Australian salt lakes: their history, chemistry, and biota - a review

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Abstract

A vast number of large lakes (⩾ 100 km^2) are typically very old features of the Australian landscape; they occupy areas which have changed little tectonically (e.g., they occupy ancient drainage systems in Western Australia or lie in deep depressions such as the Great Artesian Basin: Lake Eyre) and have not been transgressed by the sea since at least the Palaeogene. Other salt lakes, most of which are small (⩽ 50 km^2), have been affected morphologically during recurring glacial-interglacial cycles (e.g., lakes associated with gypsum or clay lunettes, sabkhas, pans, lakes near the coast behind barrier dunes as a result of sea-level changes) and their sedimentary records represent comparatively much shorter periods of time. There are also a number of unusually young (< 30 000 years) crater lakes, some of which are the best studied lakes in Australia.

The major ions encountered today in Australian salt lakes consist of sodium and chloride although some lakes are also calcium sulphate rich. The origin of these ions is briefly discussed. Sodium carbonate lakes are rare in Australia today. Under past climatic/hydrological conditions the chemistry of a number of lakes was apparently different.

The biota of Australian salt lakes is mostly endemic; it is highly diversified as witnessed by the crustacean fauna and is well adapted to the harsh conditions prevailing in saline water. This is the result of a long history of aridity in Australia. The characteristics of this biota are presented together with data on its distribution which is primarily related to climatic conditions.

Introduction

In recent years there has been increased interest in salt lakes from most parts of the world, even in areas as remote as Antarctica. This interest is caused not only by the significant economic value now associated with salt lakes, for the mineral deposits they yield, but also for their biological components, some of which can be significant sources of food and of various chemicals such as food dyes. A broad review of the importance of salt lakes from the view point of their economic value and biological interest is presented in Williams (1981b) where an exhaustive bibliography on the subject is provided. Additionally, more interdisciplinary studies of salt lakes have been carried out since it has been demonstrated that salt lakes occurring in enclosed basins can retain valuable and sometimes extensive sedimentary records of great value to investigators of continental history. Two significant volumes illustrating the multidisciplinary approach to salt lakes have been edited by Nissenbaum (1980) and Williams (1981a).

Since the data on Australian salt lakes is sparse, due mainly to the diversity of interests of individual sciences (therefore material is scattered in a great variety of journals), the aim of this paper is to review the state of knowledge on salt lakes in Aus-

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tralia, a continent where salt lakes are common features of the landscape and have been so for a long period of geological time.

Information presented here will emphasise the factors which typify the Australian salt lakes in addition to data dealing with their history, chemistry and biological components. It is hoped that this review will outline fields of interest and areas still in need of investigation but also enable comparative studies of Australian salt lakes with those elsewhere.

It is recommended that the reader refer to the detailed review prepared by Williams (1981c) of recent studies carried out on salt lakes in Western Victoria as this area is the most studied one in Australia.

Throughout the text the arbitrary value of 3‰ was chosen to delimit fresh and saline waters; similarly only athalassohaline lake *(sensu* Williams 1981b) will be considered herein.

Geomorphological setting

Salt lakes are numerous in Australia. Major salt lakes or the basins in which they occur are shown in Fig. 1. Nearly all salt lakes occur in the arid or semi-arid zone of the continent as shown in Fig. 2.

