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Physical and chemical conditions in an hypersaline spring in the Namib Desert

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Abstract

Hosabes is a small mineralized spring lying in a gypsous crust in the central Namib Desert on the south-western coast of Africa. It is fed by virtually fresh groundwater that wells to the surface at this and other similar fracture lines. The extremely high rates of evaporation and solar radiation result in intense concentration of the salts and the formation of strong salinity and therefore density gradients in the deeper parts of the system. These in turn produce a "solar pond" effect with a reversed temperature gradient; temperatures reach 50 °C within the water column. The deeper parts of the system appear to be monomictic. Although the surrounding crust is largely gypsous, the water in the spring is dominated by NaCl as a result of precipitation of $CaSO_4$ in the highly concentrated water.

Introduction

The coastal reaches of the Namib Desert in South-West Africa/Namibia are characterised by a number of saline or hypersaline springs in gypsous beds (Watson, 1979). These are found, within a hundred kilometers of the coast, from Cape Frio (18°15′S/11°56′E) in the north to Gobabeb (23°34′S/15°03′E) in the south. Surface waters associated with these springs may be extremely salty, with TDS (total dissolved solids) levels exceeding 200 g l^{-1}.

Saline and other minerally rich springs and streams are known from many parts of the North American deserts (see, for example, Cole & Batchelder, 1969; Sommerfeld *et al.*, 1974; Blinn *et al.*, 1981; Whittig *et al.*, 1982). Even in the absence of human disturbance, some rivers in the Middle East (Krinsley, 1970) and Australia (Australian Water Research Council, 1976) may be somewhat saline in certain reaches, while human-induced salinization is a perennial problem in many arid areas of North America (see, for example, Stanford & Ward 1986), Austrialia (Australian Water Research Commission, 1976) and southern Africa (Williams *et al.*, 1984).

Extremely hypersaline systems similar to those under discussion in the present paper have been noted in certain areas of the western United States, for example in the High Plains of Texas (Bell & Sechrist, 1972) and Death Valley (Hunt *et al.*, 1966), and in Chile (Stoertz & Erickson, 1974), Iran (Krinsley, 1970) and Australia (Twidale, 1972). Only those in the Mohave Desert and Death Valley, California, have been examined limnologically (see, for example, Brock 1967, 1969; Cole, 1968; Naiman & Gerking, 1975; Naiman, 1976a), probably because they support populations of desert pupfish, particularly several subspecies of *Cyprinodon nevadensis* (Naiman, 1976b) or occasionally of *C. salinus*.

All of these systems appear to be associated with playas, which are essentially the basins of endorheic catchments in arid areas that often support playa (intermittent) or pluvial (permanent) lakes (Neal, 1975). In contrast, Hosabes is situated in the bed of the Sout (Salt) River, a dry tributary of the Kuiseb River, which in turn is a normally-dry river that intermittently carries water to the sea south of Walvis Bay (Stengel, 1964). Despite this apparent geomorphological inconsistency, the Sout River can be considered to be endorheic to all intents and purposes since it is essentially a non-functional river that flows once every ten years or so, and then for a matter of hours or days.

This paper describes the physicochemical conditions in Hosabes as a preliminary to examining the biological features at a later date.

Study area

Hosabes lies in the bed of the Sout River in the Central Namib Desert, approximately 5 km north of Gobabeb, which in turn is about 56 km east of Sandwich Harbour on the west coast of southern Africa (Fig. 1).

