

Limnological studies on the Pretoria Salt Pan, a hypersaline maar lake

I: Morphometric, physical and chemical features

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Abstract

The Pretoria Salt Pan is shallow (maximum depth 2.85 m) and alkaline (surface water pH varied from 9.6 to 10.9) with pronounced mesothermy (38.2 °C in spring) at a depth of between 0.55 and 0.7 metres. Secchi disc transparencies ranged from 7 to 19 cm. A total ionic concentration gradient increasing from 59 500 mg · l⁻¹ near the surface to 298 000 mg · l⁻¹ at 2.75 metres stabilized the thermally inverted water column. Sodium was the major cation and nearly equal proportions of chloride plus carbonate and bicarbonate accounted for over 98% of the anions. The lake was meromictic with a steep chemocline, persistent thermally inverted temperature profile and complete anoxia at depths greater than 50 cm. The diel pattern of dissolved oxygen distribution involving a nocturnal deoxygenation and diurnal reoxygenation was unusual.

Introduction

Endorheic or closed drainage basins are widely distributed in many climatic conditions. Where evaporation exceeds precipitation, closed lakes within the basins become saline, particularly if they receive inflows sufficient to maintain a standing body of water. The process accelerates when the inflowing water contains high solute loads. When the concentration of salts by evaporation becomes sufficiently high, salt deposition occurs. Although salt lakes occur on every continent, and are economically significant as sources of important chemicals and scientifically useful as sensitive indicators of past tectonic and climatic events, few extensive studies have been carried out on them. This is regrettable, since they can reveal much about processes under extreme conditions and also improve our understanding of normal lakes (Eugster & Hardie 1978).

Those saline lakes most studied occur in Africa, Australia, North America and Asia. Prominent recent studies include those of Beadle (1966), Arad &

Morton (1969), Aleem & Samaan (1969), Melack & Kilham (1972, 1974), Talling *et al.* (1973) and Melack (1978, 1979) in Africa; Bayly & Williams (1966), Bayly (1969), Walker (1973) and Williams (1964, 1978) in Australia; Anderson (1958), Wetzel (1964), Kibby *et al.* (1968), Barica (1978), Axler *et al.* (1978), Hammer (1978a, 1978b) and Hammer & Haynes (1978) in North America; Hutchinson (1937a), Löffler (1961) and Cohen *et al.* (1977) in Asia. The chemical and mineralogical aspects of several classes of saline lakes have been thoroughly reviewed by Eugster & Hardie (1978). From these studies, it is evident that saline lakes, as a group, are extremely diverse in their origin, biology and chemical composition and possess a number of unique features.

Saline lakes in semi-arid regions of volcanic activity are of particular interest because of features of their hydrochemistry (Prosser *et al.* 1968; Melack & Kilham 1972), a very restricted biota (Talling & Talling 1965), high rates of primary production (Talling *et al.* 1973; Melack & Kilham 1974) or a combination of these phenomena. Hutchinson

(1957) recognized the distinctive mode of origin of volcanic lakes, and distinguished six classes within the group. The most important of these are caldera lakes (type 12), occupying collapsed magma chambers, and maar lakes (type 11), which are often very much smaller than caldera lakes and occupy explosion craters (Ollier 1967). Some of the best-known maar lakes are to be found in and around the East African Rift Valley. Among these lakes there is considerable variation in depth, degree of wind shelter, insolation, temperature, nature and concentrations of dissolved solutes, and productivity.

Several of the East African maar lakes have been investigated limnologically, though with varying degrees of thoroughness. These studies have included descriptions of physical features such as morphometry, temperature and oxygen stratification, density gradients and meromixis (Beadle 1966; Melack & Kilham 1972; Wood *et al.* 1976; Melack 1978) and primary productivity studies (Talling *et al.* 1973; Melack & Kilham 1974; Melack 1979). The extreme variability in chemical composition of these lakes has been highlighted by the studies of Talling & Talling (1965), Beadle (1966), Arad & Morton (1969), Melack & Kilham (1972) and Hecky & Kilham (1973).

Although there are numerous volcanic crater lakes in East Africa, there is only a single maar lake in southern Africa. This lake, the Pretoria Salt Pan, lies near Pretoria in the Transvaal Province of South Africa. A preliminary investigation in February 1978 showed the lake to be shallow, meromictic and hypersaline, with high levels of trace elements and dense populations of bacteria and cyanobacteria. The lake's small size, ease of access, and unusual hydrochemistry prompted a further study aimed at obtaining a better understanding of the functioning of the lake as an ecosystem. In this paper we report on the morphometry and physico-chemical limnology of the lake, viewed as an essential background to the biological studies. The results of studies on the bacteria and phytoplankton will be reported later.

The study area

The Pretoria Salt Pan is located at 25°24'S and 28°05'E, some 50 km north of Pretoria in the Transvaal Province of South Africa (Fig. 1). The

lake is small (0.07 km² in area) and lies at an altitude of 1045 m above sea level (Wagner 1922) within a clearly defined crater. The crater rim is approximately circular in outline, 1.1 km in diameter and varies in height between 75 and 123 m above the high water level. The vegetation on the steep inner slopes of the crater is similar to that of the surrounding countryside – grassland mixed with deciduous forest dominated by species of *Acacia* and *Combretum* (Acocks 1975). Each year the region receives between 400 and 750 mm of rain, mainly in the form of localized thunderstorms during the months October to April. Monthly maximum and minimum air temperatures at the lake varied from 14.2 to 35.2 °C and -3.6 to 20.0 °C, respectively (Weather Bureau, unpubl. data).

The geology of the region forms part of the Bushveld Igneous Complex and is characterized by orthoclase granites, tuffs, breccias and feldspars (Wagner 1922). Soils on the inner slopes of the crater are coarse sandy loams grading to dark brown organic clays around the lake margin. These organic clays are unvegetated, fringed by coalescing alluvial fans, and are inundated only during rare periodic exceptionally high water levels. Borings carried out in the crater floor during the 1920's revealed brines, organic clays intercalated with layers of brucite, crystals of trona, halite and gaylussite to a depth of at least 80 metres (Wagner 1922). One boring struck a perennial source of water at a depth of approximately 150 metres. Since this bore is about 10 metres below the water table in the surrounding countryside, it now acts as an artesian spring.

