The Geomorphology and Hydrology of Saline Lakes of the Middle Paroo, Arid-zone Australia.

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Sixteen subsaline (0.5 – 3 gL^{-1}) and saline lakes (> 3 gL^{-1}) of the Paroo have been studied for periods of up to 18 years. Many were formed by drainage routes being blocked by dunes, some lie in dune swales, some lie at the edge of the Paroo floodplain where alluvial sediments are thinner, and Lake Wyara lies in a depression on a fault line. All developed further by deflation and owe their form to wind-induced currents and wave action shaping shorelines. Most saline lakes have lunette dunes on the eastern shore, and many larger ones have migrated westwards. Lakes of low salinity have sandy beaches and no, or poorly developed, lunettes. Lakes with N-S axes have the southeastern corner cut off by spits generated by currents induced by northwesterley winds. A few lakes are filling with sediment derived from the overgrazing of catchments associated with European settlement.

Larger lakes with inflowing streams fill in El Niño years, then dry over the next few years. Smaller lakes without surface inflows may fill a few times in wet years but dry quickly. Most lakes remain dry in La Nina years. Salinity regimes fluctuate widely and, while instantaneous faunal lists may be depauperate, cumulative species lists can be long. However, lakes which normally are fresh, but become saline in their final stage of drying, develop only a limited saline lake fauna.

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KEYWORDS: biodiversity, El Niño, lake compartmentilisation, lake migration, lake origins, lake sedimentation, lunette dunes, saline lakes, spits.

INTRODUCTION

In most hot arid lands, geomorphic processes and resultant landforms are dominated by wind action on unconsolidated surfaces (Thomas, 1989). Therefore depressions and their lakes are likely to owe their origin to aeolian processes, or at least have their basins and shorelines modified by wind. Furthermore, because drainage is often uncoordinated, most lakes are closed hydrologically (Cole, 1968, 1983), so that saline waters abound. Lakes fill and dry intermittently (Williams, 1984), either seasonally or episodically according to prevailing climate. The extent of filling is influenced by the interaction between rainfall, evaporation, lake basin geomorphology and hydrological character of the catchment. In total, the geomorphology and hydrology of arid-zone lakes, particularly if saline, are likely to be distinctive.

In the Australian context, these issues have been partly explored at the large scale (lake areas > 100 km^2) on Lake Eyre (Kotwicki, 1986) and its predecessor Lake Dieri (de Vogel et al, 2004), on Lake Victoria in southwestern New South Wales (Gill, 1973; Lees and Cook, 1991; Chen, 1992), and on lakes of Salinaland in Western Australia (Van de Graaf et al., 1977). The SLEADS program on large salina playas in Australia's arid and semi-arid inland (Chivas and Bowler, 1986), besides its main aim of interpreting past climates from lake sediments and lunettes, has confirmed the role of wind in lake basin evolution. Besides these studies on large salinas, much can also be learnt from comparative studies on smaller lakes (A < 50 km^2, often < 5 km^2) of a confined area where the hydrological pattern is known. The middle Paroo of northwestern New South Wales and southwestern Queensland has many small saline lakes and a few freshwater lakes (Fig. 1) that salinise as they dry, and moreover hydrological data covering many years (up to 18) are available for most. It is the aim this contribution to explore role