The wide open plains on which the Sout River is

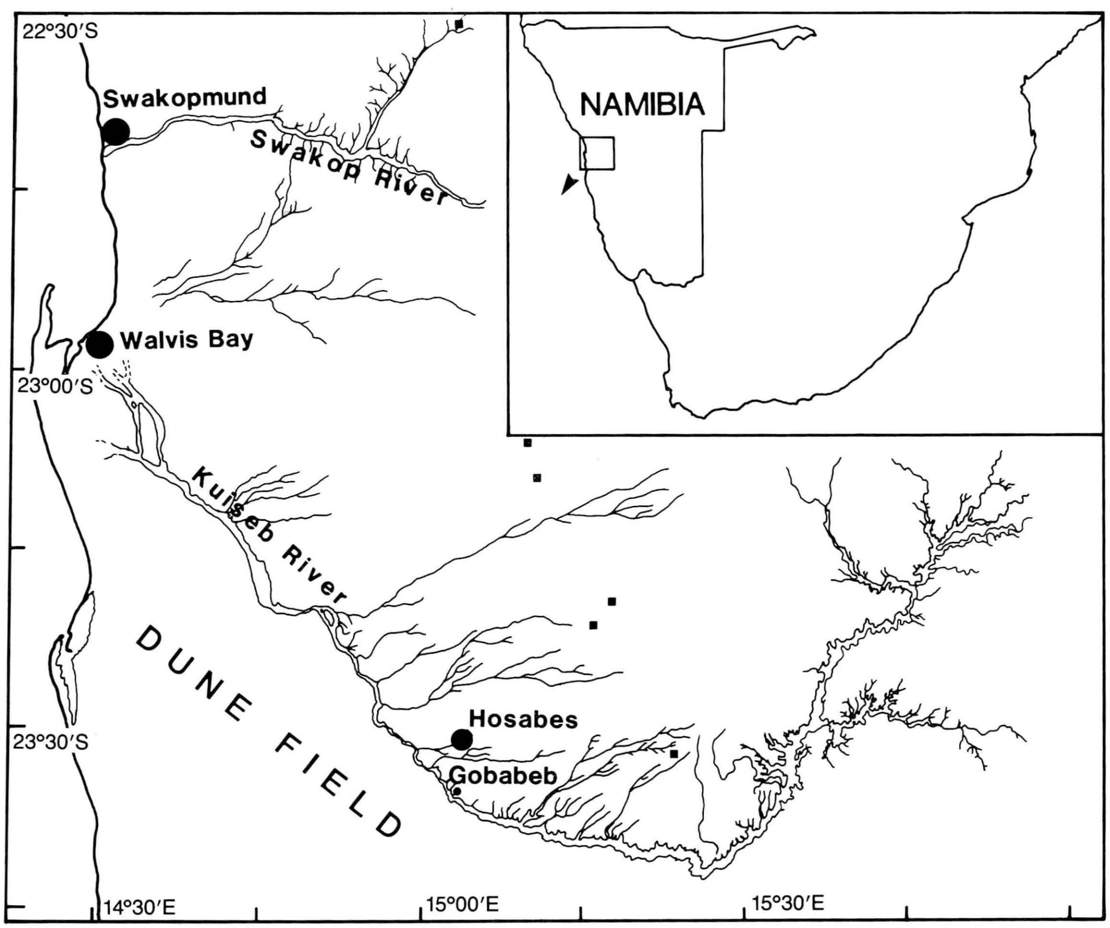

Fig. 1. Map showing the position of Hosabes in the drainage of the Kuiseb River in the central Namib Desert. The small squares indicate the positions of other similar mineral springs.

situated consist mainly of Damara sequence bedrock pediplains mantled with a thin veneer of rubble, calcrete, gypcrete and unconsolidated sands (Ward, 1984). The bedrock, which reaches the surface in several places at Hosabes, is largely mica schist with some intruded granite; a dolerite dike is exposed on the left bank but does not appear to be in contact with the spring in the river bed.

The climate of the region is extremely arid (Miegs, 1966). Mean annual rainfall at Gobabeb is less than 30 mm y^{-1}; precipitation is extremely erratic, almost half of the total amount of rain recorded since 1966 having fallen in only two years (1976 and 1978). Nevertheless, the Namib is not considered to be a particularly hot desert, the maximal temperature at Gobabeb not exceeding 43 °C. Mean pan evaporation is 3168 mm y^{-1} (Lancaster *et al.*, 1984).

The bed of the Sout River in the vicinity of Hosabes is approximately 35 m wide and the most recent banks are about 600 mm above the level of the water in the spring. The valley in which the river-bed lies is about 300 m wide in the vicinity of the spring. The entire bed of the river for a distance of several hundred metres consists of so-called "puffy" ground: a thin (5 – 10 mm), dry crust of sand and gypsum raised 50 – 300 mm above the moist, clayey underlying sediment. Delicate filaments of gypsum crystals sometimes form a white network between the crust and the ground. Puffy ground is said to result from the evaporative concentration of salts in spring water or in groundwater near the surface (Motts, 1970).

The white, salty ground formed by the stream itself is about 18 m wide and stretches from a distance of less than three metres from the lefthand bank more or less to the middle of the dry river-bed. The flowing part of the stream extends longitudinally for some 80 – 100 m, depending on flow-rate and evaporation. At the time of the intensive studies it formed a braided channel 0.5 – 3 m wide, interspersed by slower-flowing pools, the largest of which had a surface area of 5 – 6 m^2 and a depth of up to 260 mm. The stream has changed its course over the last couple of years. Several of the pools have now salted up and the stream forms fewer but rather more distinct channels 300 – 400 mm wide and 10 – 50 mm deep, interspersed with pools reaching depths of *ca.* 150 mm. Despite the changes in channel morphology, the total amount of water on the surface at any one time does not seem to be appreciably different.

The edges and parts of the bottom of the stream are encrusted with salt, largely NaCl, embedded with unicellular green algae. The bottom of the deeper areas is covered by a microbial mat up to 120 mm deep. This appears reddish-brown on the surface but bright green below and incorporates spongy, decaying fragments of wind-blown grass and twigs.

The water is extremely clear and green-tinged. It is considerably warmer and denser towards the bottom and distinct density currents can be seen when the water is disturbed.

Methods

Every second month, from October 1980 to December 1981, data were collected hourly over a period of eighteen hours. Vertical temperature profiles were taken from the deepest pool by inserting a wooden pole bearing thermocouples at intervals of *ca.* 25 mm; these and air temperatures were read from a Bailey Bat-4 with an accuracy of ±0.2 °C. A six-inch (152 mm) black bulb at a height of one metre above the water surface was used to measure black bulb air temperatures. Wind-speed was measured with a hand-held 3-cup Lambrecht wind-totalising anemometer. Pan evaporation was determined by means of a Lambrecht pen-recording six-inch (152 mm) evaporating pan, using water from the spring. When the water was particularly saline, a salt crust developed on the surface of the water in the pan, thus reducing evaporation, and had to be broken and removed. Thus these results are not particularly reliable and are low rather than high estimates.

The stream was too shallow to use a flow-meter, so flow was estimated by timing the passage of small pieces of paper (approximately 100 mm^3) over a given distance and taking the average of ten readings.

Salinity was measured with an American Optics optical refractometer calibrated for salinity in the laboratory by constructing a refractive index/TDS curve. pH was determined by means of an Extech digital portable pH meter.

On three occasions, twice in winter and once in

Table 1. Chemical composition of the water of Hosabes.

Date	TDS	pH	Na	K	Ca	Mg	Cl	SO_4	TA	F	NO_3
29.6.1982	115444	8.3	1782.6	37.8	41.3	1000	1549.3	335.4	3.9	0.1	22.3
6.3.1984	159990	8.0	2582.6	56.4	2.9	142	2112.7	479.2	4.6	0.1	65.1

TDS is given in mg l^{-1}. Individual ions are quoted in milliequivalents l^{-1}.

late summer, vertical differences in oxygen, temperature and salinity were measured using a portable YSI series 3 oxygen meter and probe with calibrated thermocouple and salinity was measured with an American Optics refractometer calibrated for salinity.