In historical times, the brines and evaporite deposits of the lake were used as a source of 'salt'. Sodium salt and trona were commercially extracted during the early part of the twentieth century (Wagner 1922). The development of cheaper alternative sources of salt made the venture economically unpractical and the diggings were abandoned during the 1930's. Subsequent flooding of the diggings by the artesian spring created a small permanent pond. During the 1930's, a promontory was built to the east of the artesian spring from the northwest shore to facilitate access.

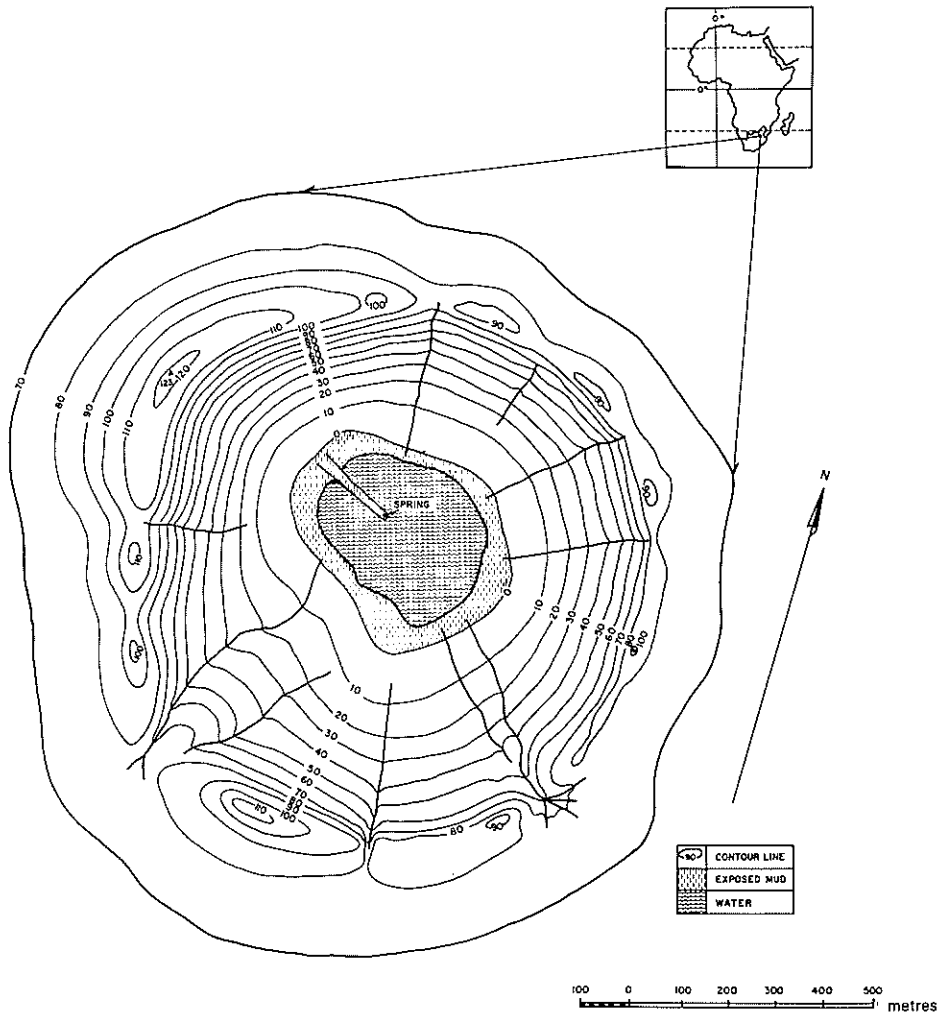


Fig. 1. Map showing location of the Pretoria Salt Pan and morphometry of the crater. Contour intervals are in metres above edge of exposed mud (O).

Materials and methods

Morphometry and bathymetry

The lake and crater were surveyed during high water in March 1978 with a standard dumpy level and plane table, using the artesian spring as datum point. To determine the bathymetry, 50 fixed points were staked around the lake perimeter and the water depth plumbed with a weighted line at 1 m intervals along 28 transects across the lake. From these measurements, a bathymetric map was drawn (Fig. 2) and hypsographic relationships between

depth, area and volume were derived by planimetry. Monthly variations in lake depth were recorded at a fixed marker and changes in area and volume were calculated from the hypsograph plots.

Measurement of water inflow

A flexible connection, consisting of a wide-necked plastic bottle with its base removed and attached by its neck to a length of rubber piping was used to measure artesian spring flow rates. The bottle was clamped to the protruding bore casing and outflowing water collected in a calibrated

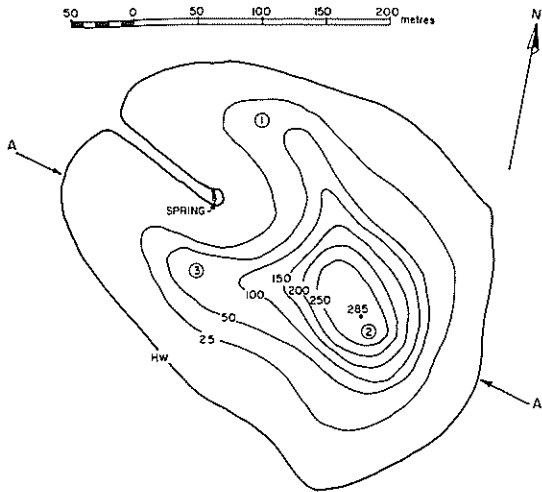


Fig. 2. Bathymetric map of the Pretoria Salt Pan showing location of sampling sites 1, 2 and 3. Contour intervals are in centimetres below the high water mark (HW). A-A' indicates longest transect.

bucket. The mean of five measurements of the time taken to fill the bucket to the 20 litre mark was used to calculate daily flow rates at each sampling trip. Total rainfall and evaporation were calculated from unpublished data provided by the South African Weather Bureau.