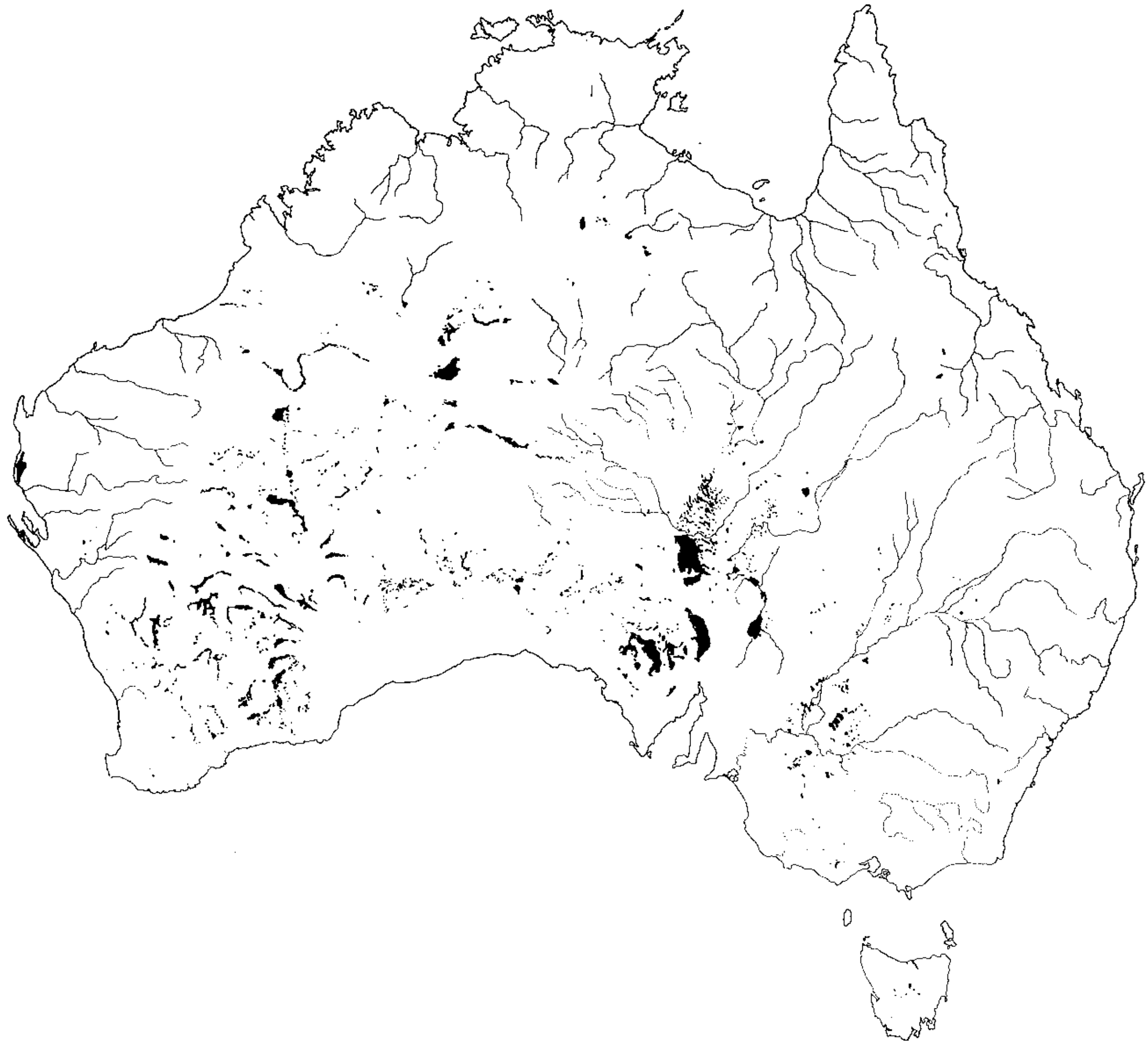

Fig. 1. Map of Australia showing the major lake basins; all are ephemeral today (redrawn from Bowler, 1981).

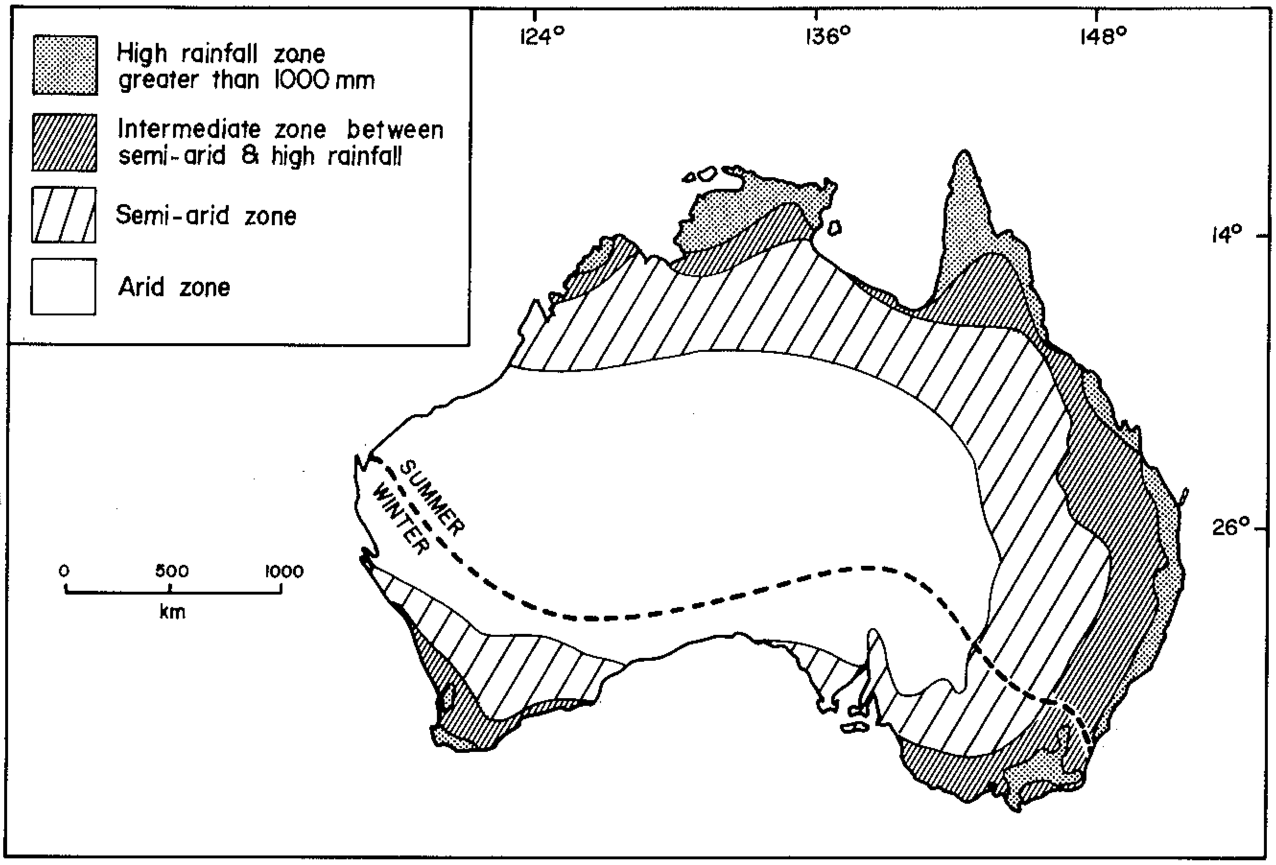

Fig. 2. Map of Australia showing the simplified climatic regions based on precipitation. Note the line which marks the summer-winter rainfall boundary.