At the extremely high salt concentrations and temperatures encountered in the spring water, there are very considerable density gradients in all but the shallowest reaches. Thus removal of more than a couple of millilitres of water from below the surface, or indeed careless stirring of any sort, disturbs the gradient. For this reason, all salinities were measured using the refractometer, which requires only a few drops of water, and pH was measured occasionally throughout the day. Water for these measurements was extracted from the appropriate depths by means of a thin plastic tube attached to the end of an hypodermic syringe.

Owing to the likelihood of interference from the highly concentrated ions in solution, oxygen was determined both with the YSI meter and also by Winkler titration (Golterman *et al.* 1978). Titrations gave a linear relationship between salinity and apparent oxygen concentration, indicating overwhelming interference from certain of the ions in solution. Thus any reaction due to oxygen itself is masked and the Winkler titration cannot be used for oxygen determinations.

There are apparently no tables giving percentage saturation of oxygen at the relevant temperatures and salinities and, since saturation values drop dramatically at these high temperatures and salinities, readings obtained by the oxygen meter will be inaccurate. Conversion nomograms were constructed from extrapolations of Strickland & Parson's (1968) nomograms and all oxygen values given here have been converted in this way. It is unlikely that these are entirely accurate but they do provide a set of reasonably comparable figures.

Water for the chemical analyses shown in Table 1 was collected in one-litre plastic bottles and sent unpreserved to the laboratory of the Department of Water Affairs in Windhoek for analysis. The proportions of the major ions would be unaffected by this procedure, and these are reported here. Analyses of nutrients and dissolved organic carbon (DOC) cannot be measured accurately on such samples. Nitrate levels are reported here because, even if the values are not very accurate, they do reflect the commonly high levels found in many Namibian waters. The values reported in Table 2 were obtained from 100 ml samples frozen at between −4 and −15 °C until analyses could be performed in Cape Town.

TDS values were obtained by evaporating 400 ml of water at 70 °C. pH and conductivity were analysed by Water Affairs (Table 1) using a CD6N Tacussel pH/conductivity meter and the conductivities reported in Table 2 were determined with a portable Crison CDTM 523 temperature-compensated meter. Sodium and potassium levels were measured with a Gallenkamp Flame Photometer. Calcium and

Table 2. Total ionic concentration, as conductivity and salinity, and chloride levels at various positions in Hosabes on 26.6.1986.

Distance from source (m)	Description	Conductivity (mS m^{-1})	Salinity (‰)	Cl^- (meq l^{-1})
0	at spring	7100	36	600
20	surface, deepest pool	16300	98	1700
20	bottom, deepest pool	21500	134	2200
40	channel	11300	72	1160
60	channel	24800	150	2800
80	extreme end	13500	88	1352

magnesium were calculated from titrimetric determinations of calcium and total hardness with versenate using sodium hydroxide and ammonium chloride respectively. Chlorides analysed by Water Affairs (Table 1) were determined titrimetrically with silver nitrate and those reported in Table 2 were determined by titration with mercuric nitrate. Total alkalinity was titrated against sulphuric acid. Sulphates were determined nephelometrically after precipitation with barium chloride and fluorides with a model 401 Ionalyser after treatment with TISAB diluted standards. Nitrate levels were determined spectrophotometrically by the sodium salicylate method.

Results

Ambient physical conditions

Seasonal variations in hourly measurements of black-bulb air temperature and air temperature 10 mm above the water are shown in Fig. 2, and evaporation rate and wind speed in Fig. 3.

Clearly the rate of evaporation increases with an increase in both wind speed and air temperature. The highest rate of evaporation was 1.2 mm h^{-1} and the lowest was considerably less than 0.1 mm h^{-1}. Daily evaporation varied from 5.0 mm in November to 8.2 mm in September, with an average of 6.2 ± 1.1 mm. This gives a mean annual evaporation rate from the surface of the spring of 2287 mm. Considering that the rate of evaporation from highly-mineralised waters is considerably less than that from purer waters (see, for example, Langbein, 1961), and that the method provides an underestimate of evaporation, this is in keeping with the overall mean annual evaporation rate of 3168 mm quoted by Lancaster *et al.* (1984).