Sampling frequency and sample collection

Samples of the artesian spring and lake waters were collected at intervals of approximately 30 days for a period of 28 months from February 1978 to May 1980. In the lake, samples were collected at depths of 5 and 20 cm below the surface at the two shallow stations (1 and 3) and at 5, 25, 50, 75, 100, 150, 200, 250 and 275 cm at the deepest point (station 2; Fig. 2). At this deep station, samples were collected with a 5 l capacity, horizontally-mounted, opaque plastic Van Dorn bottle. At the two shallow stations, samples were collected with a corked 2 l capacity bottle attached to a calibrated rod. Two 2 l capacity polyethylene bottles of water were collected from the inflow and at each depth sampled in the lake. These were stored on ice in the dark until return to the laboratory. One millilitre of concentrated HgCl_2 was added to one bottle of each pair immediately after collection to preserve nitrogen and phosphorus compounds.

Field measurements

At the three lake stations, water temperature were measured at 5 cm intervals from the surface to the bottom with a Yellow Springs Model YS thermistor probe. Dissolved oxygen values were also measured at 5 cm intervals (or 2.5 cm intervals during periods of intense surface stratification) with the modified Miller technique recommended by Walker *et al.* (1970) for waters of high alkalinity. Reagents were dispensed with syringes and titrations were done in the field with a microburette readable to 0.01 ml. The azide modification of Winkler titration (Golterman & Clymo 1970) was unsuitable due to severe effervescence. Water temperature was measured with a portable Metrohm Model E-444 pH meter equipped with a glass electrode. The total alkalinity of each water sample was determined in the field by titrating 100 ml of sample with 0.05 N H_2SO_4 , using a pH meter to determine end point. (A.P.H.A. 1975). Underwater transmittance were estimated with a 20 cm Secchi disc. Extinction of photosynthetically available light (400 to 700 nm) was measured with a 'qualitative photometer' (Lambda Instruments Model LI-100). Readings were taken at 5 cm intervals until light extinction was obtained.

Chemical analyses

One half of each preserved sample and all unserved samples were filtered prior to analysis (washed Whatman GF/C filters). Because of the high solute content, all samples were diluted with deionized distilled water, to give final dilutions of 1/10, 1/100 and 1/1000, before analysis. One hundred millilitre aliquots of the remainder of the preserved sample were used for the analysis of particulate nitrogen and phosphorus. Each aliquot was sonicated for 2 min to disintegrate cellular material and then analyzed for total nitrogen and phosphorus. Particulate nitrogen and phosphorus were calculated by difference from filtered and unfiltered samples.

In this laboratory, chemical analyses are determined from published methods (Environmental Protection Agency 1974; A.P.H.A. 1975). Technological AutoAnalyzers were used to carry out the following analyses on the filtered water samples: sodium and potassium by flame photometry, with lithium

internal standard; fluoride by inverse colorimetry utilizing SPADNS reagent after distillation; chloride by colorimetry after reaction with mercuric thiocyanate in the presence of a ferric ion; sulphate by turbidimetry as barium sulphate; silica by the molybdenum blue colorimetric method using ascorbic acid as reductant, phosphate interference eliminated by prior treatment with oxalic acid; nitrate by colorimetry after reduction to nitrite; ammonium by colorimetry after reaction with alkaline phenol and hypochlorite; orthophosphate by colorimetry of the molybdenum blue colour; total phosphorus as orthophosphate after digestion with sulphuric acid and persulphate; and Kjeldahl nitrogen as ammonium after digestion of the sample with sulphuric acid in the presence of a mercury catalyst. Electrical conductance (standardized to 25 °C) was measured on a Radiometer conductivity meter. Calcium, magnesium, iron, manganese, cobalt, boron, chromium, zinc, copper, nickel, cadmium and lead were determined by atomic absorption spectrometry. Total (dissolved) nitrogen was calculated as the sum of Kjeldahl nitrogen, nitrate plus nitrite and ammonium (as N), and organic nitrogen was obtained by the difference between Kjeldahl nitrogen and ammonium (as N). The water analyses were within 5% of chemical balance. Salinity was calculated as the sum of the major ionic constituents (Hutchinson 1957) and total dissolved solids (TDS) were determined gravimetrically after evaporating a filtered (Whatman GF/C) sample to dryness at 105 °C.

Results

Morphometric features

The morphometry of the crater and lake are illustrated in Fig. 1. The crater is approximately 1.1 km in diameter with a total area of 95 ha. At high water level, the lake has a length of 350 m along its longest axis (transect A-A'; Fig. 2), a width of 275 m and is 7.57 ha in area. At this level, the lake has a maximum depth (Z_m) of 2.85 m and a mean depth (\bar{Z}) of 0.49 m. The development of volume, approximated by mean depth divided by the maximum depth (Hutchinson 1957), is 0.17 and the relative depth (Z_r), defined as the maximum depth as a percentage of the mean diameter (Hutchinson 1957), is 0.92%.

The unusual bathymetry of the lake (Fig. 2) is due to the topography of the abandoned salt diggings, where two access routes (visible as troughs) enter the flat-bottomed deepest section.

The water budget of the lake is governed by evaporation, precipitation and the inflow of spring water. Careful examination revealed that the artesian spring located at the end of the promontory (Fig. 2) was the only source of inflowing water, other than direct rainfall and surface run-off, to enter the lake. Monthly data for rainfall, evaporation, spring inflow and lake volume are shown in Fig. 3.

Evaporation in the region of the Pretoria Salt Pan ranged between a summer maximum of 274 mm month⁻¹ (December 1978) and a winter minimum of 108 mm · month⁻¹ (July 1979). The annual average evaporation for the region is 2.375 m. The variable precipitation patterns in the Pretoria Salt Pan area are typical of the South African highveld summer rainfall zone (Weather Bureau 1955). Rainfall in this region is mainly of thunderstorm origin and during our survey, total annual rainfall varied between 414 mm (1978–79)

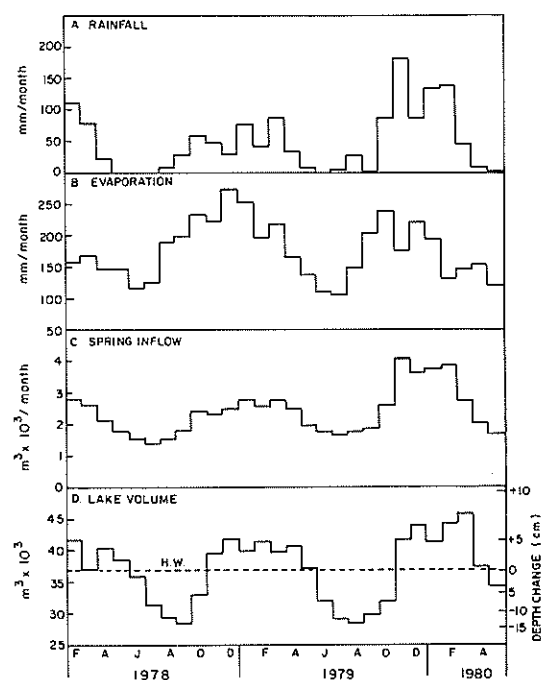


Fig. 3. Histograms showing monthly variation of A) Rainfall, B) Evaporation, C) Spring inflow, and D) Lake volume for the study period.

