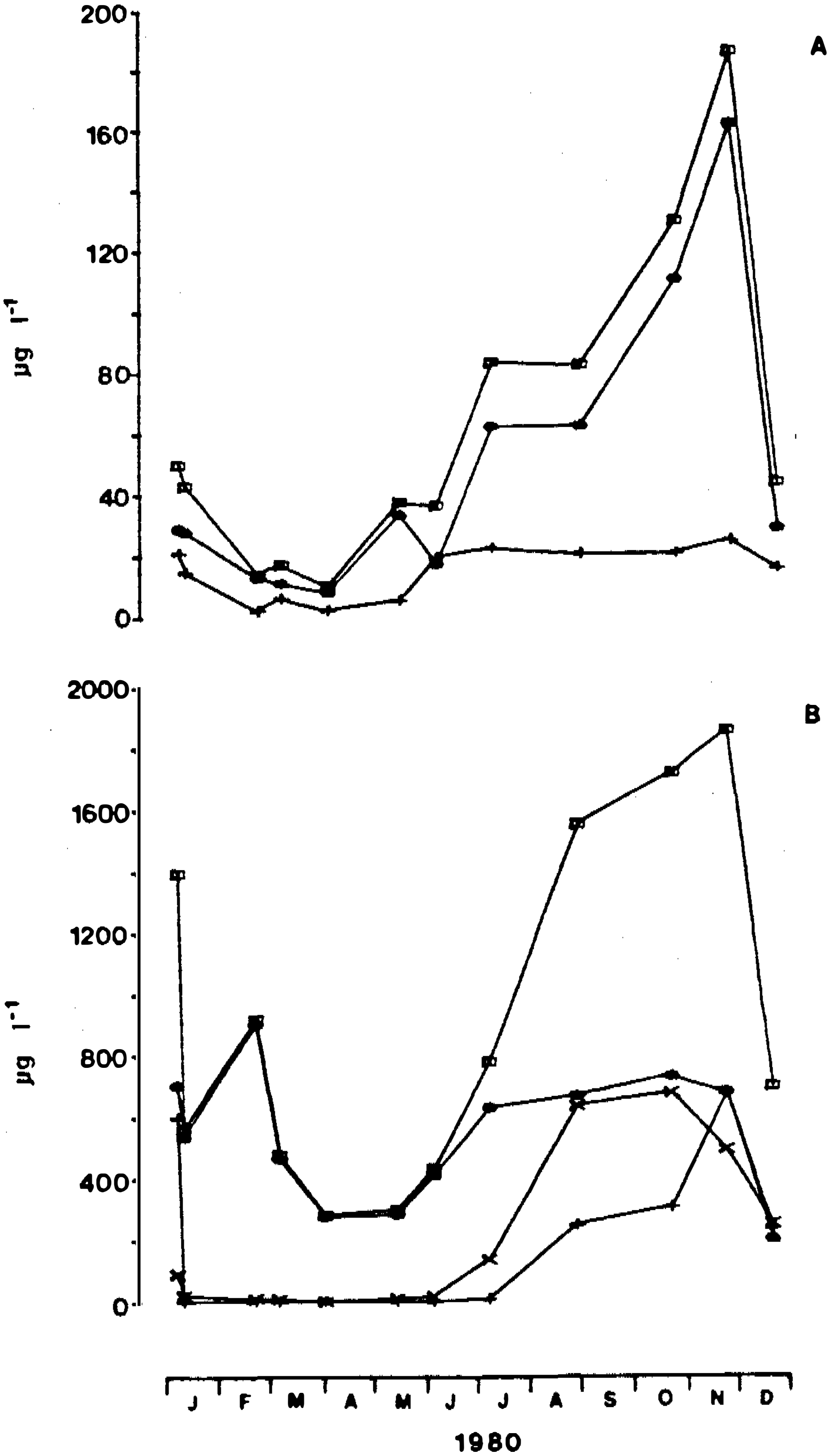

Fig. 5.5.4 Seasonal variations in nutrient concentrations in Jabiluka billabong during 1980. Symbols as for Fig. 5.4.1.

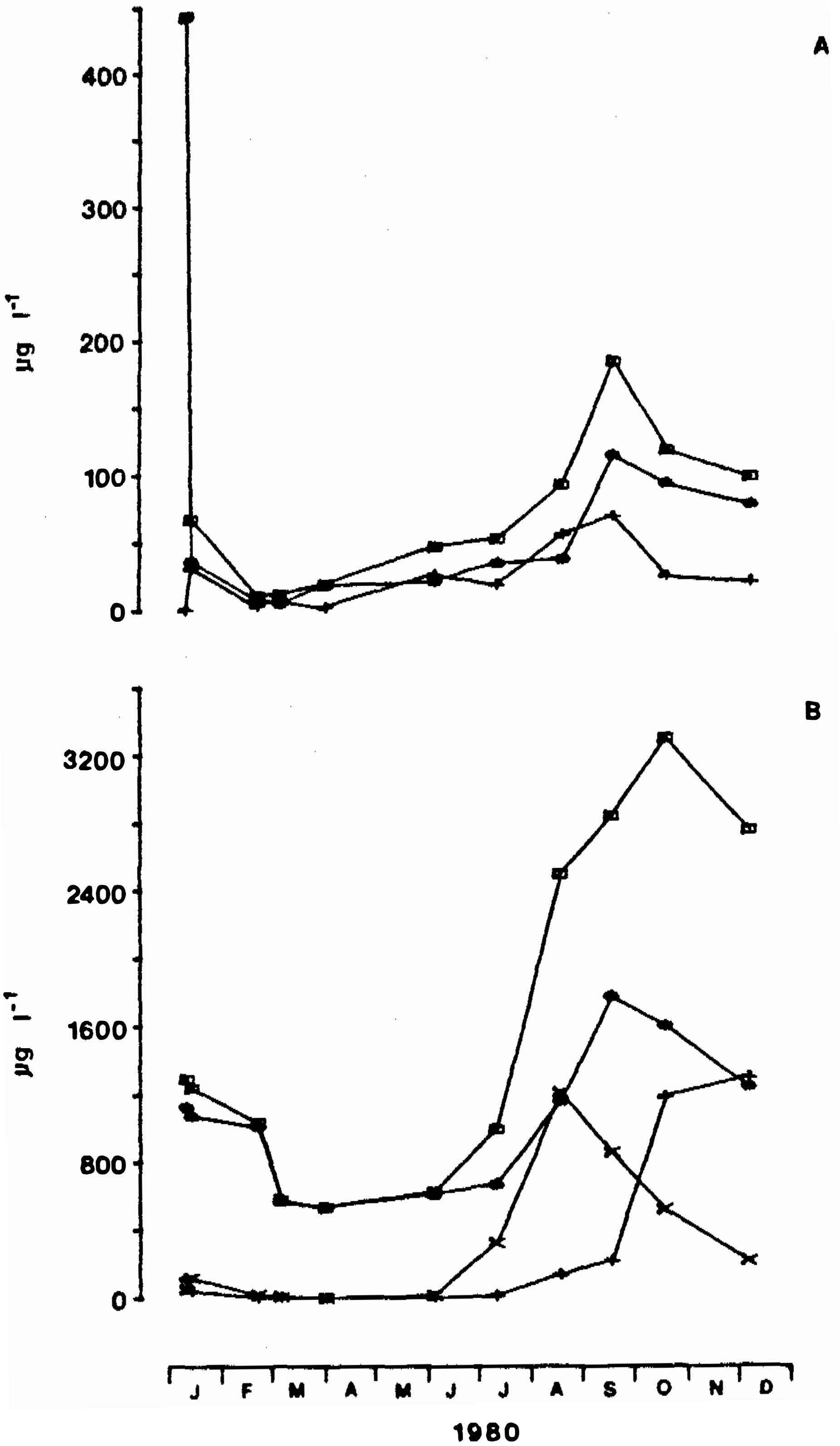

Fig. 5.5.5...Seasonal variations in nutrient concentrations in Nankeen billabong during 1980. Symbols as for Fig. 5.4.1.

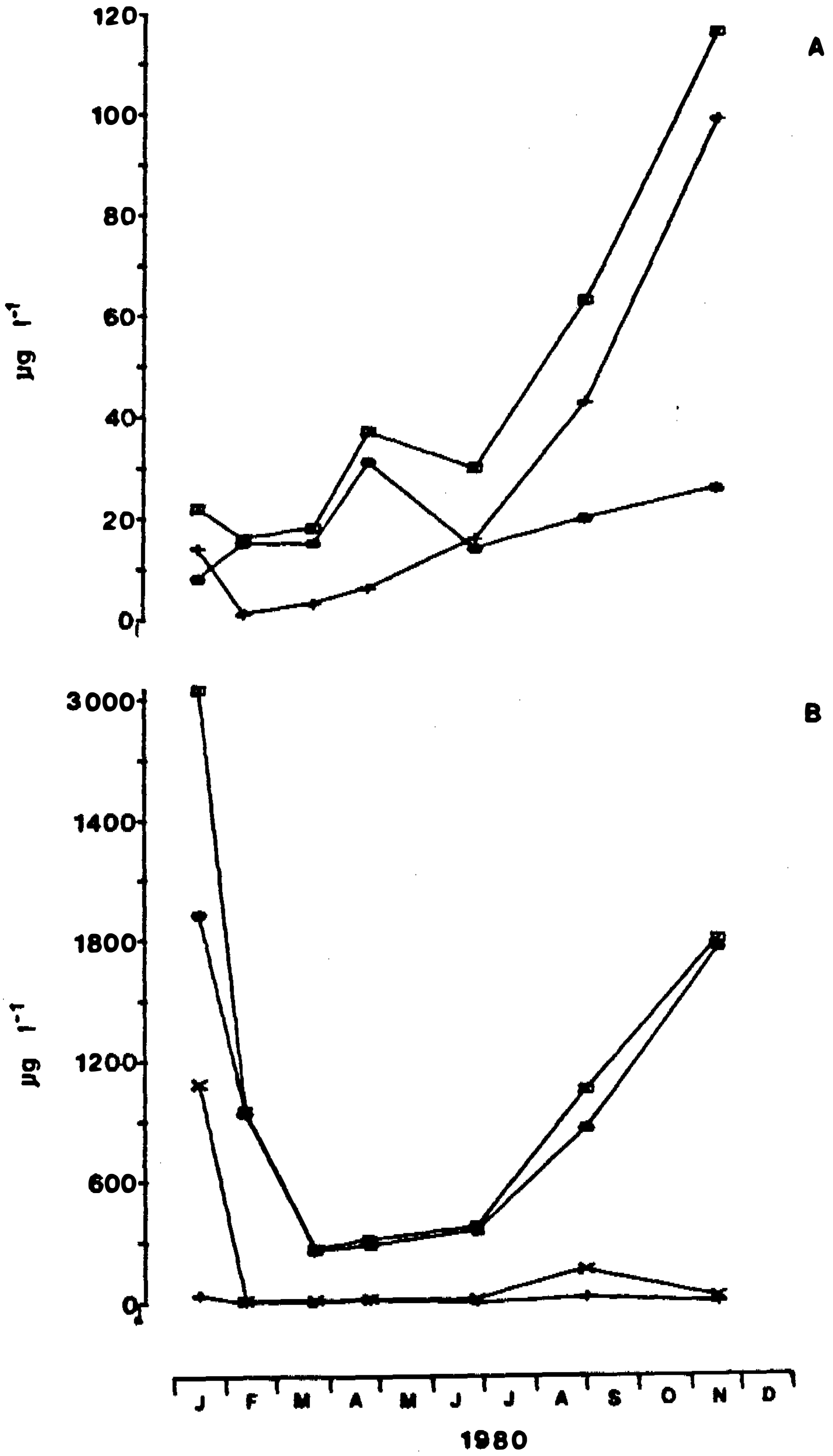

Fig. 5.5.6...Seasonal variations in nutrient concentrations in Jingalla billabong during 1980. Symbols as for Fig. 5.4-1.

5.6 Backflow billabongs

The distinguishing features of this group of billabongs are that, first, TP values at the end of the Dry considerably exceed those of all other billabongs (Table 5.3-5) and, second, that nutrient levels remain more or less constant through the early Dry then rise abruptly (Figs. 5.6-1-4). By the time this increase commences TP concentrations in many of the flood-plain billabongs are already at or near their seasonal maximum (Figs. 5.5-2-5). Unlike the floodplain billabongs, TP and TN concentrations increase in phase.