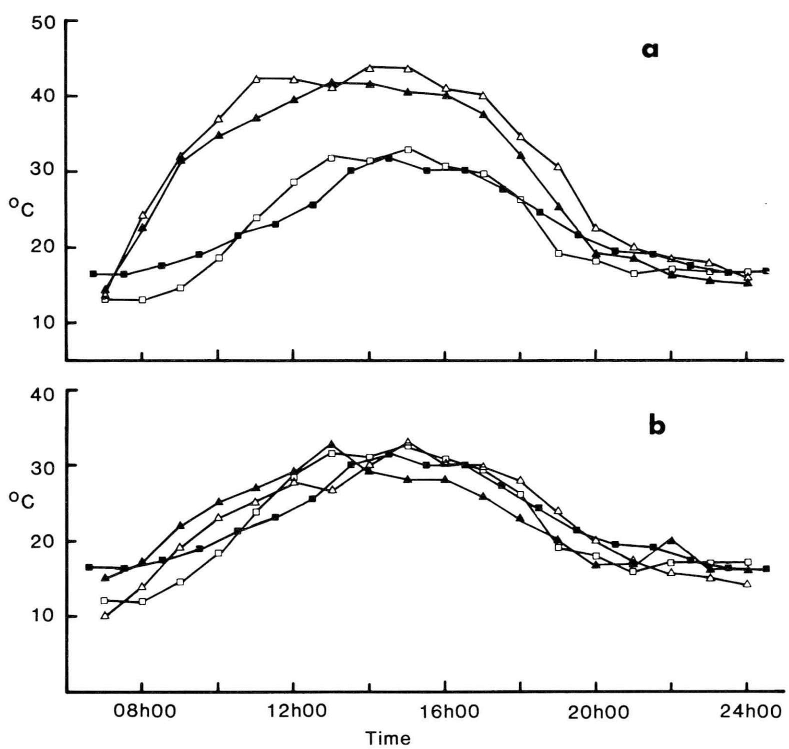

Fig. 2. Black bulb temperature one metre above the ground (a) and air temperature 10 mm above the water (b) at Hosabes. Solid squares: 2.3.1981; open squares: 2.7.1981; solid triangles: 6.11.1981; open triangles: 18.12.1981.

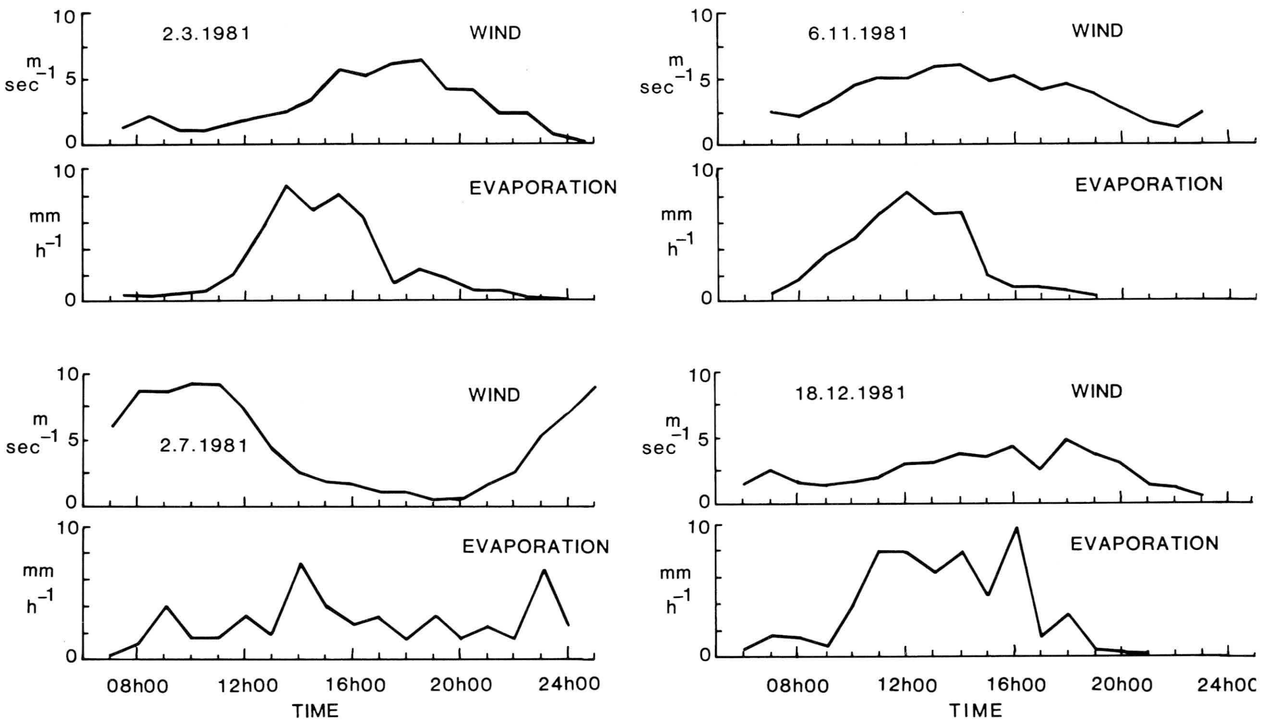

Fig. 3. Hourly recordings of wind-speed and evaporation rate for the same days as the data given in Figs. 2 and 4.

Physical conditions in the spring

Flow-rates varied from minima of 0.012–0.019 m s^{-1} in November 1981 to maxima of 0.017–0.023 m s^{-1} in December 1981. The higher figure in each case was estimated for "rapids", through which only one channel of the braided stream flowed. The lower figure in each case represents almost the entire flow of the stream in unbraided areas. Taking profile area into account, and using the lower flow-rates, discharge for the entire system varied from 0.22 litres s^{-1} in September to 0.75 litres s^{-1} in December 1981.

Since the stream decreases in length by as much as 30% (from 92 to 65 m) during the course of a single day, but increases again at night (Fig. 4), the entire discharge must be evaporating during this time. For example, using the values given above for December 1981, when the stream shrank from 92 to 65 m between 10.00 h and 18.00 h, 16.2m^3 must have evaporated from a surface of considerably less than 1800 m^2 (the total area of the stream bed).

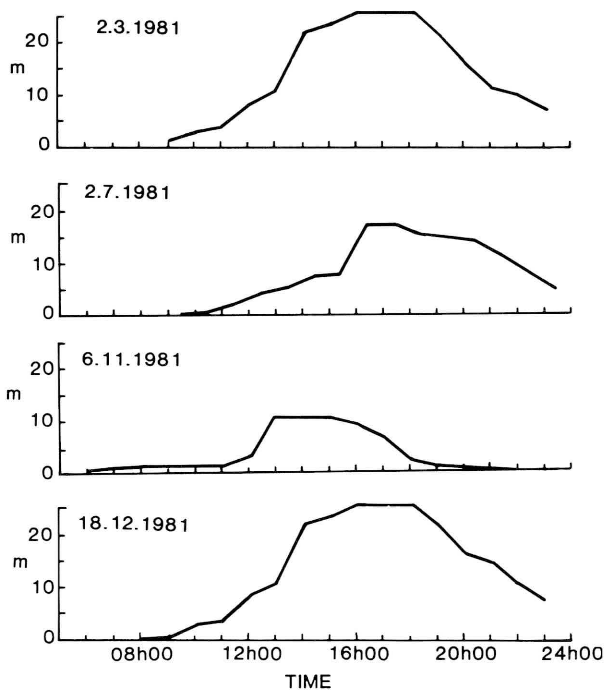

Fig. 4. Diel reduction in stream length for the same days as the data given in Figs. 2 and 3.