and 716 mm (1979–80). On average, rainfall was recorded in 10 months of the year, with summer maxima and winter minima (Fig. 3A). The volume of water delivered by the artesian spring (Fig. 3C) followed a similar pattern. The annual average rainfall (measured from 1921 to 1980) of 631 mm can add about 48 000 m³ of water directly to the lake. During this investigation, contributions from surface run-off were not measured. However, the presence of large alluvial fans on the crater floor suggests that the contribution by run-off must be highly significant. Based on measured spring flow rates (Fig. 3C), the artesian spring contributed an average of 26 000 m³ to the lake each year. Integrated values for monthly evaporation at the lake, using the hypsographic depth–surface area relationship, yielded a total loss of 175 000 m³ per year. Therefore, balancing evaporative loss against sources of inflowing water, surface run-off must have contributed approximately 100 000 m³ to the lake each year. Since the ratio of catchment area to mean lake surface area is about 11.5:1, the calculated contribution from run-off is approximately 18% of the total annual rainfall received by the crater. This value is lower than calculated contributions made by run-off to other salt lakes (e.g. run-off = 40% of total rainfall in catchment at Solar Lake, Sinai; Cohen *et al.* 1977).

The water balance can be formulated as:

$$\Delta V = V_{in} + V_p + V_r - V_e \quad (1)$$

where V_{in} = inflowing spring water, V_p = direct precipitation on the lake surface, V_r = surface run-off and V_e = evaporation. Monthly calculations of the water balance yielded a negative value for ΔV in winter (April to September) and positive values for ΔV in summer (October to March). These values are supported by the recorded changes in lake volume shown in Fig. 3D.

During the summer filling phase the lake level rose, on average, 7 cm above the high water mark (14% increase in volume) and dropped 13 cm below the high water mark (23% loss in volume) during the winter drying phase. Extensive evaporite deposits formed at the lake edge during the drying phase. Samples of these deposits contained approximately 80% trona ($\text{NaHCO}_3 \cdot \text{Na}_2\text{CO}_3 \cdot 2\text{H}_2\text{O}$) and 20% halite (NaCl).

Physical features

Secchi disc transparencies varied from 19 cm. Seston colour in the lake showed spectral variability, from greenish-yellow to bright violet-red and affected Secchi disc visibility. Light Secchi disc values were recorded in summer and occasional blooms of photosynthetic bacteria. Highest Secchi disc values were recorded in winter months May to August. Typical summer and winter light energy profiles are shown in Fig. 4. Light extinction was extremely rapid during summer, due to the phytoplankton density and turbidities, and total light extinction occurred in 25 to 30 cm. In winter, lower turbidity and phytoplankton densities permitted greater penetration and decreased lake levels allowed light to penetrate to the benthic communities located on the sediment surface of the peripheral areas (Fig. 4).

Water temperatures of the artesian spring remained remarkably constant ($15.7 \pm 0.9^\circ\text{C}$). Spring water was considerably less saline than the lake waters (Table 1) and, on calm days, remained as a thin (1.5 ± 0.5 cm) discrete layer at the surface of the lake. The midday temperatures of the spring waters varied from 33.8°C in summer to 19.7°C in winter. In the shallow marginal areas of the lake (station 1), water temperatures were occasionally isothermal from top to bottom (0 to 25 cm) during periods of high winds. The more general pattern, however, was the development of intense thermal stratification in the upper 15 cm during

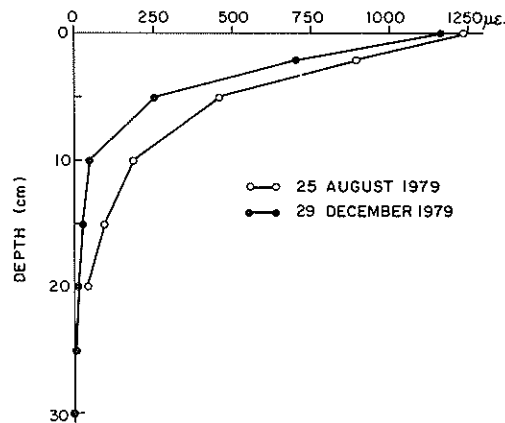


Fig. 4. Light energy profiles at station 1 for late winter (December) and mid-summer (August).

Table 1. Major chemical constituents of the inflowing spring and seven depths in the Pretoria Salt Pan. Figures in brackets indicate the milliequivalent percentage of the sum of anions or cations. All other values are in $\text{mg} \cdot \text{l}^{-1}$ except total alkalinity ($\text{mequiv} \cdot \text{l}^{-1}$), conductivity ($\text{mS} \cdot \text{m}^{-1}$), TDS ($\%$) and pH.

Parameter	Inflow	Depth below surface of lake						
		0.0 m	0.25 m	0.5 m	1.0 m	1.5 m	2.0 m	2.5 m
Na^+	1 300 (98.7)	29 000 (99.7)	35 000 (99.7)	49 000 (99.7)	64 000 (99.7)	69 500 (99.7)	82 000 (99.7)	103 000 (99.7)
K^+	12 (0.5)	130 (0.3)	180 (0.3)	230 (0.3)	290 (0.3)	330 (0.3)	370 (0.3)	500 (0.3)
Ca^{++}	7 (0.6)	<1	<1	<1	<1	<1	<1	<1
Mg^{++}	1 (0.1)	<1	<1	<1	<1	<1	<1	<1
Cl^-	1 650 (79.2)	30 000 (67.6)	35 000 (65.2)	46 000 (60.7)	60 000 (61.1)	65 000 (58.9)	72 000 (57.2)	85 000 (53.1)
SO_4	10 (0.4)	240 (0.4)	300 (0.4)	6.3 (<0.1)	0.5 (<0.1)	0.6 (<0.1)	0.55 (<0.1)	0.8 (<0.1)
Total alkalinity ($\text{mequiv} \cdot \text{l}^{-1}$)	12 (20.4)	400 (32.0)	520 (34.4)	840 (39.3)	1 080 (38.9)	1 280 (41.1)	1 520 (42.8)	2 120 (46.9)
Si	14	120	190	240	200	220	380	2 300
TDS ($\%$)	3.43	72.16	87.25	122.64	158.76	175.35	201.87	254.03
Conductivity (K_{25}) ($\text{mS} \cdot \text{m}^{-1}$)	578	5 820	6 960	10 150	12 730	14 310	16 570	20 850
pH	8.8	10.4	10.2	9.8	9.5	9.4	9.3	9.2