Salt lakes occur today in regions characterized by both winter or summer rainfall (see Fig. 2).

Salt lakes in Australia are classified here into 4 major types based on geomorphological grounds.

1. *Large closed basins with (often) extensive internal drainage areas* (e.g., Lake Eyre in central Australia). Such endorheic basins are common in Australia. A large number of the lakes (often called playa lakes) also occur in ancient drainage (= palaeodrainage) systems, and therefore have a characteristic elongated shape, as seen for many large lakes in Western Australia (Van de Graaf *et al.* 1978; Fairbridge & Finkl 1978). The age of some of these palaeodrainage systems can extend to the early Tertiary in Western Australia (Van de Graaf *et al.* 1978). The Great Artesian Basin, which encloses the playa Lake Eyre, which is in adjacent to the main depression in that basin (Habermehl 1980), was already the site of lacustrine sedimentation at the end of the Cretaceous (Johns & Ludbrook 1963) and intermittently since then.

2. *Small closed basins with small internal drainage areas.* These lakes originate under a variety of circumstances and types vary from interdune corridors to evaporation – deflation pans. These lakes are a direct consequence of the groundwater and local climatic conditions. The best known example in Australia is the lunette lake. The term lunette, coined by Hills (1940), refers to crescentic dunes formed by deflation of lake floors (usually pans) which eventually contribute to the configuration of deeper lakes (which are bound on one side by one or more such dunes). Their formation and (palaeo)-climatic and -hydrologic significance have been discussed in Bowler (1973). In contrast to the large closed basins, the lunettes and other small basins

(e.g. sebkhas) are *usually not* old features of the landscape. The constantly changing local hydrological regime and associated aeolian phenomena during a complete glacial/interglacial cycle (which sees changing conditions ranging from extremely arid to very wet) contribute to their formation and often their destruction. This is particularly the case with sand lunettes described by Campbell (1968). However some lunette lakes can remain as features of the landscape for long periods of time; they cannot be easily eroded away since they are made of clay pellets. Bowler (1976b) cites some lunettes which are of considerable antiquity – some 120 000 years old – in the Willandra system of western New South Wales. The lunette lakes as described by Bowler (1973) require for their formation 'a combination of two factors, including the presence of a shallow saline waterbody with reasonably exposed marginal mud flats and strong and preferably unidirectional winds coinciding with a hot dry season'. Very few clay lunettes are being formed under the present day climatic conditions in Australia.

3. *Crater lakes.* In Western Victoria, there is a vast number of maar lakes, many of which retain saline water. These lakes are considered to be ideal (palaeo)-hydrological/climatic recorders (Bowler 1981; De Deckker 1982) because they possess small, well defined, internal catchments and with water-level and salinity depending directly upon the balance of precipitation and evaporation on and around the lakes. Some of these lakes in Victoria are the best studied saline lakes in Australia (Yezdani 1970; Bowler 1970, 1981; Timms 1973, 1981; Tudor 1973; Walker 1973; Dodson 1974; Barton 1978; De Deckker 1982).

4. *Coastal lakes.* Lakes connected to the sea are not considered here since this discussion only deals with athalassohaline lakes *sensu* Williams (1981b). Coastal lakes commonly occur behind a dune barrier formed in association with sea level change. Others can result from the isolation of embayments from the sea. However, small closed basins such as lunette lakes which occur near the sea are also considered here because the major difference between coastal lakes and those situated further inland is that the former's hydrology is affected by marine groundwater. This will affect water chemistry, salinity and water regime.

Saline pools are an additional type of water body commonly found in Australia. They are the obvious result of the widespread aridity which now prevails. Some pools also occur in dry river beds where some water is usually retained during dry periods. These pools are not significant in this discussion as their sedimentary records are not retained and their salinities, which are a direct reflection of the local geology, are often very low. The biota they yield is characteristically a freshwater one but which can tolerate slightly saline conditions for short periods of time.

While discussing the history, chemistry and biota of salt lakes in Australia it is important to be aware that a number of those lakes might have, or did, retain fresh water instead of saline water at different periods of time. This phenomenon would have occurred during the less arid periods and is more characteristic of the small lakes (e.g., crater lakes) where dilution of salts can be extensive and sometimes salts can even be flushed out of the drainage basin (e.g., by water overflowing the crater rim in the maar lakes).

History

Sedimentological history

An extraordinary feature of Australian lakes is that a large number of them have been in existence for a very long period of time. The playa lakes which occur in palaeodrainage systems in Western Australia have been the sites of periodic lacustrine deposition, in some cases, since the mid-Miocene (Van de Graaf *et al.* 1978). The playa lakes in that part of the continent have remained in existence as a result of tectonic stability and also because of a dramatic change in climatic conditions which saw the Australian continent become arid. This phenomenon also applies to the large playa lakes such as Lake Eyre which are part of large endorheic basins. The interesting feature of all these lakes is that they have the potential to provide the best sites for long sedimentary records, providing information on a long continental history and palaeoclimates. Good sites for such studies for example would be Lakes Torrens and Frome which existed since the Eocene and Mid-Miocene respectively (Johns 1968; Callen 1977).