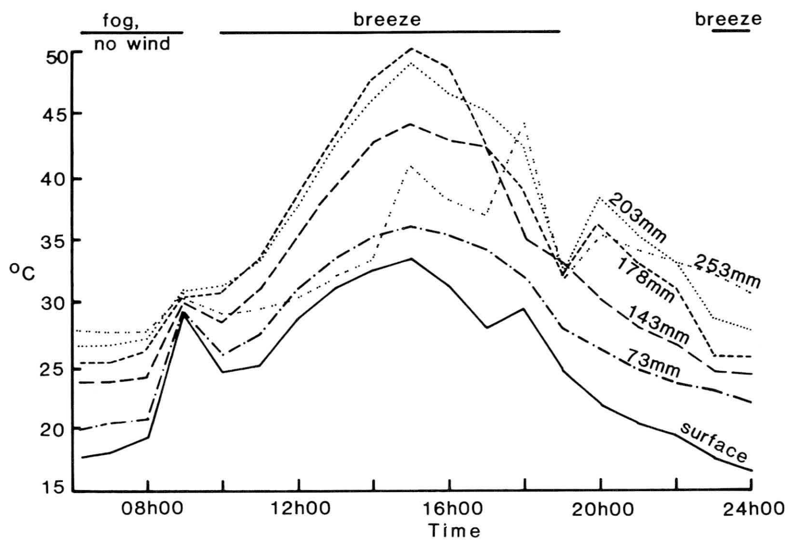

Fig. 5. Temperatures at various depths throughout the day on 29.12.1980.

Temperatures show an interesting inverted pattern, the surface layers being considerably cooler than those near the bottom. An example of this inverted pattern is illustrated in Fig. 5, which shows the temperatures recorded by several of the probes in the water-column between 06.00 h and 24.00 h on 29th December 1980. This particular set of data has been chosen because it illustrates firstly, at 15.00 h, the highest temperature recorded during the study (50 °C at a depth of 178 mm); secondly, at 10.00 h, the mixing effect of a breeze and thirdly, at 19.00 h, the effect of a drop in wind-speed, which appears to retard the rate of cooling in the bottom layers.

Temperature profiles for 29.12.1980 and 2.7.1981 are given in Fig. 6. A synthesis of temperature profile with depth throughout the year is given for 07.00 h and 15.00 h in Fig. 7. Both of these figures show that the reversed temperature gradient is main-

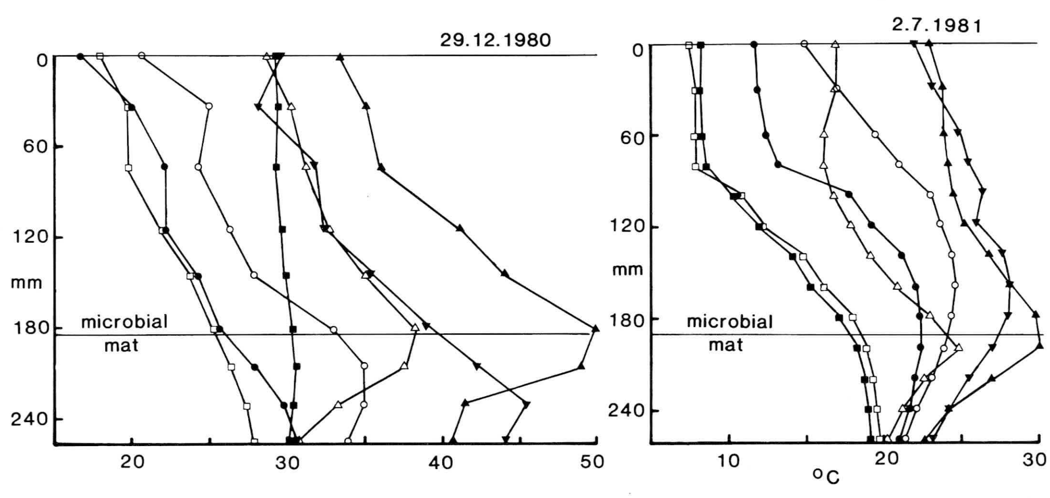

Fig. 6. Depth-temperature profiles throughout the day for 29.12.1980 and 2.7.1981. Open squares: 07.00 h; solid squares: 09.00 h; open triangles: 12.00 h; solid triangles: 15.00 h; inverted triangles: 18.00 h; open circles: 21.00 h; solid circles: 24.00 h.