summer days (Fig. 5). In the deepest portion of the lake (station 2), a relatively deep, solar-heated, mesothermal profile occurred together with thermal stratification of the surface waters, causing a bimodal profile (Fig. 6). This mesothermal profile persisted throughout the study, and varied from 38.2°C at 0.55 m in spring to 26.4°C at 0.7 m in

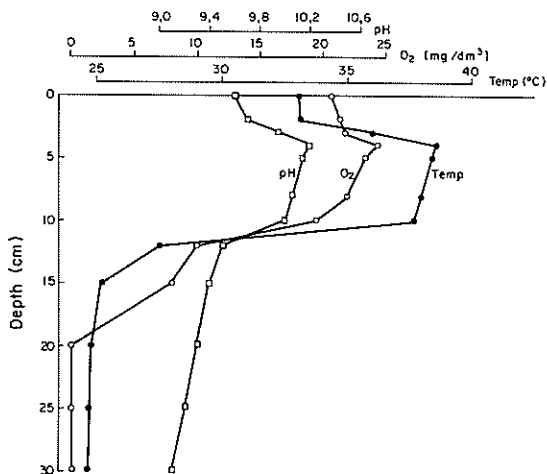


Fig. 5. Typical profiles of water temperature, pH and dissolved oxygen at the shallow sampling station (station 1), during mid-summer (29 December 1979).

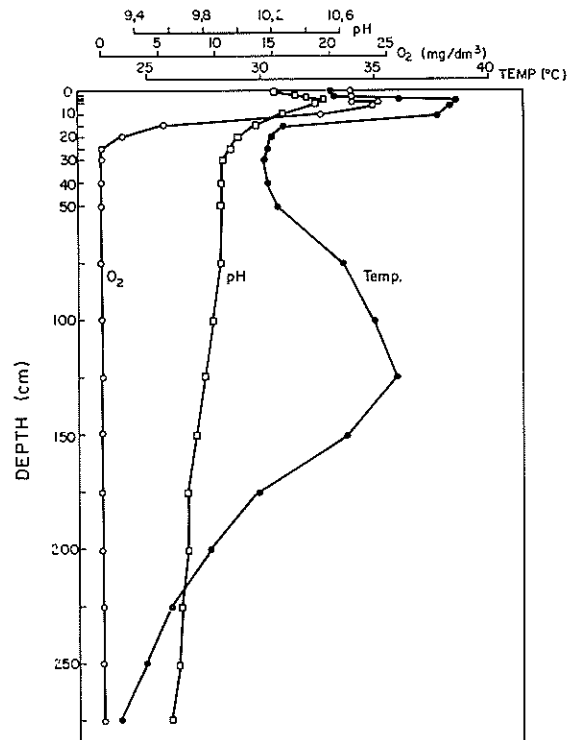


Fig. 6. Typical profiles of water temperature, pH and dissolved oxygen at the deep sampling point (station 2), during mid-summer (29 December 1979).

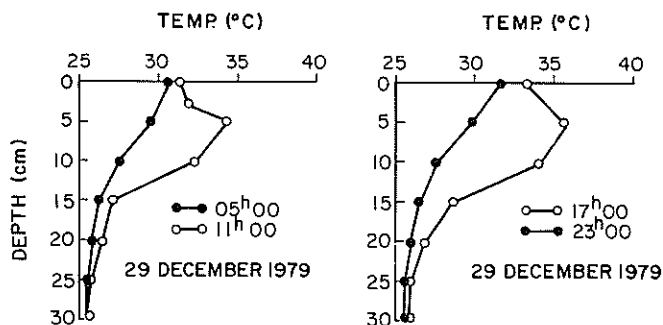


Fig. 7. Diurnal record showing variations in water temperature profiles at the shallow sampling point (station 1).

autumn. The diurnal record showed thermal stratification of the surface waters to be transient, shifting between morning and afternoon, and being overnight (Fig. 7).

Chemical features

Typical analyses of the major constituents of artesian spring and lake water at seven depths listed in Table 1 and minor elements are shown in Table 2. The concentrations of anions and cations in the artesian spring varied by up to 50%. In concentrations of most elements occurred since the lowest values were recorded towards the end of winter when inflows were lowest. The high concentrations

Table 2. Mean and ranges of minor chemical constituents in the inflowing spring and seven depths in the Pretoria Salt Pan. All values given in $\text{mg} \cdot \text{l}^{-1}$. (BD indicates below detection limit of analytical technique used.)