Surface changes through time

It is also necessary to recognize that the size of those lakes has varied through time, sometimes extensively, thus forming mega-lakes *(sensu* Bowler 1981) which expand during wet and/or low evaporation periods. During that time raised-beaches are formed and these features are best seen during drier periods when lake surface areas have shrunk considerably as observed today for the large Australian lakes (for more detail refer to Bowler 1981). The palaeoclimatic implications of the recognition of expanded lake phases in the case of mega-lakes are significant and have been discussed in Bowler (1981) and Dury (1973). The most striking example is that of Lake Eyre. Using satellite imagery Löffler & Sullivan (1979) recognized a parallel alignment of pans reflecting a gradually diminishing lake on the eastern side. It is suggested that the former lake, called Lake Dieri, covered as much as 110 000 km^2, more than six times the present day lake surface. Centres of deposition in a number of large lakes could have moved laterally through time due to a number of factors. These changes could have been either tectonically controlled or have resulted in lateral migration of the deepest part of the lake basin during cliff erosion and deflation. The best example is the tectonically controlled Great Artesian Basin which is bound by many faults and which encloses Lake Eyre; the latter is at present one of the loci towards which regional groundwater flows (Habermehl 1980) and therefore can act as a groundwater discharge area but there is no indication that this was always the case. Extensive deflation of lake floors on the other hand is controlled by the movement of groundwater at or near the lake surface: when the water table recedes from the surface, deflation can occur, thereby changing the lake topography. This is the case at Lake Frome where large islands formed on the lake floor during the last extreme arid period around 18000 y BP (coinciding with the maximum advance of glaciers in the northern Hemisphere). These islands consist of gypseous clays deflated from the lake floor and margins. Similarly, salt supplied in solution from groundwater discharge zones along the basin margin and by spring discharge from aquifers can contribute to cliff recession during the dry periods, and promote the lateral migration of lake surfaces. This phenomenon appears to have occurred at Lake Tyrell (J. M. Bowler & J. Luly, pers. commun.).

Preservation of sedimentary record

Small enclosed basins, such as pans, are not old sites of lacustrine sedimentation. During the span of a complete glacial/interglacial cycle, they will be formed and eventually eroded away or buried by non-lacustrine sediments.

Crater lakes can retain continuous sedimentary records for long periods of time (provided they are deep enough and do not dry up) since their morphology is not likely to be affected drastically by changes of climatic regimes. However, none of the saline lakes of Victoria is so far known to have a long sequence comparable to those of the freshwater crater lakes of southeast South Australia (Dodson 1975) or the Atherton Tableland in North Queensland (Kershaw 1976, 1978). Sometimes when barrier dunes form parallel to a coast with changes in sea level, lakes form in the interdune corridors. Sedimentation in these lakes can continue for long periods of time, and therefore provide valuable palaeoclimatological information. Cook *et al.* (1977) demonstrated this in their study of the interdune corridors (some of which are filled by lacustrine sediments) parallel to the southeastern coast of South Australia. The Coorong Lagoon and its associated chain of salt lakes occur in the last formed of such corridors. Its formation was initiated approximately 6000 y BP (Von der Borch 1976), but a Late Cainozoic sequence has been recovered in the corridors further inland (Cook *et al.* 1977).

Chemistry

Predominance of sodium chloride lakes

In contrast to salt lakes of other continents, those in Australia can be uniformly described as sodium chloride-rich lakes. This surprising feature can be explained by the absence of active volcanism. If the latter is associated with certain tectonic settings (e.g. rifting), it will affect the water chemistry of lakes by supplying a great variety of salts resulting from the weathering of volcanic rocks and to a lesser extent via mineralized, usually thermal, springs.

The most comprehensive papers on Australian salt lake water chemistry are: a general review on major ions by Williams (1967); Williams & Buckney (1976) for South Australia, southwest Western

Australia and Northern Australia; Geddes *et al.* (1981) for Western Australia; Bayly & Williams (1966) and Maddocks (1967) for south eastern Australia; Buckney & Tyler (1967) and De Deckker & Williams (1982) for Tasmania. Maddocks (1967) provided information on bromide, boron, silicon, phosphorus and nitrogen for Victorian lakes and Förstner (1977) described the mineralogy and geochemistry of sediments from a number of Western and South Australian arid lakes including information on some trace elements. The best documented lake geochemistry in Australia is from Lake Frome where major ions and trace elements have been analyzed for surface and subsurface sediments and subsurface brine (Draper & Jensen 1976).

There are a few exceptions to the generalization that Australian salt lakes have all sodium chloride-rich waters. These occur in Western Victoria where a cluster of small crater lakes are highly alkaline since carbonate and bicarbonate there account for a large proportion of the total ions. For more detail on these lakes refer to Bayly (1969). It is thought that the chemistry of these lakes results from the alteration of volcanic rocks which surround the waterbodies. In addition, small pans and lakes, all ephemeral, scattered in the Monaro Plain of New South Wales, where volcanic rocks outcrop, retain sodium chloro-carbonate-rich waters (Williams *et al.* 1970). Finally there are also a few known examples of large lakes (Lakes Bathurst and Jillamatong in New South Wales, Lake Gregory in the Northern Territory) which have waters of high pH; these high values are considered to result from substantial photosynthetic activities by halophytes during periods of high water level and corresponding low salinities.