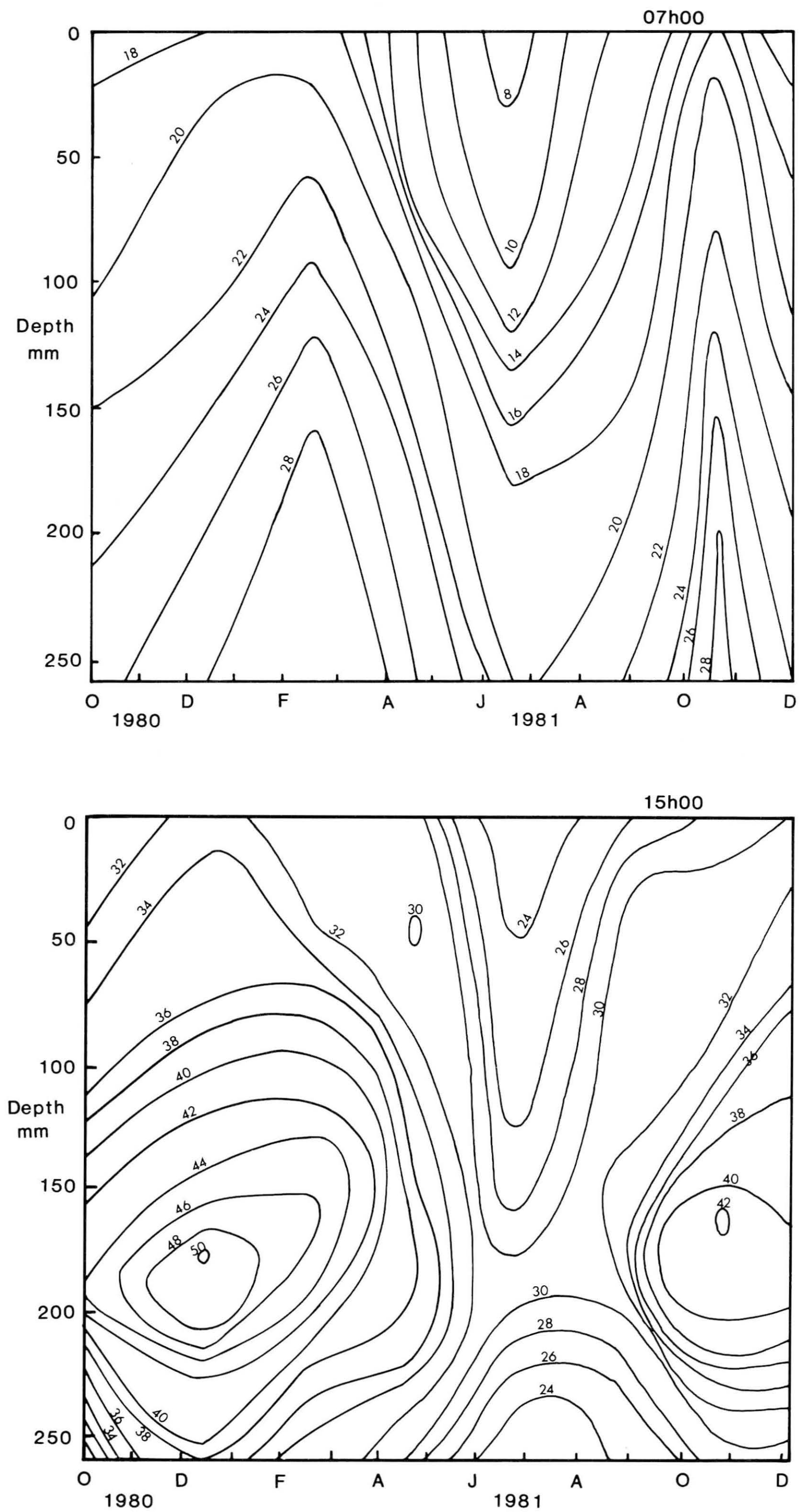

Fig. 7. Annual depth/temperature profile in the deepest part of Hosabes at 07.00 h and 15.00h.

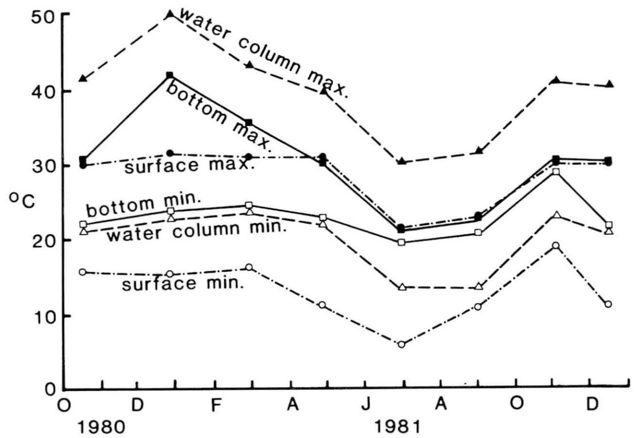

Fig. 8. Summary of temperature data for Hosabes: monthly maxima and minima.

tained virtually at all times, while the heating of the water column above the microbial mat develops anew each day as a result of solar heating. These data are further summarised in Fig. 8, which shows maximal and minimal temperatures throughout the year at the surface, above the microbial mat, and immediately above the bottom. Temperatures are always highest immediately above the mat, which shades the deepest areas from the intense solar radiation. Thus temperatures within the mat are both more equitable and more constant than those above it: for much of the year, the daily fluctuation within the mat is less than 10 °C, while the fluctuations within the water column reached nearly 25 °C on one occasion (December 1980).

Chemical conditions

Oxygen and salinity

As might be expected, chemical gradients reflect those of temperature. Figure 9 shows profiles of oxygen concentration, salinity and temperature on three separate occasions. The upper set of curves (for 24.3.1982) reflects conditions when the water-level was low (depth 168 mm), despite the fact that some rain (about 0.5 mm) had fallen in the previous two weeks. The water-level was 240 mm on both 1.7.1982 and 6.3.1984, despite the fact that 4.5 mm of rain had fallen in the week preceding 1.7.1982. (The two periods of rain were purely coincidental and are in fact extremely unusual). In each case salinity was lowest at the surface, rising sharply towards the upper surface of the algal mat and dropping slightly within the mat after both periods of rain, suggesting that some seepage occurs towards the bed of the stream. In all cases, temperatures followed the patterns described above.