Parameter	Inflow	Depth below surface of lake						
		0.0 m	0.25 m	0.5 m	1.0 m	1.5 m	2.0 m	
NH ₄ -N	1 (0.4-1.3)	2 (1-3)	2 (1-3)	30 (25-32)	40 (31-45)	100 (89-107)	140 (133-146)	(210)
NO ₂ -N	1 (0.8-1.1)	5 (3-6)	5 (3-6)	6 (4-7)	6 (4-10)	6 (4-10)	7 (4-10)	(8)
NO ₃ -N	1 (0.7-1.2)	5 (4-7)	7 (5-9)	3 (1-7)	4 (2-8)	6 (2-10)	38 (27-46)	(82)
PO ₄ -P	1 (0.5-1.2)	7 (6-9)	8 (6-11)	32 (25-40)	42 (35-45)	62 (55-70)	87 (75-95)	(110)
Total P	22 (15-25)	9 (7-12)	16 (12-20)	48 (35-55)	63 (55-70)	86 (70-95)	109 (85-115)	(175)
B	0.1 (0.08-0.15)	20 (15-27)	22 (16-30)	42 (33-50)	55 (49-62)	65 (56-70)	87 (81-96)	(82)
F	8.4 (7.1-9.0)	0.30 (0.21-0.36)	0.29 (0.22-0.35)	0.14 (0.09-0.17)	BD	BD	BD	
Cd	BD	0.04 (0.02-0.06)	0.04 (0.03-0.06)	0.09 (0.05-0.11)	0.11 (0.09-0.15)	0.12 (0.10-0.15)	0.12 (0.10-0.15)	(0.10-0.15)
Co	BD	0.35 (0.28-0.41)	0.32 (0.25-0.37)	0.66 (0.49-0.73)	0.86 (0.76-0.93)	0.95 (0.84-0.99)	0.95 (0.88-1.04)	(0.90-1.00)
Cr	BD	BD	BD	0.12 (0.09-0.19)	0.16 (0.11-0.20)	0.17 (0.11-0.21)	0.17 (0.13-0.22)	(0.15-0.20)
Cu	BD	0.04 (0.03-0.05)	0.05 (0.03-0.06)	0.13 (0.10-0.15)	0.15 (0.10-0.18)	0.16 (0.11-0.23)	0.16 (0.12-0.23)	(0.12-0.15)
Fe	BD	0.29 (0.24-0.31)	0.29 (0.25-0.31)	0.73 (0.64-0.80)	0.98 (0.85-1.10)	1.14 (1.05-1.27)	1.25 (1.15-1.32)	(1.35-1.40)
Mn	BD	BD	BD	0.07 (0.05-0.09)	0.09 (0.07-0.12)	0.12 (0.09-0.14)	0.13 (0.10-0.15)	(0.12-0.15)
Ni	BD	0.37 (0.25-0.42)	0.40 (0.30-0.44)	0.78 (0.65-0.85)	1.01 (0.92-1.06)	1.10 (1.02-1.15)	1.12 (1.05-1.20)	(1.01-1.10)
Pb	BD	0.08 (0.05-0.10)	0.08 (0.06-0.09)	0.22 (0.18-0.27)	0.29 (0.21-0.36)	0.26 (0.20-0.33)	0.29 (0.20-0.35)	(0.19-0.25)
Zn	BD	BD	BD	BD	0.03 (0.03-0.04)	0.03 (0.03-0.04)	0.03 (0.03-0.04)	(0.03-0.04)

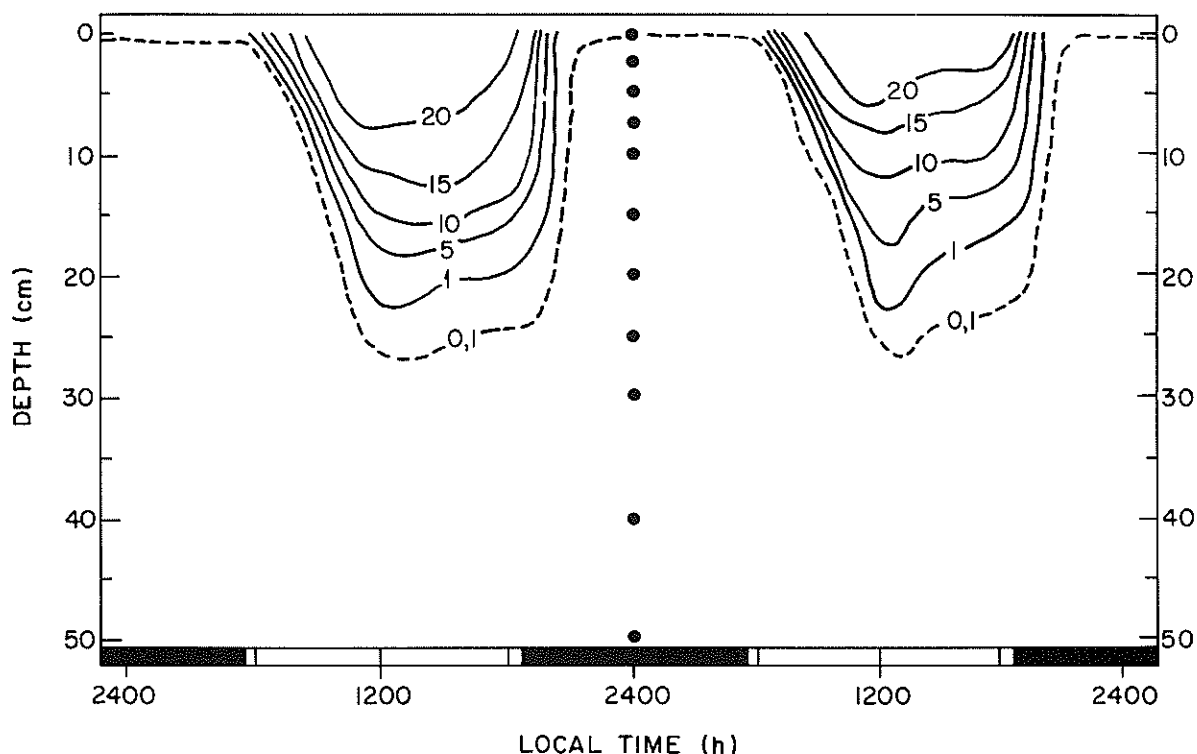


Fig. 8. Isopleth plot of diel dissolved oxygen variations at station I, 28–29 December 1979. (All values are in $\text{mg} \cdot \text{l}^{-1}$; ● indicates depths at which hourly samples were collected; Shaded bar indicates darkness, open bar indicates daylight.)

trations of fluoride in the spring water are most unusual for underground waters in South Africa (Bond 1946).

In the lake, concentrations of major cations and anions varied by up to 40% in the upper 0.5 m. The virtual absence of calcium and magnesium in the lake, compared to the spring inflow, indicated that these elements were precipitating, probably as carbonates. Summer concentrations were often far lower than winter values and reflect dilution by rainfall, surface run-off and increased spring inflows. Higher winter values were caused by evaporative concentration. Sodium was the major cation and chloride and bicarbonate plus carbonate, in nearly equal proportions by mass, accounted for over 98% of the anions. In the lake, electrical conductivities and concentrations of major cations and anions increased with depth, though the degree of dominance of chloride over bicarbonate plus carbonate (by equivalents) at the surface was reduced with increasing depth.