For all, TP values indicate eutrophic status early in the Dry rising to extremely hypereutrophic later. On the basis of IN values, initially all were ultra-oligotrophic, but at peak concentrations ranged from meso-eutrophic (Georgetown and Goanna) through eutrophic (Gulungul) to extremely hypereutrophic (Umbungbung).

As with both channel and floodplain billabongs PO_4-P was a significant component of TP (Figs. 5.6-1-4). IN values did rise when the peak in TN occurred but not in the same proportion as in the floodplain billabongs. Hence, IN:PO_4-P ratios did not exceed 12 in October (Table 5.3-5).

The distinctive characteristic of the backflow billabongs, then, is the consistently high phosphorus and the late, sudden increase in both nutrients in the Dry.

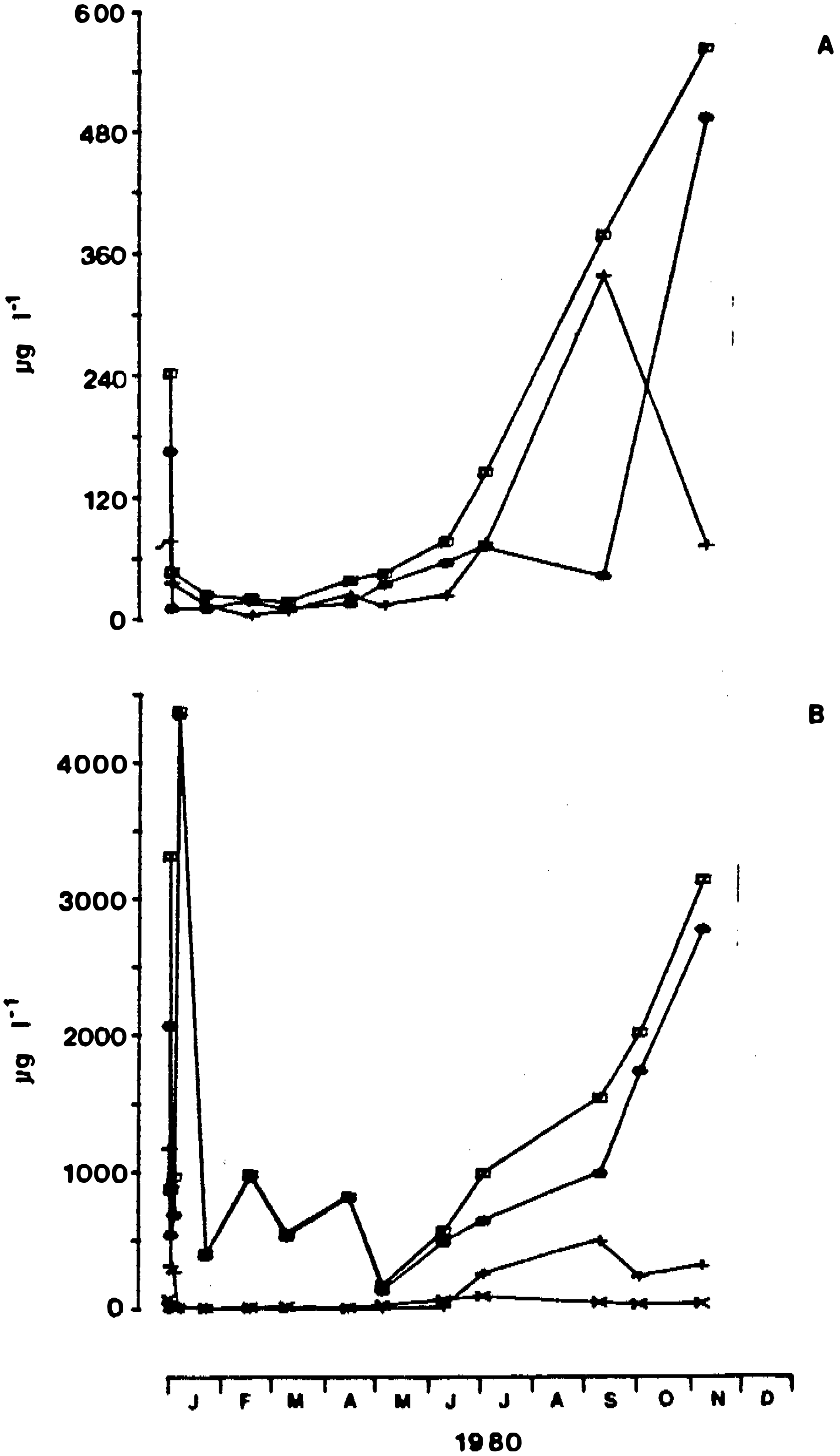

Fig. 5.6.1...Seasonal variations in nutrient concentrations in Georgetown billabong during 1980. Symbols as for Fig. 5.4.1.

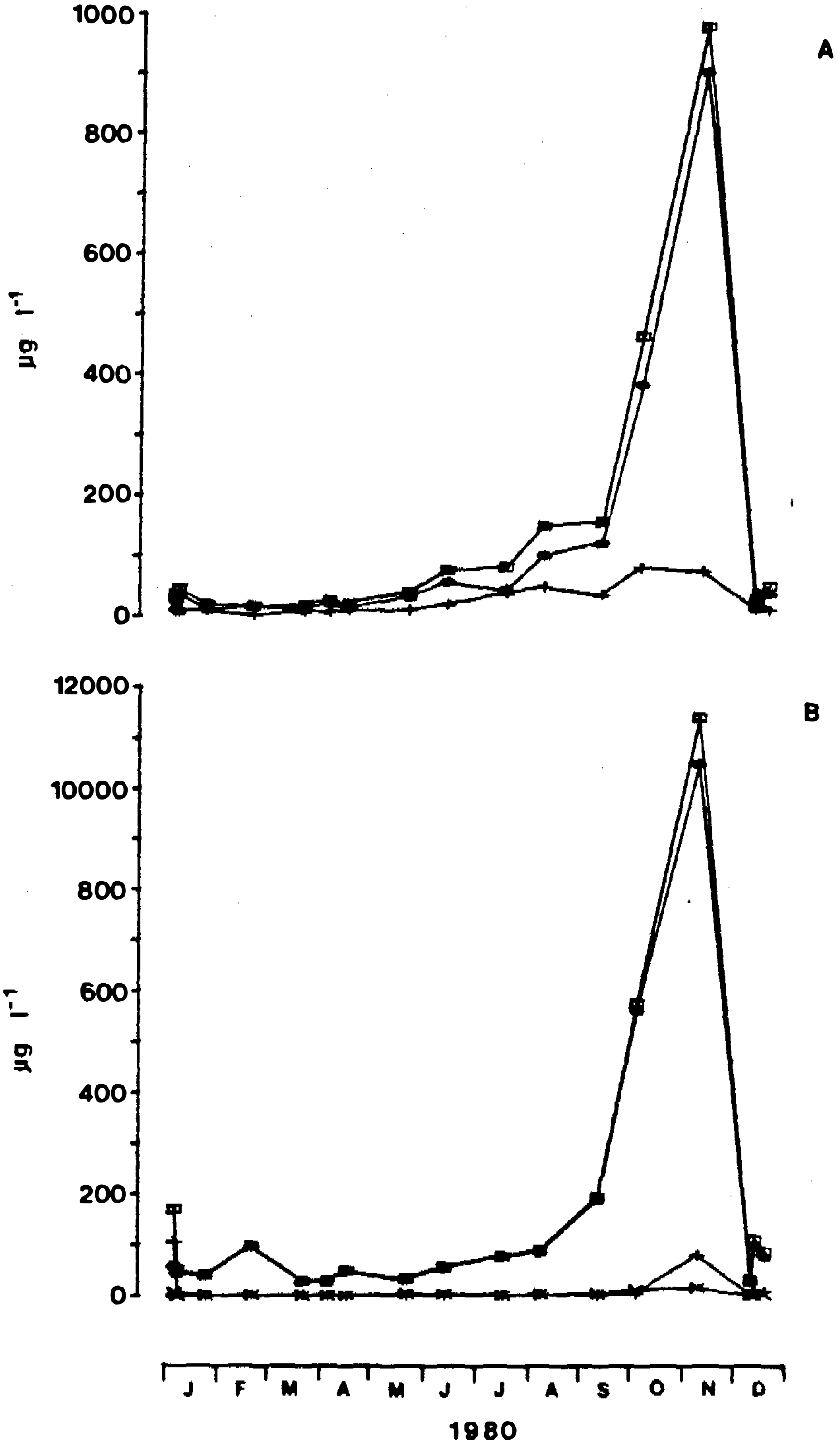

Fig. 5.6.2...Seasonal variations in nutrient concentrations in Gulungul billabong during 1980. Symbols as for Fig. 5.4.1.

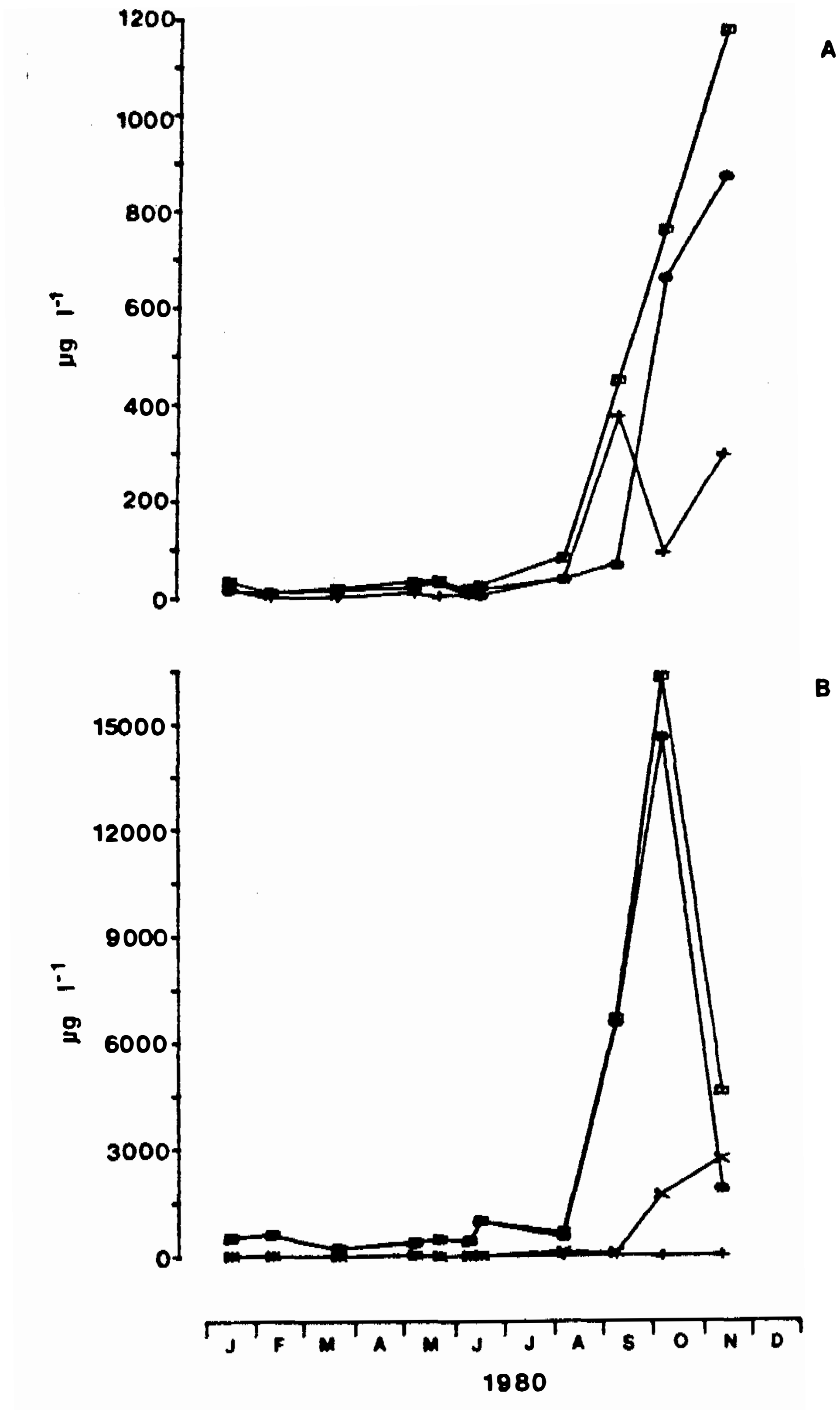

Fig. 5.6.3...Seasonal variations in nutrient concentrations in [illegible] billabong during 1980. Symbols as for Fig. 5.4.1.