Origin of salts

The origin of the salt in Australian lakes has been the subject of much discussion. The latest review on the topic is presented by Johnson (1980) where an extensive bibliography on the subject is provided. It is not the purpose of the present paper to discuss at length the various theories put forward but it is important to note that there is an unequivocal similarity between several ionic ratios of sea water and of most salt lake waters in Australia, especially for the large basins. This phenomenon suggests an oceanic origin of the lake waters but it is still debatable whether the composition of the waters in most parts of Australia, especially in the centre, resulted from the retention of connate salts originated from erosion of marine strata or from airborne sea salt (= cyclic salt). Both theories could account for the composition of major ions of most inland waters since there does not appear to have been any obvious interactions from other sources such as the supply of salts associated with volcanism through springs.

The unusual amount of some elements in lake waters can sometimes easily be explained by examining the local geology. One such case occurs in central Tasmania where the few salt lakes there have a high content of magnesium, very likely the result of weathering of the surrounding dolerite. (De Deckker & Williams 1982).

An additional feature of Australian salt lakes is that, although most are today sodium chloride rich, with halite and gypsum as common precipitates, it appears that in the past chemical processes in the lakes were very different. It is now known from coring carried out at Lakes Eyre (Johns & Ludbrook 1963), Torrens (Johns 1968) and Frome (Callen 1977) that carbonate sediments (mostly dolomite-rich) are encountered below gypseous sediments. The latter are considered to be Quaternary in age, while the carbonate sediments are referred to as the Etadunna Formation of about Middle Miocene age. Lake chemistries, at least in central Australia, were definitely different during the deposition of the Etadunna Formation. Our understanding of the drastic changes in water chemistry which occurred in those lakes is still poor. Climatic conditions were certainly different. In the instance of Lake Frome, Callen (1977) suggests on fossil evidence that the Namba Formation (= equivalent to Etadunna Formation at Lake Eyre), which represents an alkaline lacustrine sequence, was deposited under a warm, high rainfall climate. If this were the case, timing of the change from carbonate sedimentation to a sulphate/chloride mode is important in palaeoclimatic reconstruction in Australia.

Biota

The characteristics of the biota of Victorian salt lakes have already been reviewed by Williams (1978, 1981c) and the aim of the present paper is to augment this information by adding data for areas of Australia not discussed in Williams (1978, 1981c). However one should be aware that most of the work carried out on the Australian biota is from Victorian lakes. Additional information has been drawn from two publications: one for southeast South Australia (De Deckker & Geddes 1980) and the other for Western Australia (Geddes *et al.* 1981). Information on halophytes from southeast South Australia is now available in Brock (1979, 1982a, b).

Crustacea

The most conspicuous elements of the biota found in Australian salt lakes are the crustaceans. They are mostly endemic to Australia and some demonstrate a surprising tolerance to high salinities and other harsh conditions, such as long periods of lake desiccation and high temperatures. Ostracods form the most diversified group: 37 species so far have been found living in salt lakes – a much larger number compared to the ostracod fauna of other continents (for a review see De Deckker 1981). [Note that a few more ostracods are known to tolerate salinities in the vicinity of fresh water (3‰), they will be ignored here as they inhabit temporary pools and most of them are cosmopolitan species]. Two ostracods only are of marine ancestry and require permanent water to reproduce; other ostracods can live in ephemeral waters because their eggs can withstand desiccation. Their salinity range is described in De Deckker (1981, in press).

Other crustaceans of interest are the copepods. The calanoids are represented by two species of *Calamoecia*. Contrary to the ostracods, 10 other species of *Calamoecia* are inhabitants of freshwater. It appears therefore that the calanoid copepods derive from a freshwater ancestor (which originally derived from a marine ancestor (Bayly 1964a)), whereas there is no direct evidence for such recent freshwater link (and definitively not a marine one) for the ostracods. The latter are grouped in genera which have no freshwater representatives except for one species of *Trigonocypris (T. timmsi*, see De Deckker 1981). An additional calanoid copepod, *Boeckella triarticulata*, which is typically a freshwater species (Bayly 1964b) can also occur in saline waters. Bayly (1969) discussed the factors permitting the occurrence of that species in saline waters up to 22.3‰ salinity.

Little published information is available for the cyclopoid copepods, although a revision of the taxonomy of the group has already been carried out (Morton 1977). Prior to that revision it was thought that cyclopoids in Australia were cosmopolitan. Morton (1977) demonstrated that this is not the case, as illustrated by the halobiont cyclopoid fauna which consists of six endemic *Microcyclops* species, in addition to the cosmopolitan *M. dengizicus*, and two endemic *Halocyclops* species.

Of the harpaticoid copepods, there is only one species which is presently known in inland salt lakes (Hamond 1971). There is, however, in addition to *Mesochra baylyi* a number of marine species in coastal lakes with permanent water in southeast South Australia (Hamond 1973a, b; Bayly 1970).