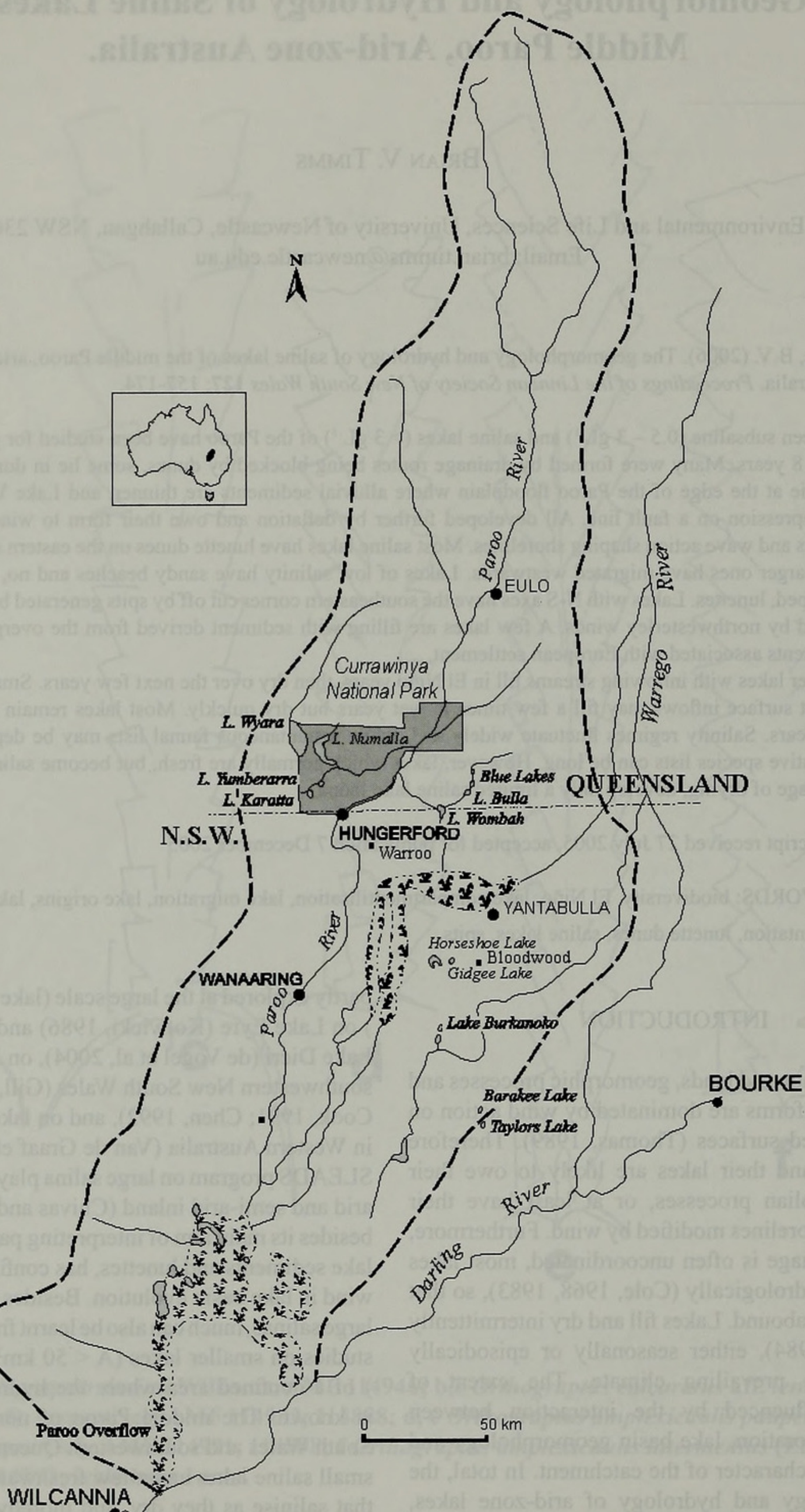

Figure 1. Map of the Paroo catchment, southwestern Queensland and northwestern New South Wales. The location of most of the lakes mentioned in the text are shown.

of hydrology and geomorphology in the limnology of the Paroo lakes, as well as the significance of wind action for determining lake basin process and form.

METHODS

Most of the middle Paroo study lakes are closed hydrologically, so that water levels fluctuate according to the balance between precipitation and evaporation, both on the lake basin and its catchment. Evenso, each lake generally has a distinct shoreline visible on an aerial photograph to which it has filled many times. This was designated the 'full' level and used as the lake outline on the accompanying maps. Occasionally, perhaps once in 20-100 years, a lake may fill to a greater depth, as Lake Wyara (Fig. 1) has done four times in the last 110 years (Timms, 1998a); such fillings are not accounted for geomorphogically in this study (i.e. shorelines, areas and depths refer to normal 'full' conditions, unless noted otherwise).