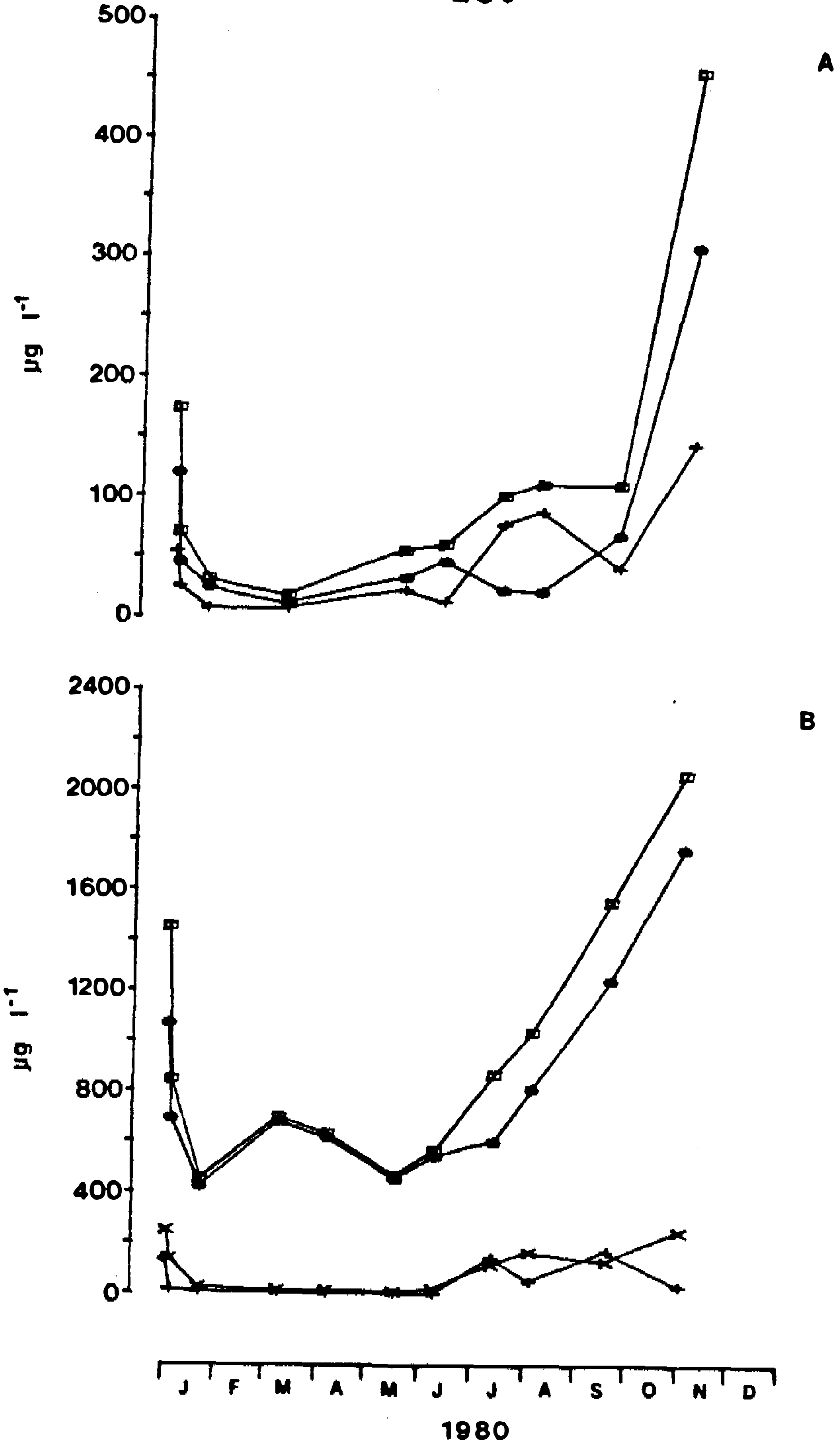

Fig. 5.6.4...Seasonal variations in nutrient concentrations in. [illegible]..
billabong during 1980. Symbols as for Fig. 5.4.1.

6. DISCUSSION

The study of limnology in Australia's tropics is in its infancy. Most investigations have been limited to chemical analysis of the waters and, for this, sufficient data are available to permit Farrell *et al.* (1979) to consider northern Australian waterbodies as being either sodium chloride or magnesium bicarbonate in ionic character. Many lakes of inland Queensland are of the sodium chloride type (Bayly and Williams 1972) and the same authors (1973) have claimed this to be the usual ionic character for most of Australia. Lakes on the Atherton Tableland and in the headwaters of the Burdekin River, both in Queensland, are dominated by magnesium bicarbonate (Bayly & Williams 1972), like Gieckie Gorge (Fitroy River) (Williams and Buckney 1976) in Western Australia. Exceptions to this generalization are Lake Moondarra (Mt. Isa, Queensland) (Farrell *et al.* 1979) which has sodium bicarbonate dominance and Lake Argyle (Ord River, Western Australia) (Millington 1975) where calcium bicarbonate predominates.

For most of tropical Africa, lakes are dominated by sodium bicarbonate (e.g. Beadle 1974; Harding 1961; Heeg *et al.* 1978; Seamen *et al.* 1978; Talling and Talling 1965; Thomas and Ratcliffe 1973) and in the tropics generally, it seems that the calcium bicarbonate composition of World Average Freshwater, so common in the temperate region (Hutchinson 1957; Rodhe 1949; Wetzel 1975), is rare. However, some tropical lakes and rivers do exhibit calcium bicarbonate dominance, such as Lake George and Lake Chad in Africa (Beadle 1974) and, notably, the Amazon basin (Schmidt 1972a, b; 1973).

Water of World Average Freshwater composition is rare in the Alligator Rivers Region. Only Red Lily displayed this composition, and then only in the Wet and early Dry. The overwhelming condition for the three creek systems studied is for all billabongs in the Wet to be dominated by the bicarbonates of sodium and magnesium, in near equimolar amounts. This is the water chemistry of the dilute floodwaters, and in the channel billabongs it is virtually unchanged through the Dry. In the backflow and floodplain billabongs, however, ionic composition changes with evaporative concentration of the waters. This leads to strong sodium chloride dominance by the late Dry. In the floodplain billabongs only, this displacement of bicarbonate by chloride is accompanied by a preferential enrichment of sulphate, probably from groundwater seepage.

Much of the data from which Farrell *et al.* (1979) recognized their two major ionic types for northern Australia, is based upon limited sampling with scant seasonal interpretation. The detailed sampling of Alligator River billabongs has clearly shown a regular seasonal transition from the one category of Farrell and co-workers (sodium/magnesium bicarbonate) to the other (sodium chloride) whenever considerable concentration takes place during the Dry. An annual change in water chemistry, typical of many small tropical lakes (Heeg *et al.* 1979; Rai and Hill 1981; Schmidt 1973; Thomas and Ratcliffe 1973), emphasizes the need for proper seasonal coverage in sampling.

The selective concentration of sodium chloride during the Dry, which characterized all but the channel billabongs, has been observed elsewhere in the tropics. Heeg and co-workers (1978) noted a similar event in the Pongolo River pans during the African dry season. There, as in the Alligator Rivers Region, sodium bicarbonate dominated during the wet season, to be replaced by sodium chloride as the waters became more concentrated. Since, except at very high concentrations (Gibbs 1970), a proportional increase in chloride cannot result from evaporative concentration alone, an external source must be sought. For the Pongolo, the source was traced to highly-mineralized seepage water, rich in chlorides. Such a mechanism of chloride enrichment is unlikely for the Alligator Rivers billabongs. Of the many bores sunk in the Region (eg. Pancontinental Mining Limited 1981) very few struck saline water, except perhaps those adjacent to the estuaries. Certainly, the shallow bores close to the billabongs contain more sulphate than chloride.

One possible source of the sodium chloride enrichment of most billabongs is the atmosphere. The importance of oceanic salt from the atmosphere to Australian inland waters has been stressed by many authors (e.g. Bayly 1964; Bayly and Williams 1973; Cole 1975; Maddocks 1967; Timms 1970; Williams 1967). Atmospheric salt can be supplied by rain or as dry fallout. Bayly and Williams (1973) envisage sodium and chloride being supplied initially as rain, to relatively coastal salt lakes, then being transported further inland from dried pans. This repetitive process would allow salts of oceanic origin to find their way far inland. The possibility exists, then, that during the Dry, all billabongs receive dry salt fallout from the infrequent northerly winds (Walker, Waterhouse and Tyler 1982) carrying the salt of evaporated sea spray, or from the predominant south-westerly winds carrying salt from dried pans of the arid hinterland. In the dilute waters of the Region's billabongs little atmospheric salt would be necessary to produce noticeable effects on water chemistry, when accompanied by concomitant evaporative concentration in backflow and floodplain billabongs. Channel billabongs would be less affected because, with small surface area to volume ratios, evaporative concentration is minimal (Pancontinental Mining Limited 1981). Further, it is suspected that for much of the Dry, dilute groundwater with chemical characteristics of the Wet, enters the channel billabongs from sandy aquifers.

The distinguishing feature of the sulphate group of billabongs is that during the Dry, in addition to the preferential concentration of sodium chloride, sulphate assumes significant proportions at a time when the sediments are resuspended. This situation is similar to that noted by Schmidt (1973) for the low water period in Lago do Casthano, a small Amazonian varzea (= floodplain) lake, when sediment resuspension signals the ascendancy of sodium and magnesium over calcium, the former clear dominant. Simultaneously, chloride and sulphate attain dominance over bicarbonate. Schmidt offers no explanation for these events. In the present case, the chemistry and hydraulic conditions of boreholes adjacent to the sulphate-type billabongs implicates an influx of sulphate-rich groundwater through localized aquifers. Additional sulphate may be derived from oxidation of sulphide-rich sediments upon resuspension.

Any discussion of the nutrient elements phosphorus and nitrogen is inextricably bound up with the notion of trophic status and eutrophication. Worldwide experience shows that, almost invariably, it is, first, phosphorus and, second, nitrogen, which hold production at levels below those theoretically possible with the available energy. Behind this recognition lies decades of agricultural practice in the use of fertilizers, and the potential for biological production has been adduced in terms of nutrient concentrations or nutrient loads (Sakamoto 1966; Vollenweider 1968; Walmsey and Butty 1980a,b). The demanding business of estimating nutrient loads was beyond the scope of this investigation and, therefore, the widely-used scheme of Vollenweider (1968), based on nutrient concentrations, was adopted. On this basis, in terms of total-phosphorus concentrations, the billabongs of the Region stand out as fertile, even in the Wet, at their most dilute. Then, on Vollenweider's scheme, they would all be classified, variously, as meso-eutrophic to hypereutrophic. Later, in the Dry, all except the channel billabongs, which change little, would be termed hypereutrophic.

In strong contrast, in terms of inorganic nitrogen, during the Wet all billabongs would be regarded as ultra-oligotrophic. As for phosphorus, inorganic nitrogen concentrations in the channel billabongs change little during the Dry, whilst in all others they increase, leading to a range of trophic conditions from mesotrophic to hypereutrophic. The apparent contradiction between predictions based on phosphorus levels and those for nitrogen highlight the occasional difficulties in determining trophic status without reference to consequent biotic responses. In some instances, abundant nutrient supplies do not lead to the high productivity which usually signals the hypereutrophic condition. On the basis of these nutrient data, it would appear that nitrogen, not phosphorus, is the most likely limiting nutrient, the reverse of usual experience.

The nitrogen:phosphorus content of algal cells is approximately 7:1 by weight* (Vallentyne 1974; Wetzel 1975). In natural waters, an N:P ratio deviating from this value suggests that one or other of the two nutrients is limiting. In addition, several authors (e.g. Edmondson 1972; Nalewajko and Lean 1980; Rhee 1978; Schindler 1977; Sze 1975) have suggested that species composition can be determined by N:P supply ratios, with low ratios favouring nitrogen-fixing blue-green algae. Thus, examination of the pools of biologically-available nitrogen and phosphorus can be of considerable assistance in evaluating the trophic status of waters.