Pronounced chemical stratification was recorded on 28 consecutive months indicating that the lake

was meromictic and had not turned over during this period. The junction between mixolimnion and monimolimnion was located each time between 0.25 and 0.5 m where the greatest change in conductivity and ionic concentrations per unit depth occurred.

Orthophosphate and total inorganic nitrogen concentrations at the surface ranged from 5.5 to 8.0 $\text{mg} \cdot \text{l}^{-1}$ and 10.1 to 14.0 $\text{mg} \cdot \text{l}^{-1}$ respectively and increased with increasing depth. Silica and sulphate concentrations were very high, and also increased considerably with depth. The only trace element which did not increase in concentration with depth was fluoride, possibly due to its precipitation. Water samples from depths greater than 1.0 m were blackish in colour and smelled strongly of H_2S .

Midday percentage saturation of oxygen in the surface waters of the lake varied from 12% to 415%, with maxima in summer and minima after prolonged periods (2 to 4 days) of cloudy weather in winter. Dissolved oxygen distribution was highly stratified and typical examples for deep and shal-

low sampling stations are shown in Fig. 5 and 6. The diel pattern of dissolved oxygen distribution was remarkable and a typical summer pattern is shown in Fig. 8. From early morning, dissolved oxygen concentrations increased rapidly from the surface to between 25 and 30 cm. In the late afternoon, oxygen concentrations declined so that by 22^h00 local time the lake was anoxic. Anoxia was maintained until early next morning when the pattern was repeated. Similar patterns of diurnal oxygenation followed by nocturnal deoxygenation were recorded in 8 diel studies conducted during this investigation. However, maximum concentrations of dissolved oxygen in the surface waters seldom attained the high values recorded on 29 December 1979 (Fig. 8) and during four winter diel studies, were lower than 10 mg · l⁻¹.

Discussion

The Pretoria Salt Pan is an excellent example of a maar crater as defined by Ollier (1967). The exact mode of formation of the crater is, however, uncertain. The shallow water table in the surrounding countryside and the presence of ejecta (fragments of volcanic tuff) up to 0.5 km away from the crater point to the possibility that the crater was formed by a phreatic explosion followed by collapse and slumping of the inner slopes. Wagner (1922) indicated that the original depth of the crater was considerably greater than it is at present and that prior to commercial extraction of salt and trona, the original lake was very shallow and evaporated to dryness each year. The present perennial lake is thus approximately 50 years old. Evaporative concentration of the slightly saline (approximately 3‰) spring water gave rise to the present hypersaline lake waters.

On the basis of its bathymetry, the lake consists of two distinct depth zones. A 'shallow zone' (0–50 cm) within the original gently sloping basin overlies a smaller 'deep zone' (50 cm–2.85 m), the abandoned salt diggings. The low values for relative depth (0.92%) and volume development (0.17) are atypical of crater lakes (Hutchinson 1957; Melack 1979) and reflect the extent of gently sloping peripheral regions. At the high water mark, the lake volume is approximately 36 800 m³, 54% within the 'shallow zone' and 46% in the 'deep zone'. The

winter drying phase caused a lake level decrease approximately 20 cm from the average su level, a drop in volume of some 13 600 m³. Cr line and efflorescent crusts formed on the sloping margins of the lake by the evaporat interstitial brines drawn to the mud surface pillary action (the 'evaporative pumping' of Siegenthaler 1969). The dominance of trona over halite (20%) in the crusts reflected the co sition of the interstitial brines beneath the n the lake margin. The dry, powdery efflor crusts were completely solubilized by surfac off with the first summer storms, thereby incr the solute load, particularly in the shallow ma areas. Crystalline crusts washed in by surfac off were only partly solubilized and rapidly p tated out on the sediment surface.

The relatively high crater rim and small s area of the lake inhibited extensive wind mix the water. This, plus the inflow of less saline has resulted in a steep salinity gradient from bottom and a very stable meromictic stratifi pattern. In contrast to classical examples of mictic lakes, the Pretoria Salt Pan cannot be separated into mixolimnion and monimolimnion. Many meromictic lakes (Hutchinson 1973; Anderson 1958) have mixolimnia of uniform c throughout, which circulate freely except thermally stratified. In the Pretoria Salt Pa steep density gradient from top to bottom wa more abrupt (the pycnocline) between 0.5–0.5 m, and the mixolimnion (0–0.25 m) wa often stratified due to salinity differences. Co us inflows of less saline spring water, s mented by summer rainfall and surface r resulted in a three-layered mixolimnion. T layer (layer I: 0–2 cm), composed of spring was relatively fresh. Below this, a layer of (~80 JTU) more saline water (layer II: 2–15 turn overlaid a less turbid (~30 JTU), but more saline, layer (layer III: 15–25 cm). Du the high degree of wind protection affordec crater rim, mixing took place slowly and up saline water (layer I) gradually mixed wit more saline waters (layers II and III). Co inflow of less saline spring water tended to n the layered structure of the mixolimnion, p larly during calm periods. Evaporation de the depth and volume of the mixolimnion, salinity changes of up to 40%, decreas

abruptness of the chemocline, and permitted some mixing of mixolimnetic and upper monimolimnetic waters. Increased summer inflows of less saline spring water and surface run-off re-established the chemocline. Seasonal losses of solutes from the monimolimnion due to entrainment with and diffusion into the mixolimnion were probably replaced by the influx of partly dissolved evaporite crystals from the lake margins.

Below the chemocline, monimolimnetic salinity and TDS values increased steadily to the bottom of the lake. However, two distinct layers could be distinguished within the monimolimnion: A thin upper layer (50–80 cm), immediately below the chemocline, characterized by extremely high turbidity (~600 JTU) and a lower layer (80–285 cm) with very low turbidity (<30 JTU). Despite seasonal fluctuations in mixolimnion depth, the depths of the two monimolimnion layers remained more or less constant relative to the bottom of the lake.