Oxygen levels were variable on the surface (possibly an effect of the time of day) but all peaked immediately above the algal mat and dropped sharply within it, indicating that the production: respiration (P:R) ratio is >1 above the mat and $\ll 1$ within it.

pH

pH was not measured together with the other variables shown in Fig. 9 because too large a sample would have been required and this would have disturbed the salinity and other gradients. Even in the two-monthly sampling no clear trends were seen, possibly because of mixing of water during sampling. Values were generally a few tenths of a unit lower towards the bottom and also tended to be lower at 09h00 than at 15h00. The maximal value recorded was 8.75 and the lowest was 7.25.

Major ions

Analyses of surface water samples taken on 29.6.1982 and 6.3.1984 are shown in Table 1 and the ionic proportions for the second of these samples are

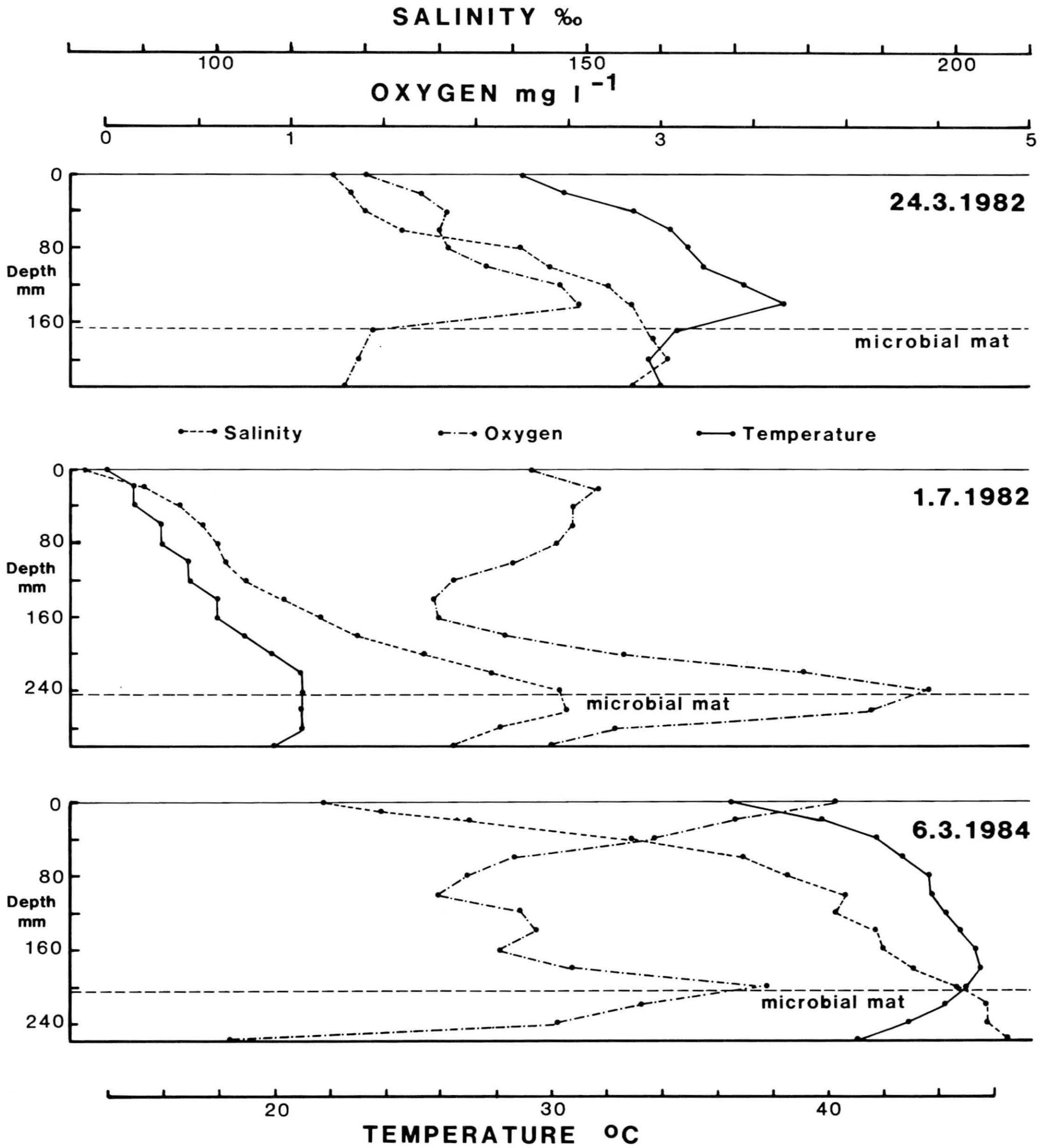

Fig. 9. Profiles of salinity, oxygen and temperature in Hosabes. Readings were taken at 12.00 h on 24.3.1982, at 10.00 h 1.7.1982 and at 14.50 h on 6.3.1984. Rain had fallen in the fortnight preceding the sampling on the first two occasions.

illustrated in Fig. 10. The salinity levels clearly reflect the surface conditions shown in Fig. 9. The only major difference in ionic proportions between the two samples concerns calcium, which represents 2.1 equivalents per cent of the more dilute sample but only 0.1 equivalents per cent of the more concentrated sample, reflecting the precipitation of gypsum ($CaSO_4$) from the more concentrated brine.

Table 2 shows the conductivity, salinity and chloride concentration of samples from various positions in the spring on 26.6.1986. Clearly the total ionic concentration is much lower near the source of the spring, increasing both downstream and with depth. The concentrations found in the sample nearest the end of the spring are anomalously low and suggest that further spring water is seeping in at this point.