There is some confusion as to which chemical forms of the two nutrients comprise the biologically-available pool, and as such, considerable variation in the computation of N:P ratios. Because of the rapidity with which phosphorus is recycled, some authors (e.g. Cole 1975; Vollenweider 1968; Wetzel 1975) consider that total phosphorus is more indicative of the phosphorus pool than orthophosphate. By contrast, Cowen *et al.* (1978) found that total phosphorus gave an 80% overestimation of available phosphorus. Whatever the case, N:P ratios have been calculated on the basis of orthophosphate-P (e.g. Chiaudani and Vighi 1974; Golterman and Kouwe 1980; Rai and Hill 1981; Schindler *et al.* 1973; Walmsley and Butty 1980).

Similar confusion surrounds identification of available nitrogen. Nitrate tends to be the predominant form of inorganic nitrogen in surface waters (Brezonik 1978), and may be used alone as an indicator of the available nitrogen (e.g. Golterman and Kouwe 1980; Rai and Hill 1981). Ammonia, however, which is present in significant amount in some waters, is the preferred form of inorganic nitrogen for planktonic assimilation, since

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* N:P ratios are usually quoted by weight but some authors use atomic ratios.

it is already at the reduction level of organic nitrogen (Brezonik 1973), and several authors have used the combined concentrations of ammonia and nitrate to estimate total inorganic nitrogen (e.g. Chiaudani and Vighi 1974; Rhee 1978; Ryther and Dunstan 1971; Walmsley and Butty 1980b).

The N:P ratio of 7:1 by weight is an average value for algal cells (Vallentyne 1974; Wetzel 1975). In fact, experimental evidence indicates considerable variation in N:P ratios, depending on species composition and nutrient concentrations in the water (Nakanishi and Monsi 1976), and, accordingly, a range of values for the ratio of N:P requirements has been quoted. Rhee (1978) determined that a freshwater *Scenedesmus* sp. was limited solely by nitrogen at ratios below 14:1, and by phosphorus at ratios above that value. Welch *et al.* (1975) considered that N:P ratios of 7-10 were required for algal growth. Both Golterman and Kouwe (1980), using NO_3-N:PO_4-P, and Chiaudari and Vighi (1974) using (NO_3+NH_4)-N:PO_4-P, found that ratios exceeding 10 were indicative of phosphate limitation. For the billabongs of the Alligator Rivers, N:P ratios ((NH_4+NO_3)-N:PO_4-P) were usually below seven, often considerably so (Tables 5.3-1,2). Only on the floodplain, and in some backflow billabongs, did values exceed 10 and then only late in the Dry. This suggests again that, in contrast to usual experience worldwide (Golterman and Kouwe 1980), it is nitrogen, not phosphorus, which is limiting in the Alligator Rivers Region. This is not unusual for the tropics (Moss and Moss 1969; Sioli 1975; Talling 1966; Talling and Talling 1965). An abundance of phosphorus with a scarcity of nitrogen should favour green algae (Chlorophyta), which have low cellular N:P ratios, and the blue-green algae (Cyanophyta), which are capable of fixing atmospheric nitrogen (Ryther and Dunstan 1971).

During the current eutrophication debate, much attention has been focussed upon the external loading of nutrients into freshwaters since "it is generally accepted that for any further increase in the (algal) population, nutrients must be derived from an external source" (Walmsley and Butty 1980b). However, internal loading, from the release of nutrients from sediments, may play a highly significant role in lake fertilisation, particularly in shallow lakes where turbulent mixing extends to the bottom, with resultant mixing at the sediment-water interface. It has been shown that dissolved inorganic nutrients (PO_4-P, NH_4-N) are released more readily from the sediments by turbulent mixing than by simple diffusion (see Ryding and Forsberg 1977). Further, turbulence resuspends sediments which frequently contain adsorbed nutrients,which are available to algae (Brezonik 1973; Golterman 1977; Golterman *et al.* 1969; Healy and McColl 1974; McColl 1975). Suspended sediments may also act as a nutrient buffer system. In the turbid Amazon River, Gessner (1960) found that when soluble phosphorus exceeds 10 $\mu g l^{-1}$, it is adsorbed by the fine, suspended sediments, and when less than 10 $\mu g l^{-1}$, the adsorbed phosphorus is released. Thus, suspended sediments may account for a substantial portion of the biologically-available nutrient pool.

Preliminary investigations (Van der Wiele 1981) suggest that sediments of backflow and,especially, floodplain billabongs are indeed high in nutrient concentrations. The massive increase in turbidity in the Dry, so characteristic of these billabongs (Walker, Kirk and Tyler 1982), is brought about mainly by wind-induced resuspension of fine sediments,and the concurrent increases in total nutrient levels strongly suggest that the suspended sediments contribute in a major way to the nutrient pool.

In most considerations of nutrient dynamics in lakes it is algae, the consumers of nutrients, which are stressed. However, interactions with other elements of the biota are obvious and perhaps of equal significance. Zooplankton may constitute a large proportion of the total nutrient reservoir

(Howard-Williams 1979), and may figure largely in nutrient cycling (Rigler 1973). Removal of all fish from a Swedish lake resulted in a distinct shift towards oligotrophy (Henikson *et al.* 1980). The potential importance of bird excreta as an external nutrient source (Manny *et al.* 1975) may be of particular significance in tropical Australia. For Hickling Broad, England, the dynamics of phytoplankton populations can only be understood in terms of resident and immigrant water birds (Leah *et al.* 1978). Birds feeding mainly within a lake would affect only internal cycling, whereas those feeding elsewhere, and roosting on the lake, constitute an external source of nutrients. In this context, the large flocks of magpie geese (*Anseranas semipalmata*), feeding on the floodplains, but congregating at selected billabongs (especially Jingalla, locally known as Goose Camp), must bring in nutrients during the Dry. The same may be said of the fruit bat (Black Flying Fox - *Pteropus alecto*) colony at Leichhardt. Buffalo almost certainly affect nutrient cycles by stirring up sediments whilst wallowing, and by contributing ~~urea~~ manure and ~~manure~~ urea.* Their droppings on the floodplain during the Dry contribute to the nutrient pool of the new waters of the Wet. Mitchell (1973) demonstrated that large quantities of nutrients were released from animal droppings by the rising waters of Lake Kariba, causing rapid increases in productivity of inshore areas.

Because of the peculiar hydrological circumstances, the nutrient cycles of the billabongs can be envisaged as closed systems during the Dry (Fig. 6.1), in contrast with the open systems of temperate lakes. The river or stream inputs of temperate lakes, which normally persist throughout the year, are replaced in the billabongs by biotic inputs and, perhaps, groundwater. There is no outflow other than biotic outflows such as emerging insects. Internal loading is maximised by sediment resuspension. It is during this time of closed, endorheic cycling that the massive increases in nutrient concentrations occur in the backflow and floodplain billabongs. The channel billabongs also become closed systems, but

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rea lies between ammonia and nitrate in order of preference for uptake by algae (McCarthy et.al. 1977).

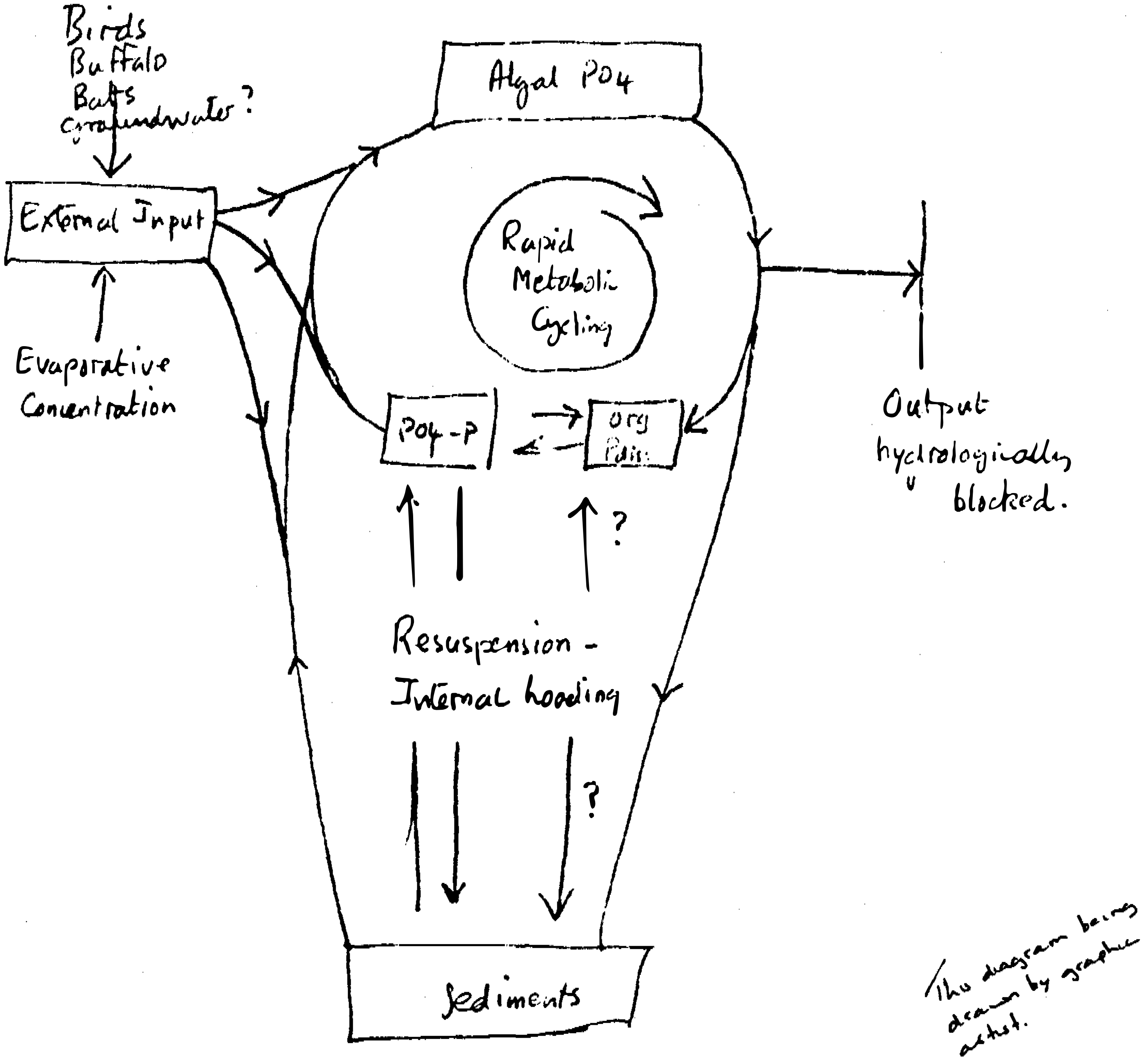

Fig. 6.1 The likely phosphorus cycle for closed billabongs during the Dry.

both external and internal loading is much less. In these billabongs, evaporative concentration is minimal, their restricted littoral zones support few birds or animals, and their coarse sediments are not resuspended. The contribution from groundwater is unknown but must be small since scant increase in nutrients occurs in these billabongs in the Dry.

The chemistry of the billabongs has been treated quite separately in terms of major ions, and related parameters, and in terms of nutrients. Both lead to essentially the same classification of billabongs, and to one which conforms to the traditional divisions based on morphology, geography and hydrology. Thus, on chemical grounds the channel, backflow and floodplain billabongs respectively are recognised, with few exceptions, ~~recognised~~ as those which change little through the Dry, those which become high nutrient, sodium chloride billabongs, and those with high nutrients and an input of sulphate.

8. REFERENCES

Atkins, R.P. (1978). *Methods for Examining the Physical, Chemical, and Biological Parameters of Aquatic Environments.* Botany Dept., University of Western Australia.

APHA (1971). *Standard Methods for the Examination of Water and Wastewater.* 13th Ed. American Public Health Association, Washington D.C.

APHA (1975). *Standard Methods for the Examination of Water and Wastewater.* 14th Ed. American Public Health Association, Washington D.C.