Haloniscus searlei, which represents a rare occurrence of an aquatic oniscoid isopod, is another endemic crustacean. It is a common inhabitant of Australian salt lakes. It is a truly aquatic and one of the few halobiont animals which has been adequately studied (Bayly & Ellis 1969; Ellis & Williams 1970; Williams 1983). For comments on the other species of *Haloniscus* refer to Williams *(op. cit)*. Published records on halobiont cladocerans in Australia so far refer to only one species, *Daphniopsis pusilla*. It was first studied by Hedley (1969) but supplementary information is available in Geddes (1976) and De Deckker & Geddes (1980). It is now thought that more than one species of *Daphniopsis* occurs in Australia (V. Sergeev & W. D. Williams, pers. commun.). Of interest also is the record of *Moina mongolica* from at Lake Eyre (Bayly 1976), in a pool near Lake Buchanan in central Queensland (B. V. Timms, pers. commun.) and Lake George in New South Wales (De Deckker, unpubl., identif. B. V. Timms).

The best available information on any crustacean from Australian salt lakes is that for the anostracan *Parartemia zietziana* (Geddes 1975a, b, c, 1976, 1981b; Marchant & Williams 1977a, b, c; Marchant 1978; Mitchell & Geddes 1977; Manwell 1978). This 'brine shrimp' belongs to a genus endemic to Australia which presently comprises 9 species. Their distribution is presented in Geddes (1981a) and Geddes *et al.* (1981) and the salinity tolerance for most of these species is discussed in Geddes *et al.* (1981) and De Deckker & Geddes (1980). *P. zietziana* is known to tolerate salinities up to 353‰

(Geddes 1981b). The cosmopolitan brine shrimp *Artemia salina* now occurs in Australia in solar ponds but has been introduced recently by man (Geddes 1979, 1981b).

Two species of amphipods are recorded in Australian salt lakes; they belong to the same genus, *Austrochiltonia,* and there is now consensus that they maybe conspecific (W. D. Williams, pers. commun.). Lim & Williams (1971) recorded both species at up to 25‰ salinity and De Deckker & Geddes (1980) recorded *A. australis* up to 62.2‰ in the field. It is of interest to note that the same species of *Austrochiltonia* also inhabit(s) fresh waters and is by far the commonest amphipod in Australian surface waters (Williams 1981b).

Gastropoda

Among other significant components of the halobiont fauna in Australia are those gastropods grouped in the genus *Coxiella.* The revision of this genus by McPherson (1957) is now considered to require further study (Mellor 1979; De Deckker & Geddes 1980). The works of Kirton (1971) on a Victorian species and of Mellor (1979) for (perhaps) another species from South Australia are of importance for the biology of *Coxiella,* as are the data on salinity tolerance in the field presented in Mellor (1979) and De Deckker & Geddes (1980).

Rotifera

Walker (1973) examined the population dynamics of the rotifer *Brachionus plicatilis* which was the dominant zooplankter in Lake Werowrap, a permanent shallow lake in western Victoria. Data is also available on another rotifer *Hexartha jenkinae.* Hammer (1981b) reported very high populations of these species in Red Rock Tarn but much lower populations of *B. plicatilis* and *H. fennica* in Lake Corangamite.

Other invertebrate groups

Racek (1969) recorded the presence of a spongillid sponge *Heterorotula capewelli* tolerant to saline waters in Central Australia but provided no additional information. Ruinen (1938a, b) and Ruinen & Baas Becking (1938) discuss the occurrence of protozoans in Australian salt lakes. These papers will not be discussed further as they have been updated recently by Post *et al.* (1983).

There are also many other invertebrates which have been recorded in Victorian and Western Australian lakes but they will not be discussed further as little information is available on them except for field salinity ranges. Many of these organisms have not been identified at the species level. Hemipterans, odonatans, lepidopterans, coleopterans, dipterans, oligochaetes, cnidarians, nematodes have been recorded; for further information on them refer to Williams (1981c) for Victoria and Geddes *et al* (1981) for Western Australia. Of interest is the study of Knowles & Williams (1973) which shows that corixids in Victoria do not live in highly saline waters (highest record 13.4‰) and only six species were recorded. Walker (1973) studied the chironomid *Tanytarsus barbitarsis* in Lake Werowrap. The seasonal study of the invertebrate communities in two Victorian salt lakes by Timms (1981) presents additional information on a number of taxa mentioned above. In addition, seasonal studies for a number of Victorian saline lakes by Geddes (1976) and lakes near the Coorong Lagoon in South Australia by De Deckker & Geddes (1980) provide pertinent data on seasonal fluctuations of species, most of which are crustaceans. One should be aware that the lakes studied by Timms (1981) have permanent water with low fluctuating salinity and that those studied by De Deckker & Geddes (1980) are ephemeral and with great salinity fluctuations. These factors (permanent *vs* emphemeral water, and stable *vs* fluctuating salinity) control the composition of the fauna in the lakes.

Vertebrata

There are 19 species of waterfowl in Australia and most frequently visit salt lakes. Data on their distribution, feeding requirements and other aspects of their ecology are summarized in Frith (1967) and MacDonald (1973). It is surprising to find that flamingos which are commonly associated with salt lakes in many parts of the world are absent today in Australia. However, fossil remains of a number of species from Miocene to Pleistocene in age have been found in Australia (Rich 1975). One wonders whether their disappearance was caused by a change in hydrological regime in Australian salt lakes with lakes becoming more frequently dry or with a change in water chemistry affecting the plankton on which they usually feed.