The superficial thermal stratification pattern recorded in the Pretoria Salt Pan (Fig. 5) has also been recorded in other shallow African salt lakes during calm conditions (Prosser *et al.* 1968; Melack 1978). The maxima of this superficial thermal stratification indicated the depth of mixolimnion layer II. The thin transparent layer of spring water (layer I) caused a 'greenhouse effect', allowing absorption of solar energy and rapid diurnal heating of the more turbid waters of layer II. The lower temperature of layer I accentuated nocturnal cooling. Wind mixing of the three mixolimnion layers resulted in a lower uniform turbidity which permitted greater penetration of solar energy. The decrease in mixolimnion depth during winter allowed solar heating of the highly turbid upper monimolimnion layer, giving rise to a bimodal temperature profile during calm conditions. The upper monimolimnion layer reached maximum temperature in September–October each year, immediately before the summer rains. Throughout the summer months, temperatures in this layer gradually decreased by conduction to a minimum in March, before winter heating was repeated. Throughout an annual cycle, temperatures in this upper turbid monimolimnion layer were greater than the temperatures of the water layers above or below. This pattern of superposition of two heliothermal profiles, one transient and the other persistent, is highly unusual and, as far as we can ascertain, has not been previously

reported in the literature. The shallowness of the persistent mesothermal profile, its stable depth relative to the bottom of the lake and the constant salinity gradient clearly indicate the stability of meromixis in the lake.

Solar heating of the lower layers of saline lakes has been widely recorded (Beadle 1943; Anderson 1958; Wilson & Wellmann 1962; Cole, Whiteside & Brown 1967; Melack & Kilham 1972; Cohen *et al.* 1977). In most cases the mixolimnia (whether of one or more layers) were relatively deep (1.0–3.0 m) and highly transparent. Rapid solar heating occurred in the upper layer of the monimolimnion, or in brines below the pycnocline, and recorded temperature maxima (up to 65 °C) are far in excess of values recorded at the Pretoria Salt Pan. In the Pretoria Salt Pan, absorption of most of the incident solar energy by the middle turbid mixolimnion layer (Fig. 4) prevented heating of the monimolimnion when the mixolimnion was thermally stratified. A decrease in mixolimnion depth caused by evaporation during winter, accompanied by lower turbidities due to wind mixing, permitted only a small portion of the solar energy to reach the monimolimnion. Thus the heating rate of the upper monimolimnion layer was slow and often interrupted by calm periods when the mixolimnion restratified, resulting in a lower maximum temperature compared with other solar-heated salt lakes.

Bond (1946) classified the artesian spring water at the Pretoria Salt Pan as an alkali-carbonate type and pointed out its similarity, in ionic proportions, to the water of the well-known thermal springs at the town of Warm Baths, some 60 km distant. The ionic proportions of both water types are characteristic of waters from igneous alkaline rocks. Higher concentrations of Na and Cl in the Pretoria Salt Pan spring water must be due to the local dissolution of halite layers below the lake sediments.

According to the brine classification system of Eugster & Hardie (1978), the Pretoria Salt Pan can be classified as a Na–Cl–CO₃ type brine. Because of the high HCO₃ + CO₃/Ca + Mg mole ratio of the artesian spring water (>27), the lake brine must have evolved by the rapid precipitation of Ca and Mg as carbonates, followed by evaporative concentration. This hypothesis is supported by the ultra-low (below detection limit of analytical technique) levels of Ca and Mg in the lake water.

In both the mixolimnion and monimolimnion of

the Pretoria Salt Pan (Table 1), the major cation sequence is $\text{Na} \gg \text{K} \gg \text{Ca} \gg \text{Mg}$ while the main anion sequence is $\text{Cl} > \text{HCO}_3 + \text{CO}_3 \gg \text{SO}_4$. Despite the seasonal variations in mixolimnion salinity of up to 40‰ and the great increase in salinity with depth, the ionic proportions of major anions and cations remained relatively constant. In the monimolimnion, bacterial reduction of SO_4 (as evidenced by the strong smell of H_2S in samples from this zone) must have reduced much of the original SO_4 to sulphide. The ion sequence of the artesian spring is the same as that recorded in the lake waters ($\text{Na} > \text{K} > \text{Ca} > \text{Mg}; \text{Cl} > \text{HCO}_3 + \text{CO}_3 > \text{SO}_4$), with the exception that the relative proportions of the ions are somewhat different.

Similar to the studies of Talling & Talling (1965), Walker (1973), Barica (1978) and Hammer (1978b), significant relationships were found between individual ions and conductivity, and total dissolved solids (TDS) and conductivity. In particular, the linear relationship between TDS and conductivity (K_{25}) is very good ($r = 0.998$), with a slope of 1.21. This is close to the hypothetical slope of 1.0 which would exist if total ions equalled conductivity. The divergence may be due, in part, to the loss of HCO_3 and CO_3 as CO_2 during the oven-drying process. Correlations between conductivity and other parameters were not as high. The predominance of Na and the near zero ratio of divalent to monovalent cations ($\text{Ca} + \text{Mg}/\text{Na} + \text{K}$) are in agreement with the results of Talling & Talling (1965) for other African saline lakes. The correlation between Si and Na concentrations ($r = 0.7$) conforms to the range of values expected from an evaporative concentration model (Kilham 1971; Hecky & Kilham 1973). The increase in Si with depth may be due to the slow sinking out of colloidal silicates as postulated by Talling & Talling (1965).

The increase in the ratio of alkalinity/chloride (by equivalents) with depth indicates an accumulation of carbon dioxide in the monimolimnetic waters. The decrease in pH between mixolimnion and monimolimnion supports this view (Talling & Talling 1965). The high pH of the surface waters is a characteristic shared by other alkaline saline lakes in Africa (Melack 1978). Timms (1972), however, recorded very much lower pH values in an Australian meromictic lake, possibly due to the lower proportions of HCO_3 and CO_3 relative to chloride.

In common with published data from other

highly saline and alkaline lakes, orthophosphate and total phosphorus values in the Pretoria Pan (Table 2) are very high (Hutchinson 1965; Talling & Talling 1965; Prosser *et al.* 1968; Ha 1978b; Melack 1978). No correlation was found between phosphorus concentrations and total content or conductivity. The increased concentrations of $\text{NH}_4\text{-N}$ in the monimolimnion must be due to bacterial reduction of organic nitrogen. The increased concentrations of $\text{NO}_3\text{-N}$ at the bottom of the monimolimnion are unusual and may be due to the anaerobic oxidation of $\text{NH}_4\text{-N}$, via the reduction of SO_4 by sulphate-reducing bacteria, as suggested by Hutchinson (1957).

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