Barabas, S. (Ed.) (1981). Eutrophication - a global problem. Part 1. *Water Quality Bulletin* 6(3).

Barabas, S. (Ed.) (1981). Eutrophication - a global problem. Part 2. *Water Quality Bulletin* 6(4).

Bayly, I.A.E. and Williams, W.D. (1972). The major ions of some lakes and other waters in Queensland, Australia. *Aust. J. mar. Freshwat. Res.* 15, 56-72.

Brezonik, P.L. (1973). *Nitrogen Sources and Cycling in Natural Waters.* Office of Research and Monitoring, U.S. Environmental Protection Agency, Washington D.C.

Buckney, R.T. and Tyler, P.A. (1973). Chemistry of some sedgeland waters, Lake Pedder, South-West Tasmania. *Aust. J. mar. Freshw. Res.* 24, 267-73.

Burton, J.D. (1973). Problems in the analysis of phosphorus compounds. In: Jenkins, S.H. and Ives, K.J. (Eds.). *Phosphorus In Fresh Water And The Marine Environment*, pp. 291-308, Pergamon Press, Oxford.

Chiaudani, G. and Vighi, M. (1974). The N:P ratio and tests with *Selenastrum* to predict eutrophication in lakes. *Water Research* 8, 1063-1069.

Cole, G.A. (1975). *Textbook of limnology.* The C.V. Mosby Co., St. Louis.

Conway, E.J. (1942). Mean geochemical data in relation to oceanic evolution. *Proc. Roy. Irish Acad. (B)* 48, 119-59.

Cowen, W.F., Sirisinha, K., Lee, G.F. (1978). Nitrogen and phosphorus in Lake Ontario tributary waters. *Water, Air, and Soil Pollution* 10, 343-50.

Curry, R.R. (1972). Rivers - a geomorphic and chemical overview. In: Oglesby, R.T., Carlson, C.A. and McCann, J.A. (Eds.) *River Ecology and Man.* Academic Press, New York.

Bayly, I.A.E. and Williams, W.D. (1973). Inland waters and their Ecology. Longman, Hawthorn.

Dal Pont, G., Hogan, M. and Newell, B. (1974). Laboratory techniques in marine chemistry II. Determination of ammonia in sea water and the preservation of samples for nitrate analysis. *CSIRO Division of Fisheries and Oceanography Report No.* 55, 1-5.

Droop, M.R. (1974). The nutrient status of algal cells in continuous culture. *J. mar. biol. Ass. U.K.* 54, 825-55.

Edmondson, W.T. (1972). The present condition of Lake Washington. *Verh. int. Ver. Limnol.* 18, 284-91.

Farrell, T.P; Finlayson, C.M. and Griffiths, D.J. (1979). Studies of the hydrobiology of a tropical lake in north-western Queensland. I. Seasonal changes in chemical characteristics. *Aust. J. mar. Freshwat. Res.* 30, 579-95.

Fox, R.U., Kelleher, G.G. and Kerr, C.B. (1977). *Ranger Uranium Environmental Inquiry.* Vol. 2. Australian Government Printing Service, Canberra.

Ganf, G.G. and Viner, A.B. (1973). Ecological stability in a shallow equatorial lake (Lake George, Uganda). *Oecologia,* 15: 17-32.

Gessner, F. (1960). Investigations of the phosphate economy of the Amazon. *Int. Rev. Hydrobiol.* 45, 339-345.

Gibbs, R.J. (1970). Mechanisms controlling world water chemistry. *Science.* 170, 1088-90.

Golterman, H.L. (1969). *Methods for Chemical Analysis of Fresh Waters.* Blackwell Scientific Publications, Oxford.

Golterman, H.L. (1977). Sediments as a source of phosphate for algal growth. In: Golterman, H.L. (ed.). *Interactions between Sediments and Fresh Water,* Proceedings of an International Symposium, Amsterdam, 1976, pp. 286-93. W. Junk, The Hague.

Golterman, H.L; Bakels, C.C. and Jakobs-Möglin, J. (1969). Availability of mud phosphates for the growth of algae. *Verh. int. Ver. Limnol.* 17, 467-79.

Golterman, H.L. and Kouwe, F.A. (1980). Chemical budgets and nutrient pathways. In: Le Cren, E.D. and Lowe-McConnel, R.H. (Eds.). *The functioning of freshwater ecosystems,* pp. 85-140. Cambridge University Press, Cambridge.

Gorham, E. (1961). Factors influencing supply of major ions to inland waters, with special reference to the atmosphere. *Bull. Geol. Soc. Amer.* 72, 795-840.

Gorham, E. and Cragge, J.B. (1960). The chemical composition of some bog waters from the Falkland Islands. *J. Ecol.* 48, 175-81.

Harding, D. (1961). Limnological trends in Lake Kariba. *Nature, Lond.* 191, 119-21.

..ct, B.H. (1967). Some comments on "integrative" and "specific" properties of the aquatic environment. In: Golterman, H.L. and Clymo, R.S (Eds) Chemical Environment in the Aquatic Habitat, pp 24-29. N.V. Noord-Hollandsche Uitgevers Maatschappij, Amsterdam.

Hart, B.T. and McGregor, R.J. (1980). Limnological survey of eight billabongs in the Magela Creek catchment, Northern Territory. *Aust. J. mar. Freshwat. Res.* 31, 621-26.

Healey, F.P. (1973). Inorganic nutrient uptake and deficiency in algae. *Crit. Rev. Microbiol.* 3, 69-113.

Healy, W.B. and McColl, R.H.S. (1974). Clay particles as sources of phosphorus for *Lemna* and their role in eutrophication. *N.Z. J. Science* 17, 409-20.

Heeg, J; Breen, C.M; Colvin, P.M; Furness, H.D. and Musil, C.F. (1978). On the dissolved solids of the Pongolo flood plain pans. *J. Limnol. Soc. sth. Afr.* *4*(1), 59-64.

Hem, J.D. (1970). Study and Interpretation Of The Chemical Characteristics of Natural Water. 2nd Ed. *Geological Survey Water Supply Paper 1473.* U.S. Govt. Printing Office, Washington.

Henrikson, L; Nyman, H.G; Oscarson, H.G. and Stenson, J.A.E. (1980). Trophic changes, without changes in the external nutrient loading. *Hydrobiologia* 68, 257-63.

Howard-Williams, C. (1977). The distribution of nutrients in Swartvlei, a Southern Cape coastal lake. *Water SA* 3(4), 213-17.

Hutchinson, G.E. (1957). *A Treatise on Limnology.* Vol. I. John Wiley and Sons, New York.

Kerr, J. (1960). The spectrophotometric determination of microgram amounts of calcium. *Analyst (London)* 85, 867-70.

King, R.D. and Tyler, P.A. (1981a). Limnology of Perched Lake, South-west Tasmania. *Aust. J. mar. Freshwater Res.*, 32, 501-15.

King, R.D. and Tyler, P.A. (1981b). Meromictic lakes of South-west Tasmania. *Aust. J. mar. Freshwater Res.*, 32, 741-56.

King, R.D. and Tyler, P.A. (1982a). Lake Fidler, a meromictic lake in Tasmania. *Arch. Hydrobiol.*, (in press).

King, R.D. and Tyler, P.A. (1982b). Sulphide Pool and Lake Morrison, meromictic lakes of South-west Tasmania. *Arch. Hydrobiol.*, (in press).

Leah, R.T; Moss, B; and Forrest, D.E. (1978). Experiments with large enclosures in a fertile, shallow brackish lake, Hickling Broad, Norfolk, United Kingdom. *Int. Revue ges. Hydrobiol.* 63(3), 291-310.

Lean, D.R.S. (1973). Movements of phosphorus between its biologically important forms in lake water. *J. Fish. Res. Bd. Canada* 30, 1525-36.

Lean, D.R.S. and Nalewajko, C. (1979). Phosphorus turnover time and phosphorus demand in large and small lakes. *Arch. Hydrobiol. Beih.* 13, 120-32.

Lee, D.R. (1977). A device for measuring seepage flux in lakes and estuaries. *Limnol. Oceanogr.* 22, 140-7.

Livingstone, D.A. (1963). Chemical composition of rivers and lakes. *U.S. Geol. Surv. Prof. Paper 440-G.* U.S. Government Printing Office, Washington D.C.

Lund, J.W.G. (1970). Primary production. *Water Treatment and Examination*, 19, 332-58.

Maddocks, G.E. (1967). The geochemistry of the surface waters of the western district of Victoria. *Aust. J. mar. Freshwat. Res.* 15, 35-52.

Major, G.A., Dal Pont, G., Klye, J. and Newell, B. (1972). Laboratory techniques in marine chemistry - a manual. *CSIRO Division of Fisheries and Oceanography Report No.* 51. 10-12.

Manny, B.A; Wetzel, R.S; and Johnson, W.C. (1975). Annual contribution of carbon, nitrogen, and phosphorus by migrant Canada geese to a hard water lake. *Verh. int. Ver. Limnol.* 19, 249-257.

Maucha, R. (1932). *Hydrochemische Methoden in der Limnologie. Die Binnenwässer,* 12. Schweizerbartsche Verlagsbuchhandlung, Stuttgart.

McCarthy, J.J. (1980). Nitrogen. In: Morris, I. (Ed.). *The Physiological Ecology of Phytoplankton,* pp. 191-233. Blackwell Scientific Publications, Oxford.

McCarthy, J.J; Taylor, W.R; and Taft, J.L. (1977). Nitrogenous nutrition of the plankton in the Chesapeake Bay. I. Nutrient availability and phytoplankton preferences. *Limnol. Oceanogr.* 22, 996-1011.

McColl, R.H.S. (1975). Availability of soil and sediment phosphorus to a planktonic alga. *N.Z. J. mar. Freshwat. Res.* 9(2), 169-82.

Millington, A.J. (1975). Agricultural implications of the Ord River Dam. In: Millington, A.J. (ed.), *Man-Made Lakes and Human Health,* pp. 113-35. Academic Press, London.

Mitchell, D.S. (1973). Supply of nutrient chemicals in Lake Kariba. In: Ackermann, W.C; White, G.F; and Worthington, E.B. (Eds.), *Man-Made Lakes: Their Problems and Environmental Effects.* Geophysical Monograph Series, Vol. 17. American Geophysical Union, Washington D.C.

Moss, B. (1980). *Ecology Of Fresh Waters.* Blackwell Scientific Publications, Oxford.

Nakanishi, M. and Monsi, M. (1976). Factors that control the species composition of freshwater phytoplankton, with special attention to nutrient concentrations. *Int. Revue ges. Hydrobiol.* 61(4), 439-470.

Nalewajko, C. and Lean, D.R.S. (1980). Phosphorus. In: Morris, I. (Ed.). *The Physiological Ecology of Phytoplankton*, pp. 235-258. Blackwell Scientific Publications, Oxford.

National Academy of Sciences (1969). *Eutrophication: causes, consequences, correctives; proceedings of a symposium.* International Symposium on Eutrophication, University of Wisconsin, 1967. National Academy of Sciences, Washington.

Olsen, S. (1967). Recent trends in the determination of orthophosphate in water. In: Golterman, H.L. and Clymo, R.S. (Eds.). *Chemical Environment in the Aquatic Habitat*, pp. 63-105, N.V. Noord-Hollandsche Vitgevers Maatschappij, Amsterdam.

Pancontinental Mining Limited (1981). *A review of Jabiluka Environmental Studies.* Pancontinental Mining Ltd., Sydney.

Rai, H. and Hill, G. (1980). Classification of central Amazonian lakes on the basis of their microbiological and physico-chemical characteristics. *Hydrobiologia* 72, 85-99.

Rai, H. and Hill, G. (1981). Physical and chemical studies of Lago Tupe; a central Amazonia black water 'Ria Lake'. *Int. Revue ges. Hydrobiol.* 66(1), 37-82.

Rhee, G.Y. (1978). Effects of N:P atomic ratios and nitrate limitation on algal growth, cell composition, and nitrate uptake. *Limnol. Oceanogr.* 23, 10-25.

Rigler, F.H. (1964). The phosphorus fractions and the turnover time of inorganic phosphorus in different types of lakes. *Limnol. Oceanogr.* 9, 511-8.

Rigler, F.H. (1973). A dynamic view of the phosphorus cycle in lakes. In: Griffith, E.J; Beeton, A; Spencer, J.M; and Mitchell, D.T. (Eds.), *Environmental Phosphorus Handbook*, pp. 539-72. Wiley, New York.