With regard to the presence of fish in salt lakes, Chessman & Williams (1974) reported on collections made in inland salt lakes in Victoria and Glover & Sim (1978) and Glover (1982) from central Australian waters. They gave salinity records for the species found: in Victoria, none of the six strictly inland species was found to occur at salinities in excess of 31‰, although Glover & Sim (1978) mentioned that the species *Craterocephalus eyeresii* is found in salinities up to 110‰ in the Murray Darling drainage system.

Flora

Investigations of the flora of Australian lakes are fewer than for those of the fauna. The most conspicuous halophytes in Australia are grouped in two genera: *Ruppia* and *Lepilaena*. Species belonging to both genera are at present being revised by Dr M. Brock but information is already available on *Ruppia* in Brock (1982a, b). Their ecology in slightly to moderately saline lakes in southeast South Australia is presented in Brock (1981, 1982b). In addition, she provides information (Brock 1981) (for some of the same lakes) on the charophyte *Lamprothamnium papulosum* which is known to occur in salt lakes throughout southern Australia (Burne *et al.* 1980).

Studies on the phytoplankton are also few but a greater variety of species are recognized. They will not be further discussed here but relevant references are supplied; of significance is the work of Walker (1973) on the seasonal succession and abundance of the significant blue-green algae *Anabaena spiroides* and ?*Chroococcus*, and the dinoflagellate *Gymnodinium aeruginosum*. Other blue green algae were recorded in Walker's study. However, the most comprehensive list of phytoplankton recorded in salt lakes is that of Hammer (1981b) for Walker's lake (Werowrap) and others in the vicinity (Colac, Coragulac, Red Rock, Pink and Corangamite). Three of the lakes studied by Hammer (1981b) were dominated by specific phytoplankton blooms: Red Rock *(A. spiroides)*, Corangamite *(Nodularia spumigena)* and Pink *(Dunaliella salina)*; Lake coragulac had a more diverse population. Hammer (1981a, b) also calculated primary production and found that Red Rock Tarn had some of the highest production values ever recorded which he thinks are related to high soluble phosphate and inorganic carbon concentrations.

The only record of diatoms in salt lakes is for a few crater lakes in Victoria by Yezdani (1970) and Tudor (1973). Of note also is Hussainy's (1972) work on the bacterial and algal chlorophyll in two of the same crater lakes where bacterial chlorophyll was in the highest concentration. Recently, Borowitzka (1981), in her review of the microflora from extremely saline lakes, discussed the occurrence and adaptations of *Dunaliella* and *Halobacterium* in Australian salt lakes.

So far the only published records of algal mats in Australian salt lakes is that of Walter *et al.* (1973), Bauld (1981) and De Deckker *et al.* (1982). The mats are built of cyanophytes, and similar mats have been recorded in many salt lakes across southern Australia (J. Bauld pers. comm.). It appears that substantial thicknesses of algal mats will only remain on floors of ephemeral lakes in areas where sedimentation rates are high, and can therefore prevent the erosion of mats. This would require substantial groundwater discharge or rainfall into the lakes, a phenomenon not seen in most lakes far from the today's coast.

An interesting but not surprising phenomenon is that coastal lakes which retain permanent water can have a component of their fauna which is truly marine. Such a case has been illustrated by Bayly (1970) for lakes which have salinities below that of sea water in southeast South Australia near Robe. Marine fishes, polychaetes and harpacticoids have been found (Bayly 1970; Hutchings *et al.* 1981), as well as some foraminiferans (Cann & De Deckker 1981). All these organisms which are truly marine are likely to have been transported into the lakes by birds.

Discussion

It should be noted that the long history of aridity in Australia (Bowler 1976b) is likely to have contributed to the high diversity of crustacean species and their adaptation to salt lakes; this is best illustrated by the ostracod fauna. On the other hand, the insect fauna is poorly diversified in comparison with that of other continents (Antarctica excepted) where coleopterans, corixids and ephydrids are common inhabitants of salt lakes (e.g., in British Columbia: Scudder 1969; in Africa: Beadle 1974). When examining the distribution of many organisms in Australia, it becomes evident that salt lakes near the coast (but not connected to the sea) yield the highest diversity of organisms. This was best documented in the work of De Deckker & Geddes (1980) which records up to 11 species of crustacean in a number of coastal lakes, a higher number than for lakes further inland in Victoria (Bayly & Williams 1966; Geddes 1976) and Western Australia (Geddes *et al.* 1981). The fauna was even more depauperate in the large playa lakes such as Lake Eyre which was sampled when full by Bayly (1976), or Lake Buchanan in Central Queensland (De Deckker, unpubl. data). Apart from salinity, the most likely factor controlling species diversity in salt lakes in Australia is the variability of rainfall. Information obtained from Gaffney (1975) and referred to in Fig. 3 indicates that near the coast