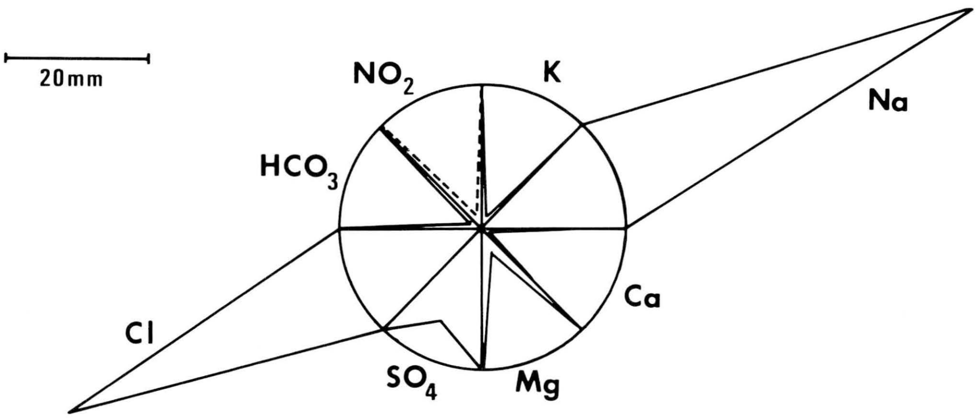

Fig. 10. Ionic diagram for mixed water from Hosabes taken on 6.3.1984. 1 mm = 4.4 meq l^{-1}; TDS = 159.9 g l^{-1}.

Discussion

Hosabes represents an extremely unusual ecosystem. It seems to have developed as a result of seepage of groundwater at a fracture zone where drainage lines have intersected north-south trending faults at approximately right angles to the strike of the fault. Several other similar systems are to be found in the central Namib Desert at roughly the same distance from the coast. Their positions are indicated by the small black squares in Fig. 1.

Groundwater welling through the fracture has a considerably lower salinity than that of the surface water in the spring. Because of the delicate nature of the system it has not been possible to excavate deeply enough to obtain groundwater itself but the variations in salinity shown in Table 2 are indicative of the much less mineralised nature of the groundwater. Further evidence that groundwater in the area is indeed low in salts is anecdotal. Gert ≠Nariseb, a Topnaar Hottentot who has lived close to Hosabes all his life, recalls that, for several months after the Great Flood of 1933/4, when the Sout River came down in flood, he was able to water his stock from this spring, which is now never less than twice as salty as seawater. Presumably the flood waters washed away accumulated salts so that virtually fresh groundwater could reach the surface.

The salts appear to be concentrated by a combination of the high rate of evaporation, caused by strong winds, a lack of rain, and solar heating. (Mean daily solar radiation for December is 23.211 MJ m^{-2} and for July is 13.840 MJ m^{-2}: Lancaster *et al.*, 1984).

Presumably the rate at which groundwater enters the system is sufficiently high to produce a layer of fresher (and therefore less dense) water overlying the warmed but more saline, and therefore denser, water below. The density gradients thus created are remarkably stable and in turn contribute to the warming effect, acting as a lens and resulting in a system equivalent to that of the "solar ponds" described by Cohen *et al.* (1977) in the Sinai Peninsula.

Although the entire system is much smaller and shallower than Solar Lake (approximately 250 mm as opposed to 4–6 m deep), maximal recorded salinities are similar (180–200‰). The highest temperature recorded in Solar Lake was 60.5 °C and in Hosabes 50 °C, so that the thermocline is much sharper in the smaller system: in Solar Lake the vertical thermal increment reaches 18 °C m^{-1}, while in Hosabes this same increment is reached over 160 mm. The maximal temperature change recorded at any one point over a single day in Hosabes was 24.7 °C between 06.15 h and 15.00 h on 29.12.1980.

In Solar Lake the main source of new, fresher, cooler water is seawater upwelling from below, while in Hosabes it is moderately fresh groundwater seeping from both below and above at the point where the spring emerges from the ground. The maximal

Table 3. Solubility of various major ions relative to that of NaCl (from Langbein, 1961).

	CO_3^{2-}	SO_4^{2-}	Cl^-
Na	0.4	0.3	1
Mg	0.0004	0.9	1.3
Ca	0.00005	0,006	1.5

salinity gradient in Solar Lake at the height of stratification varied between about 20‰ on the surface and 180‰ on the bottom, a considerably steeper gradient than the steepest recorded in Hosabes, which increased from 112‰ on the surface to 211‰ on the bottom (Fig. 9).

This may explain why Hosabes is monomictic: even when the temperature is uniform throughout the water column, the salinity (and therefore the density) gradients are such that overturn cannot occur (see, for example, the curve for 09.00 h in Fig. 6 for 29.12.1980). In contrast, flash floods cause overturn in Solar Lake in summer, a peculiar feature of this system.

The apparently anomalous presence of water dominated by NaCl in a gypsous bed is explained by the very different solubility coefficients of the major salts. Table 3 shows the solubility of the major inorganic ions relative to that of NaCl. Thus as the total concentration increases, so gypsum is more rapidly precipitated out ($CaCO_3$ is already absent from the water for the same reason) and the main salt remaining is NaCl.

In the face of the extremely harsh physical and chemical conditions in the spring, it is remarkable that a fairly complex community of organisms has developed. This consists of various ephydrid, dolichopodid and ceratopogonid (heliid) flies, dytiscid, ptilid and hydraenid beetles and a lycosid and a theriid spider amongst the animals, as well as the complex microflora making up the microbial community of the benthic mat. Further information on the biota is to be presented in a later paper.

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