Rodhe, W. (1949). The ionic composition of lake waters. *Verh. int. ver. Limnol.* 10, 377-86.

Ryding, S.D. and Forsberg, C. (1977). Sediments as a nutrient source in shallow polluted lakes. In: Golterman, H.L. (ed.), *Interactions between Sediments and Fresh Water*, Proceedings of an International Symposium, Amsterdam, 1976, pp. 227-734. W. Junk, The Hague.

Ryther, J.H. and Dunstan, W.M. (1971). Nitrogen, phosphorus, and eutrophication in the coastal marine environment. *Science* 171, 1008-13.

Sakamoto, M. (1966). Primary production by phytoplankton community in some Japanese lakes and its dependence on depth. *Arch. Hydrobiol.* 62, 1-28.

Sakamoto, M. (1971). Chemical factors involved in the control of phytoplankton production in the Experimental Lakes Area, Northwestern Ontario. *J. Fish. Res. Bd. Canada.* 28, 203-213.

Schindler, D.W. (1977). Evolution of phosphorus limitation in lakes. *Science* 195, 260-262.

Schindler, D.W; Kling, H; Schmidt, R.V; Pzokopowick, Y; Frost, V.E; Reid, R.A. and Capel, M. (1973). Eutrophication of Lake 227 by addition of phosphate and nitrate: the second, third and fourth years of enrichment, 1970, 1971, and 1972. *J. Fish. Res. Bd. Can.* 30, 1415-40.

Schmidt, G.W. (1972a). Amounts of suspended solids and dissolved substances in the middle reaches of the Amazon over the course of one year (August, 1969-July, 1970). *Amazoniana* 3, 208-23.

Schmidt, G.W. (1972b). Chemical properties of some waters in the tropical rain-forest region of central Amazonia along the new road Manaus-Caracarai. *Amazoniana* 3, 199-207.

Schmidt, G.W. (1973). Primary production of phytoplankton in three types of Amazonian waters: II. The limnology of a tropical flood-plain lake in central Amazonia, (Lago do Castanho). *Amazoniana* 4(2), 139-204.

Seaman, M.T; Scott, W.E; Walmsley, R.D; van der Waal, B.C.W. and Toerien, D.F. (1978). A limnological investigation of Lake Liambezi, Caprivi. *J. Limnol. Soc. Sth. Afr.* 4(2), 129-144.

Sze, P. (1975). Possible effect of lower phosphorus concentrations on the phytoplankton in Onondaga Lake, New York, U.S.A. *Phycologia* 14, 197-204.

Talling, J.F. (1963). Origin of stratification in an African Rift Lake. *Limnol. Oceanogr.* 8, 68-78.

Talling, J.F. (1966). The annual cycle of stratification and phytoplankton growth in Lake Victoria (East Africa). *Int. Rev. ges. Hydrobiol.* 51, 545-621.

Talling, J.F. and Talling, I.B. (1965). The chemical composition of African lake waters. *Int. Revue ges. Hydrobiol.* 50, 421-63.

Thomas, J.D. and Ratcliffe, P.J. (1973). Observations on the limnology and primary production of a small man-made lake in the West African savanna. *Freshwat. Biol.* 3, 573-612.

Timms, D.V. (1970). Chemical and zooplankton studies on lentic habitats of north-eastern New South Wales. *Aust. J. mar. Freshwat. Res.* 21,11-33.

Truesdale, V.W. (1974). The factors controlling the natural chemical composition of rivers - a critical review. *Proc. Challenger Soc.* 4(5), 229-31.

Tyler, P.A. (1974). Limnological studies. In: Williams, W.D. (Ed.) *Biogeography and Ecology in Tasmania, Monographia biologicae* 25, 29-61. Den Junk, The Hague.

45

Vallentyne, J.R. (1974). *The Algal Bowl: Lakes and Man.* Department of the Environment, Fisheries and Marine Service. Ottawa.

Vollenweider, R.A. (1968). Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication. *OECD Technical Report,* DAS/C31/68.27.

Walmsley, R.D. and Butty, M. (1980a). *The Limnology of Some Selected South African Impoundments.* Water Research Commission, Pretoria.

Walmsley, R.D. and Butty, M. (1980b). *Guidelines for the Control of Eutrophication in South Africa.* Water Research Commission, Pretoria.

Welch, E.B., Hendrey, G.R. and Stoll, R.K. (1975). Nutrient supply and production and biomass of algae in four Washington lakes. *Oikos* 26, 47-54.

Wetzel, R.G. (1975). *Limnology.* W.B. Saunders Co., Philadelphia.

Wetzel, R.G. and Likens, G.E. (1979). *Limnological analyses.* W.B. Saunders Co., Philadelphia.

Williams, W.D. (1967). The chemical characteristics of lentic surface waters in Australia. In: Weatherley, A.H. (Ed.) *Australian Inland Waters and Their Fauna: Eleven Studies.* A.N.U. Press, Canberra.

Williams, W.D. and Buckney, R.T. (1976). Chemical composition of some inland surface waters in south, western, and northern Australia. *Aust. J. mar. Freshwat. Res.* 27, 379-97.

Walker, T.D., Kirk, J.T.O. and Tyler, P.A. (1982). The Underwater Light Climate of Billabongs of the Alligator Rivers Region, Northern Territory. Office of the Supervising Scientist, Australian Government Publishing Service (in press).

Walker, T.D., Waterhouse, J., and Tyler, P.A. (1982). Thermal Stratification and the Distribution of Dissolved Oxygen in Billabongs of the Alligator Rivers Region, Northern Territory. Office of the Supervising Scientist, Australian Government Publishing Service (in press).

APPENDIX — SUMMARY OF BILLABONG WATER CHEMISTRY.

APPENDIX - TABLE.1..: Range of concentration of some chemical parameters for ..Mudginberri..billabong during..1978-81..

Parameter	Dry Season Range	n	Whole Year Range	n
Laboratory pH	5.7-7.0	19	4.9-7.0	31
Conductivity at 18°C (μScm^{-1})	14-190	19	11-190	31
Sodium (mgl^{-1})	1.0-25.1	19	0.7-25.1	31
Potassium (mgl^{-1})	0.2-2.0	19	0.16-2.0	31
Calcium (mgl^{-1})	0.2-1.1	19	0.2-1.1	31
Magnesium (mgl^{-1})	0.5-3.5	19	0.3-3.5	31
Chloride (mgl^{-1})	1.5-156.6	19	1.4-156.6	31
Sulphate (mgl^{-1})	0-6.7	19	0-6.7	31
Bicarbonate (mgl^{-1})	4.5-14.5	19	1.5-14.5	31
Orthophosphate-phosphorus (μgl^{-1})	3-43	16	1-43	22
'Organic' phosphorus (μgl^{-1})	2-51	15	2-51	21
Total phosphorus (μgl^{-1})	13-54	15	13-54	21
Ammonia (μgl^{-1})	1-31	16	1-31	22
Nitrate/Nitrite (μgl^{-1})	1-43	16	1-43	22
Organic nitrogen (μgl^{-1})	189-748	15	189-989	21
Total nitrogen (μgl^{-1})	199-756	15	199-1023	21

APPENDIX - TABLE..2..: Range of concentration of some chemical parameters for ...Buffalo.......billabong during..1978-9....

Parameter	Dry Season		Whole Year	
	Range	n	Range	n
Laboratory pH	5.9-6.4	6	5.9-6.5	9
Conductivity at 18°C (μScm^{-1})	20-28	6	13-28	9
Sodium (mgl^{-1})	1.7-2.0	6	1.1-2.0	9
Potassium (mgl^{-1})	0.3-0.4	6	0.3-0.4	9
Calcium (mgl^{-1})	0.2-0.5	6	0.2-0.5	9
Magnesium (mgl^{-1})	0.5-0.7	6	0.4-0.7	9
Chloride (mgl^{-1})	2.1-3.2	6	1.4-3.2	9
Sulphate (mgl^{-1})	0	6	0-0.5	9
Bicarbonate (mgl^{-1})	3.2-6.3	6	3.3-7.4	9
Orthophosphate-phosphorus (μgl^{-1})				
'Organic' phosphorus (μgl^{-1})				
Total phosphorus (μgl^{-1})				
Ammonia (μgl^{-1})				
Nitrate/Nitrite (μgl^{-1})				
Organic nitrogen (μgl^{-1})				
Total nitrogen (μgl^{-1})				

APPENDIX - TABLE.3..: Range of concentration of some chemical parameters for ..Nourlangie.....billabong during..1979-81..

Parameter	Dry Season Range	n	Whole Year Range	n
Laboratory pH	5.9-7.0	13	5.8-7.0	17
Conductivity at 18°C (μScm^{-1})	23-53	13	13-53	19
Sodium (mgl^{-1})	1.40-6.0	13	0.9-6.0	19
Potassium (mgl^{-1})	0.3-1.1	13	0.1-1.1	19
Calcium (mgl^{-1})	0.5-0.8	13	0.2-0.8	19
Magnesium (mgl^{-1})	1.1-1.3	13	0.4-1.3	19
Chloride (mgl^{-1})	2.3-10.3	13	1.3-10.3	17
Sulphate (mgl^{-1})	0-2.5	13	0-2.5	17
Bicarbonate (mgl^{-1})	4.9-12.0	13	3.8-12.0	17
Orthophosphate-phosphorus (μgl^{-1})	2-22	11	2-22	17
'Organic' phosphorus (μgl^{-1})	6-35	11	4-35	17
Total phosphorus (μgl^{-1})	20-37	11	12-37	17
Ammonia (μgl^{-1})	1-24	12	1-24	17
Nitrate/Nitrite (μgl^{-1})	2-83	12	2-113	17
Organic nitrogen (μgl^{-1})	205-637	12	205-925	17
Total nitrogen (μgl^{-1})	223-655	12	223-943	17

APPENDIX - TABLE..4..: Range of concentration of some chemical parameters for ..Nimbuwah...billabong during..1980-81...

Parameter	Dry Season Range	n	Whole Year Range	n
Laboratory pH	6.5-6.9	6	6.3-6.9	8
Conductivity at 18^{o}C (μScm^{-1})	44-80	6	28-38	8
Sodium (mgl^{-1})	2.9-7.1	5	2.2-7.1	7
Potassium (mgl^{-1})	0.7-1.8	5	0.4-1.8	7
Calcium (mgl^{-1})	1.2-1.8	5	0.6-1.8	7
Magnesium (mgl^{-1})	1.5-3.0	5	0.9-3.0	7
Chloride (mgl^{-1})	4.5-8.3	5	No 'wet' data	
Sulphate (mgl^{-1})	0.5-3.0	5	No 'wet' data	
Bicarbonate (mgl^{-1})	14.6-30.0	5	No 'wet' data	
Orthophosphate-phosphorus (μgl^{-1})	5-31	5	5-31	7
'Organic' phosphorus (μgl^{-1})	4-22	5	4-23	7
Total phosphorus (μgl^{-1})	22-35	5	22-35	7
Ammonia (μgl^{-1})	10-41	5	5-41	7
Nitrate/Nitrite (μgl^{-1})	1-51	5	1-51	7
Organic nitrogen (μgl^{-1})	166-760	5	166-760	7
Total nitrogen (μgl^{-1})	177-771	5	177-771	7

APPENDIX - TABLE..5..: Range of concentration of some chemical parameters for ..Mragarella.....billabong during...1980-81..

Parameter	Dry Season		Whole Year	
	Range	n	Range	n
Laboratory pH	6·4-6·7	5	6·1-6·8	8
Conductivity at 18^{0}C (μScm^{-1})	32-120	5	22-120	8
Sodium (mgl^{-1})	4·7-7·6	4	1·8-7·6	7
Potassium (mgl^{-1})	1·1-5·5	4	0·3-5·5	7
Calcium (mgl^{-1})	2·1-3·7	4	0·4-3·7	7
Magnesium (mgl^{-1})	2·4-4·1	4	0·5-4·1	7
Chloride (mgl^{-1})	8·7-16·3	4	No 'wet' data	
Sulphate (mgl^{-1})	0·1-2·4	4	No 'wet' data	
Bicarbonate (mgl^{-1})	21·8-30·6	4	No 'wet' data	
Orthophosphate-phosphorus (μgl^{-1})	3-29	4	3-29	6
'Organic' phosphorus (μgl^{-1})	20-45	4	14-23	6
Total phosphorus (μgl^{-1})	23-74	4	23-74	6
Ammonia (μgl^{-1})	13-674	4	8-674	6
Nitrate/Nitrite (μgl^{-1})	5-8	4	4-8	6
Organic nitrogen (μgl^{-1})	252-726	4	252-726	6
Total nitrogen (μgl^{-1})	269-1408	4	269-1408	6

APPENDIX - TABLE..6..: Range of concentration of some chemical parameters for ...Bowerbird.....billabong during..1978-81...