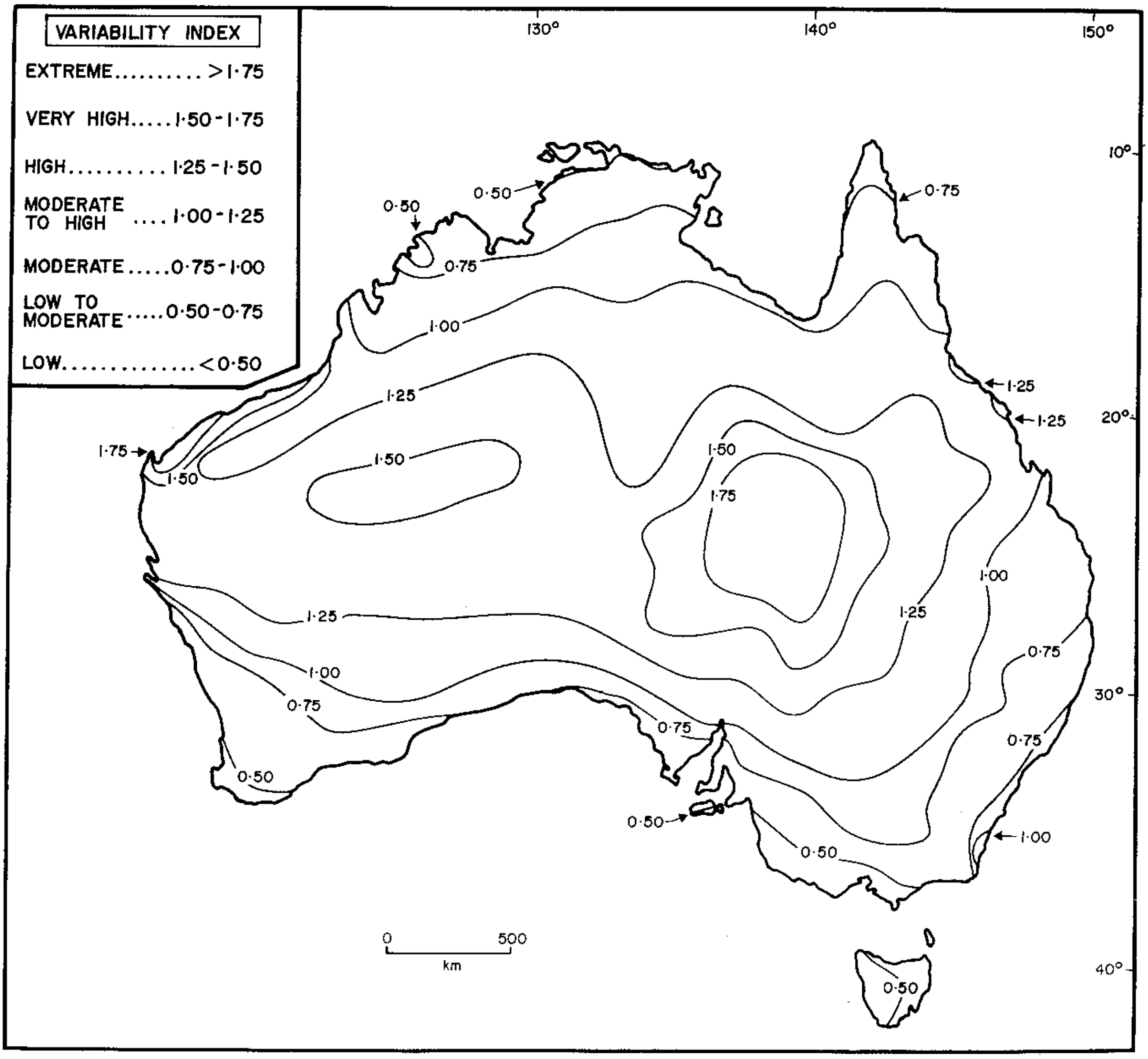

Fig. 3. Map showing the annual rainfall variability for Australia using the variability index based on annual rainfall percentiles (90, 50 and 10). The variability index is calculated as $\frac{90 \cdot 10}{50}$ Redrawn from Gaffney (1975).

rainfall variability is comparatively low but increases further inland. This has an important effect on the survival of many species: since most salt lakes are ephemeral today, low rainfall variability combined with high rainfall (the case for lakes near the coast) will fill the lakes annually and therefore permit a large number of species to survive as periods of lake desiccation are short. This is the case for the isopod *H. searlei*, the gastropods *Coxiella* spp., the amphipod *Austrochiltonia* sp., the cyclopoids, foraminiferans, etc.). On the other hand, the high rainfall variability in central Australia will prevent the above-mentioned organisms from surviving in the saline lakes which are all ephemeral today and often dry for long periods of time. However, there is evidence that *Coxiella* at least was living in large lakes in Central Australia such as Lake Eyre (Ludbrook 1956) and Frome (De Deckker, unpubl.). Foraminifers have also been recorded from sediments of these lakes (Ludbrook 1956; Cann & De Deckker 1981; Draper & Jensen 1976) but none are found living in these lakes today. The distribution of the same species of Foraminifera is at present restricted to lakes near the coast (where rainfall variability is small); for further discussion see Cann & De Deckker (1981). Conditions of low rainfall variability and most likely combined with higher rainfall must have occurred in the past at Lakes Frome and Eyre for the foraminifers to live there. This would also explain the presence of *Ruppia* seeds found in a core from Lake Frome (De Deckker unpubl.); *Ruppia* and *Lepilaena* were not seen in Lake Frome when it was recently full. It is therefore necessary to realize that present day distribution of the salt lakes biota is, to some extent, controlled by the variability of rainfall and that in the past rainfall conditions were different, implying also that salt lakes had different hydrological/chemical regimes. In addition, it is important to be aware that the biota found in Australian salt lakes is not only the result of a long history of aridity but that it also has witnessed changes of brine chemistries and hydrological regimes through time.

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