Parameter	Dry Season Range	n	Whole Year Range	n
Laboratory pH	5·8-6·8	12	5·8-6·8	14
Conductivity at 18°C (μScm^{-1})	16-30	12	10-30	15
Sodium (mgl^{-1})	1·1-1·9	12	1·0-1·9	15
Potassium (mgl^{-1})	0·2-0·6	12	0·2-0·6	15
Calcium (mgl^{-1})	0-0·5	12	0-0·5	15
Magnesium (mgl^{-1})	0·7-0·9	12	0·2-0·9	15
Chloride (mgl^{-1})	1·9-7·2	12	1·8-7·2	14
Sulphate (mgl^{-1})	0-1·6	12	0-1·6	14
Bicarbonate (mgl^{-1})	4·0-14·2	12	4·0-14·2	14
Orthophosphate-phosphorus (μgl^{-1})	3-8	7	3-31	9
'Organic' phosphorus (μgl^{-1})	5-26	6	5-26	8
Total phosphorus (μgl^{-1})	10-33	6	10-33	8
Ammonia (μgl^{-1})	4-8	7	2-8	9
Nitrate/Nitrite (μgl^{-1})	1-29	7	1-29	9
Organic nitrogen (μgl^{-1})	250-491	7	241-291	9
Total nitrogen (μgl^{-1})	258-524	7	25[illegible]-524	9

APPENDIX - TABLE..7..: Range of concentration of some chemical parameters for ...Goanna......billabong during..1978-81...

Parameter	Dry Season Range	n	Whole Year Range	n
Laboratory pH	6.0 - 7.3	20	6.0 - 7.3	24
Conductivity at 18°C (μScm^{-1})	28 - 113	20	12 - 113	26
Sodium (mgl^{-1})	3.8 - 13.8	20	0.9 - 13.8	26
Potassium (mgl^{-1})	0.7 - 3.9	20	0.4 - 3.9	26
Calcium (mgl^{-1})	0.3 - 1.4	20	0.3 - 1.4	26
Magnesium (mgl^{-1})	0.4 - 1.7	20	0.4 - 1.7	26
Chloride (mgl^{-1})	3.0 - 17.2	20	0.5 - 17.2	24
Sulphate (mgl^{-1})	0 - 3.7	19	0 - 3.7	23
Bicarbonate (mgl^{-1})	6.5 - 27.0	20	6.5 - 27.0	24
Orthophosphate-phosphorus (μgl^{-1})	14 - 147	11	7 - 147	17
'Organic' phosphorus (μgl^{-1})	12 - 337	11	3 - 337	17
Total phosphorus (μgl^{-1})	28 - 458	11	9 - 458	17
Ammonia (μgl^{-1})	11 - 256	12	6 - 256	18
Nitrate/Nitrite (μgl^{-1})	2 - 175	12	2 - 175	18
Organic nitrogen (μgl^{-1})	370 - 4517	12	169 - 4517	18
Total nitrogen (μgl^{-1})	391 - 4592	12	177 - 4592	18

APPENDIX - TABLE..9..: Range of concentration of some chemical parameters for ..Island.......billabong during..1978-81..

Parameter	Dry Season Range	n	Whole Year Range	n
Laboratory pH	2.7 - 6.9	25	2.7 - 6.9	32
Conductivity at 18°C (μScm^{-1})	15 - 453	25	11 - 453	33
Sodium (mgl^{-1})	1.4 - 9.5	25	0.8 - 9.5	33
Potassium (mgl^{-1})	0.2 - 1.4	25	0.2 - 1.4	33
Calcium (mgl^{-1})	0 - 1.1	25	0 - 1.1	33
Magnesium (mgl^{-1})	0.4 - 1.6	25	0.4 - 1.6	33
Chloride (mgl^{-1})	1.5 - 7.2	25	1.3 - 7.2	32
Sulphate (mgl^{-1})	0 - 127.7	25	0 - 127.7	31
Bicarbonate (mgl^{-1})	0 - 11.3	25	0 - 11.3	32
Orthophosphate-phosphorus (μgl^{-1})	3 - 41	22	3 - 41	25
'Organic' phosphorus (μgl^{-1})	7 - 62	21	5 - 62	24
Total phosphorus (μgl^{-1})	13 - 74	21	13 - 74	24
Ammonia (μgl^{-1})	1 - 97	22	1 - 97	26
Nitrate/Nitrite (μgl^{-1})	0 - 125	22	0 - 125	26
Organic nitrogen (μgl^{-1})	211 - 843	21	211 - 843	25
Total nitrogen (μgl^{-1})	215 - 851	21	215 - 851	25

APPENDIX - TABLE..9..: Range of concentration of some chemical parameters for ..Kulukuluku...billabong during..1979-81..

Parameter	Dry Season Range	Dry Season n	Whole Year Range	Whole Year n
Laboratory pH	5.2-7.0	13	5.2-7.0	15
Conductivity at 18°C (μScm^{-1})	10-74	13	10-74	16
Sodium (mgl^{-1})	2.3-7.6	9	1.0-7.6	12
Potassium (mgl^{-1})	0.6-1.2	9	0.3-1.2	12
Calcium (mgl^{-1})	0.4-1.8	9	0.4-1.8	12
Magnesium (mgl^{-1})	1.2-2.0	9	0.5-2.0	12
Chloride (mgl^{-1})	4.2-16.2	9	1.7-16.2	11
Sulphate (mgl^{-1})	1.0-3.3	9	1.0-3.3	11
Bicarbonate (mgl^{-1})	10.0-12.4	9	5.5-12.4	11
Orthophosphate-phosphorus (μgl^{-1})	1-39	13	1-39	15
'Organic' phosphorus (μgl^{-1})	2-46	13	2-46	15
Total phosphorus (μgl^{-1})	16-54	13	15-54	15
Ammonia (μgl^{-1})	5-23	13	3-23	15
Nitrate/Nitrite (μgl^{-1})	1-59	13	1-59	15
Organic nitrogen (μgl^{-1})	274-985	13	274-985	15
Total nitrogen (μgl^{-1})	285-1008	13	285-1002	15

APPENDIX - TABLE..10..: Range of concentration of some chemical parameters for ..Georgetown.....billabong during..1978-81..

Parameter	Dry Season Range	n	Whole Year Range	n
Laboratory pH	5.6 – 7.0	13	5.1 – 7.1	26
Conductivity at 18°C (μScm^{-1})	27-90	13	10-90	28
Sodium (mgl^{-1})	2.0-10.0	13	0.6-10.0	28
Potassium (mgl^{-1})	0.3-3.0	13	0.3-3.0	28
Calcium (mgl^{-1})	0.1-1.2	13	0.1-0.9	28
Magnesium (mgl^{-1})	0.5-1.9	13	0.3-1.9	28
Chloride (mgl^{-1})	1.7-13.2	13	1.2-13.2	26
Sulphate (mgl^{-1})	0-5.3	13	0-5.3	26
Bicarbonate (mgl^{-1})	2.8-14.1	13	1.6-14.7	26
Orthophosphate-phosphorus (μgl^{-1})	12-335	7	3-335	17
'Organic' phosphorus (μgl^{-1})	14-490	7	9-490	15
Total phosphorus (μgl^{-1})	36-559	7	16-559	17
Ammonia (μgl^{-1})	9-115	10	4-115	20
Nitrate/Nitrite (μgl^{-1})	1-650	10	1-1175	20
Organic nitrogen (μgl^{-1})	133-4545	10	133-4545	20
Total nitrogen (μgl^{-1})	169-5310	10	169-5310	20

APPENDIX - TABLE..11..: Range of concentration of some chemical parameters for ..Coonjimba...billabong during..1978-9...

Parameter	Dry Season Range	n	Whole Year Range	n
Laboratory pH	6.4-6.8	6	6.4-7.0	10
Conductivity at 18°C (μScm^{-1})	22-100	6	19-100	11
Sodium (mgl^{-1})	3.0-16.2	6	1.4-16.2	11
Potassium (mgl^{-1})	0.4-4.6	6	0.4-4.6	11
Calcium (mgl^{-1})	0.1-0.6	6	0.1-0.8	11
Magnesium (mgl^{-1})	0.2-0.6	6	0.2-0.7	11
Chloride (mgl^{-1})	1.3-26.5	6	1.3-26.5	11
Sulphate (mgl^{-1})	0-3.1	6	0-3.1	11
Bicarbonate (mgl^{-1})	0.2-14.5	6	0.2-14.5	11
Orthophosphate-phosphorus (μgl^{-1})				
'Organic' phosphorus (μgl^{-1})				
Total phosphorus (μgl^{-1})				
Ammonia (μgl^{-1})				
Nitrate/Nitrite (μgl^{-1})				
Organic nitrogen (μgl^{-1})				
Total nitrogen (μgl^{-1})				

APPENDIX - TABLE..12..: Range of concentration of some chemical parameters for ..Gulungul.....billabong during..1978-81..

Parameter	Dry Season Range	n	Whole Year Range	n
Laboratory pH	3.4-7.1	23	3.4-7.1	30
Conductivity at 18°C (μScm^{-1})	22-523	23	15-523	32
Sodium (mgl^{-1})	2.0-25.9	23	1.2-25.9	32
Potassium (mgl^{-1})	0.2-9.4	23	0.2-9.4	32
Calcium (mgl^{-1})	0.1-4.7	23	0-4.7	32
Magnesium (mgl^{-1})	0.5-5.7	23	0.4-5.7	32
Chloride (mgl^{-1})	2.2-106.8	23	0.9-106.9	30
Sulphate (mgl^{-1})	0-9.6	23	0-9.6	30
Bicarbonate (mgl^{-1})	0-15.4	23	0-15.4	30
Orthophosphate-phosphorus (μgl^{-1})	4-136	19	1-136	25
'Organic' phosphorus (μgl^{-1})	12-908	19	8-908	25
Total phosphorus (μgl^{-1})	21-978	19	16-978	25
Ammonia (μgl^{-1})	2-2700	19	2-2700	25
Nitrate/Nitrite (μgl^{-1})	0-1050	19	0-1050	25
Organic nitrogen (μgl^{-1})	150-7791	18	150-7791	25
Total nitrogen (μgl^{-1})	231-11597	19	231-11597	25

APPENDIX - TABLE. 13..: Range of concentration of some chemical parameters for ..Corndorl.....billabong during...1978-9...

Parameter	Dry Season		Whole Year	
	Range	n	Range	n
Laboratory pH	5·2-6·2	4	5·2-6·8	7
Conductivity at 18^{o}C (μScm^{-1})	20-210	4	12-210	7
Sodium (mgl^{-1})	3·9-23·8	5	0·6-23·8	8
Potassium (mgl^{-1})	1·2-7·0	5	0·6-7·0	8
Calcium (mgl^{-1})	0·6-3·7	5	0·3-3·7	8
Magnesium (mgl^{-1})	0·7-3·1	5	0·4-3·1	8
Chloride (mgl^{-1})	2·6-47·7	5	0-47·7	8
Sulphate (mgl^{-1})	0-10·3	5	0-10·3	8
Bicarbonate (mgl^{-1})	1·0-11·4	5	1·0-16·0	8
Orthophosphate-phosphorus (μgl^{-1})				
'Organic' phosphorus (μgl^{-1})				
Total phosphorus (μgl^{-1})				
Ammonia (μgl^{-1})				
Nitrate/Nitrite (μgl^{-1})				
Organic nitrogen (μgl^{-1})				
Total nitrogen (μgl^{-1})				

APPENDIX - TABLE..14..: Range of concentration of some chemical parameters for .[illegible]...billabong during..1979-81..

Parameter	Dry Season Range	Dry Season n	Whole Year Range	Whole Year n
Laboratory pH	4.3 - 7.1	17	4.3 - 7.1	19
Conductivity at 18°C (μScm^{-1})	20 - 1290	18	12 - 1290	21
Sodium (mgl^{-1})	1.6 - 108.1	18	0.9 - 108.1	21
Potassium (mgl^{-1})	0.4 - 48.8	18	0.2 - 48.8	21
Calcium (mgl^{-1})	0 - 12.6	18	0 - 12.6	21
Magnesium (mgl^{-1})	0.9 - 15.6	18	0.4 - 15.6	21
Chloride (mgl^{-1})	1.9 - 355.0	17	0.6 - 355.0	19
Sulphate (mgl^{-1})	0 - 39.9	17	0 - 39.9	19
Bicarbonate (mgl^{-1})	0 - 27.0	17	0 - 27.0	19
Orthophosphate-phosphorus (μgl^{-1})	7 - 382	15	2 - 382	18
'Organic' phosphorus (μgl^{-1})	8 - 878	15	8 - 878	18
Total phosphorus (μgl^{-1})	20 - 1182	15	13 - 1182	18
Ammonia (μgl^{-1})	1 - 3115	15	1 - 3115	18
Nitrate/Nitrite (μgl^{-1})	1 - 41	15	1 - 41	18
Organic nitrogen (μgl^{-1})	122 - 14594	14	122 - 14594	17
Total nitrogen (μgl^{-1})	122 - 26115	15	122 - 26115	18

APPENDIX - TABLE..15..: Range of concentration of some chemical parameters for ...Ja.Ja.......billabong during..1978-81..

Parameter	Dry Season Range	n	Whole Year Range	n
Laboratory pH	3.2 - 6.7	16	3.2 - 6.7	21
Conductivity at 18°C (μScm^{-1})	12 - 450	16	12 - 450	22
Sodium (mgl^{-1})	1.2 - 14.5	17	0.9 - 14.5	23
Potassium (mgl^{-1})	0.2 - 6.8	17	0.2 - 6.8	23
Calcium (mgl^{-1})	0.1[illegible] - 6.3	17	0.[illegible] - 6.3	23
Magnesium (mgl^{-1})	0.4 - 9.5	17	0.4 - 9.5	23
Chloride (mgl^{-1})	1.1 - 23.4	17	1.1 - 23.4	22
Sulphate (mgl^{-1})	0 - 26.5	17	0 - 26.5	5
Bicarbonate (mgl^{-1})	0 - 11.4	17	0 - 11.4	22
Orthophosphate-phosphorus (μgl^{-1})	3 - 73	10	3 - 73	13
'Organic' phosphorus (μgl^{-1})	8 - 171	10	8 - 171	13
Total phosphorus (μgl^{-1})	13 - 270	10	13 - 270	13
Ammonia (μgl^{-1})	3 - 1474	10	3 - 1474	13
Nitrate/Nitrite (μgl^{-1})	2 - 905	10	2 - 905	13
Organic nitrogen (μgl^{-1})	152 - 2734	10	152 - 2734	13
Total nitrogen (μgl^{-1})	157 - 5113	10	157 - 5113	13

APPENDIX - TABLE.16..: Range of concentration of some chemical parameters for .Mine.Valley.....billabong during..1979-81..

Parameter	Dry Season Range	n	Whole Year Range	n
Laboratory pH	3.4 - 7.0	17	3.4 - 7.0	19
Conductivity at 18°C (μScm^{-1})	16 - 1380	17	12 - 1380	21
Sodium (mgl^{-1})	1.3 - 98.0	17	0.8 - 98.0	21
Potassium (mgl^{-1})	0.2 - 20.4	17	0.2 - 20.4	21
Calcium (mgl^{-1})	0 - 26.2	17	0 - 26.2	21
Magnesium (mgl^{-1})	0.9 - 64.2	17	0.6 - 64.2	21
Chloride (mgl^{-1})	2.8 - 164.7	17	1.6 - 164.7	19
Sulphate (mgl^{-1})	1.1 - 215.0	17	1.1 - 215.0	19
Bicarbonate (mgl^{-1})	0 - 12.3	16	0 - 12.3	18
Orthophosphate-phosphorus (μgl^{-1})	3 - 66	16	1 - 66	20
'Organic' phosphorus (μgl^{-1})	13 - 124	16	8 - 124	20
Total phosphorus (μgl^{-1})	17 - 178	16	13 - 178	20
Ammonia (μgl^{-1})	4 - 3717	14	0 - 3717	18
Nitrate/Nitrite (μgl^{-1})	1 - 165	14	1 - 165	18
Organic nitrogen (μgl^{-1})	218 - 17800	14	218 - 17800	18
Total nitrogen (μgl^{-1})	232 - 21528	14	232 - 21528	18

APPENDIX - TABLE 17 : Range of concentration of some chemical parameters for Leichhardt billabong during 1978-81

Parameter	Dry Season Range	n	Whole Year Range	n
Laboratory pH	4·3 – 7·1	26	4·3 – 7·1	30
Conductivity at 18°C (μScm^{-1})	15 – 1290	26	14 – 1290	32
Sodium (mgl^{-1})	1·3 – 114·5	26	1·1 – 114·5	32
Potassium (mgl^{-1})	0·4 – 27·3	26	0·2 – 27·3	32
Calcium (mgl^{-1})	0·2 – 5·4	26	0·2 – 5·4	32
Magnesium (mgl^{-1})	0·5 – 26·5	26	0·4 – 26·5	32
Chloride (mgl^{-1})	1·6 – 342·5	26	1·6 – 342·5	30
Sulphate (mgl^{-1})	0 – 48·0	26	0 – 48·0	30
Bicarbonate (mgl^{-1})	0 – 15·6	26	0 – 15·6	30
Orthophosphate-phosphorus (μgl^{-1})	2 – 51	19	2 – 51	22
'Organic' phosphorus (μgl^{-1})	8 – 104	19	3 – 104	22
Total phosphorus (μgl^{-1})	10 – 155	19	10 – 155	22
Ammonia (μgl-1)	1 – 644	19	1 – 644	22
Nitrate/Nitrite (μgl^{-1})	0 – 1500	19	0 – 1500	22
Organic nitrogen (μgl^{-1})	250 – 1933	19	112 – 1933	22
Total nitrogen (μgl^{-1})	258 – 3087	19	117 – 3087	22

APPENDIX - TABLE..18..: Range of concentration of some chemical parameters for ...Jabiluka......billabong during..1978-81..

Parameter	Dry Season		Whole Year	
	Range	n	Range	n
Laboratory pH	4.1-6.8	23	4.1-6.8	29
Conductivity at 18°C (μScm^{-1})	19-196	23	13-196	29
Sodium (mgl^{-1})	1.5-17.0	23	0.9-17.0	29
Potassium (mgl^{-1})	0.3-5.0	23	0.2-5.0	29
Calcium (mgl^{-1})	0-3.1	23	0.3-3.1	29
Magnesium (mgl^{-1})	0.6-4.1	23	0.4-4.1	29
Chloride (mgl^{-1})	1.9-28.4	23	1.7-28.4	29
Sulphate (mgl^{-1})	0-26.8	23	0-26.8	29
Bicarbonate (mgl^{-1})	0-13.4	23	0-13.4	29
Orthophosphate-phosphorus (μgl^{-1})	2-38	13	2-38	15
'Organic' phosphorus (μgl^{-1})	8-161	13	8-161	15
Total phosphorus (μgl^{-1})	10-197	13	10-197	15
Ammonia (μgl^{-1})	3-681	13	3-681	15
Nitrate/Nitrite (μgl^{-1})	2-680	13	2-680	15
Organic nitrogen (μgl^{-1})	207-1450	13	207-1450	15
Total nitrogen (μgl^{-1})	284-2333	13	284-2333	15

APPENDIX - TABLE..19..: Range of concentration of some chemical parameters for ...Nankeen.....billabong during..1978-81...

Parameter	Dry Season Range	n	Whole Year Range	n
Laboratory pH	4.2-6.8	14	4.2-6.8	18
Conductivity at 18°C (μScm^{-1})	23-286	14	12-286	20
Sodium (mgl^{-1})	2.1-27.4	14	0.7-27.4	20
Potassium (mgl^{-1})	0.3-5.8	14	0.2-5.8	20
Calcium (mgl^{-1})	0.2-5.4	14	0.2-5.4	20
Magnesium (mgl^{-1})	0.7-5.4	14	0.3-5.4	20
Chloride (mgl^{-1})	3.5-59.7	14	1.8-59.7	18
Sulphate (mgl^{-1})	0.5-41.8	14	0.5-41.9	18
Bicarbonate (mgl^{-1})	0-9.9	14	0-9.9	18
Orthophosphate-phosphorus (μgl^{-1})	1-70	10	0-70	14
'Organic' phosphorus (μgl^{-1})	16-443	10	5-443	14
Total phosphorus (μgl^{-1})	19-444	10	11-444	14
Ammonia (μgl-1)	1-1209	10	1-1209	14
Nitrate/Nitrite (μgl^{-1})	1-1300	10	1-1300	14
Organic nitrogen (μgl^{-1})	533-1773	10	153-1773	14
Total nitrogen (μgl^{-1})	535-3301	10	156-1036	14

APPENDIX - TABLE.20.: Range of concentration of some chemical parameters for ..Jingalla.......billabong during..1979-81...

Parameter	Dry Season Range	n	Whole Year Range	n
Laboratory pH	4.2 - 7.7	8	4.2 - 7.7	11
Conductivity at 18°C (μScm^{-1})	105 - 6910	8	20 - 6910	12
Sodium (mgl^{-1})	10.9 - 936.1	8	1.4 - 936.1	12
Potassium (mgl^{-1})	1.4 - 39.0	8	0.3 - 39.0	12
Calcium (mgl^{-1})	0.6 - 66.0	8	0.5 - 66.0	12
Magnesium (mgl^{-1})	2.7 - 174.5	8	0.5 - 174.5	12
Chloride (mgl^{-1})	21.3 - 1963.3	8	2.5 - 1963.3	11
Sulphate (mgl^{-1})	1.9 - 111.9	8	1.9 - 111.9	11
Bicarbonate (mgl^{-1})	0 - 45.0	8	0 - 45.0	11
Orthophosphate-phosphorus (μgl^{-1})	4 - 90	7	1 - 90	12
'Organic' phosphorus (μgl^{-1})	14 - 283	7	14 - 283	12
Total phosphorus (μgl^{-1})	27 - 295	7	16 - 295	12
Ammonia (μgl^{-1})	9 - 1088	9	3 - 1088	14
Nitrate/Nitrite (μgl^{-1})	1 - 35	9	1 - 35	14
Organic nitrogen (μgl^{-1})	280 - 1926	9	253 - 1926	14
Total nitrogen (μgl^{-1})	307 - 3049	9	264 - 3049	14

APPENDIX - TABLE. 21..: Range of concentration of some chemical parameters for ...Red Lily......billabong during...1979-81.

Parameter	Dry Season Range	n	Whole Year Range	n
Laboratory pH	7·1-8·2	7	6·0-8·2	11
Conductivity at 13°C (μScm^{-1})	98-339	7	50-339	11
Sodium (mgl^{-1})	3·6-23	7	1·6-23·0	11
Potassium (mgl^{-1})	0·5-11·4	7	0·4-11·4	11
Calcium (mgl^{-1})	0·7-13·5	7	0·7-13·5	11
Magnesium (mgl^{-1})	3·1-10·0	7	1·0-10·0	11
Chloride (mgl^{-1})	4·3-31·2	7	2·3-31·2	11
Sulphate (mgl^{-1})	0·8-4·2	7	0·8-8·5	11
Bicarbonate (mgl^{-1})	53·9-153·1	7	15·9-153·1	11
Orthophosphate-phosphorus (μgl^{-1})	16-33	7	8-77	12
'Organic' phosphorus (μgl^{-1})	20-61	7	2-88	12
Total phosphorus (μgl^{-1})	34-83	7	13-132	12
Ammonia (μgl^{-1})	1-169	7	1-169	12
Nitrate/Nitrite (μgl^{-1})	2-20	7	1-20	12
Organic nitrogen (μgl^{-1})	442-1193	7	442-1193	12
Total nitrogen (μgl^{-1})	451-1224	7	451-1224	12