Lakes (Fig. 1) were mapped when dry using a dumpy level, often fitted with laser technology. In small lakes a cart-wheel system of transects were used, with the dumpy in the deepest part of the lake and measurement lines radiating outwards at 25 to 35° intervals and readings taken every 10-50 m, depending on lake size and change in elevations. If transect lines were longer than 250 m (e.g. Lower Bell Lake, Gidgee Lake, Lake Burkanoko), subsidiary lines were used commencing 100 - 250m from the central pivot point and radiating out at 15 to 25° angles, so that the shoreline was intercepted regularly at intervals of 25 -100 m, depending on lake size and lakebed irregularities. Some lines crossed each other and hence provided checks on elevations. In larger lakes (e.g. Lake Yumberarra, North Blue, Taylors Lake) cartwheels were used at each end and parallel transects in between with some lines crossing for checks on accuracy. This method enabled contours with an accuracy of ±1 cm or better to be drawn. Contour intervals of 10 to 50 cm were adopted, though occasionally intervals as low as 2.5 cm were employed. In some lakes (Lower Bell, Gidgee, Burkanoko and Barakee) it was easy to detect new red clayey sediments on older white gypseous surfaces, so it was possible to collect data on recent sediment depths at the same time as surface elevations were being recorded.

Three lakes (Lakes Wyara, Numalla and Horseshoe) were too big to be mapped efficiently by these methods, so analyses are restricted to shoreline features. There were also problems mapping Mid Blue Lake (namely, cross correlation of transects), so a detailed map of this lake is not available.

The lakes were visited at varying intervals between August 1987 and June 2005, more often in wet years (e.g. eight times in 1998) and rarely in lingering drought years (e.g. twice in 2004). On each visit, lake levels were noted and salinity (i.e. TDS) determined by gravimetry. Between visits, further information on water levels in most lakes was gained from local landowners. Rainfall data from Warroo Station (Fig. 1), in the northern part of the study area, was used as representative for the study area, though it varied monthly by up to 26% and yearly by 15% from figures for individual station properties with lakes included in this study.

Although this paper is concerned mainly with geomorphology and hydrology, some biological data on salinising freshwater lakes were collected. Methods used were as described in Timms (1998a) and Timms and McDougall (2005).

RESULTS

Rainfall

Yearly rainfall at Warroo Station fluctuated between 70.5 mm in 2002 to 685 mm in 2000 (Fig. 2), both near records for Warroo (P.and M. Dunk. pers. com.), with 1998-2000 well above the 76-year average of 301 mm and 2001-2004 well below. Rainfall events > 100 mm in a few days, of the kind that fills lakes, occurred in December 1987 (108 mm), April 1988 (103 mm), May 1989 (122 mm), April 1990 (265 mm), January 1995 (192 mm), January 1998 (162 mm), June 1998 (163 mm), November 1999 (119 mm), May 2000 (253 mm), and November 2000 (217 mm). The exceptionally wet years had positive Southern Ossication Indexes (hereafter SOIs and based on monthly fluctuations in air pressure differences between Tahiti and Darwin – Bureau of Meteorology, website). Thus from May 1998 to April 2001 all monthy SOIs were positive except two and for 2000 the average was 7.6), whereas during the dry years of 2001-2004 SOIs were almost continuously negative for 44 months and with a 2002 average of -6.1 (Bureau of Meteorology, website). Generally these rain events, and some outside the study area (the 'dry floods'), caused moderate to major flooding in the Paroo which contributed to the filling of two of the study lakes, Numalla and Wombah. The most recent inflows into Numalla and Wombah were in November 2000 (major) and January 2004 (minor).

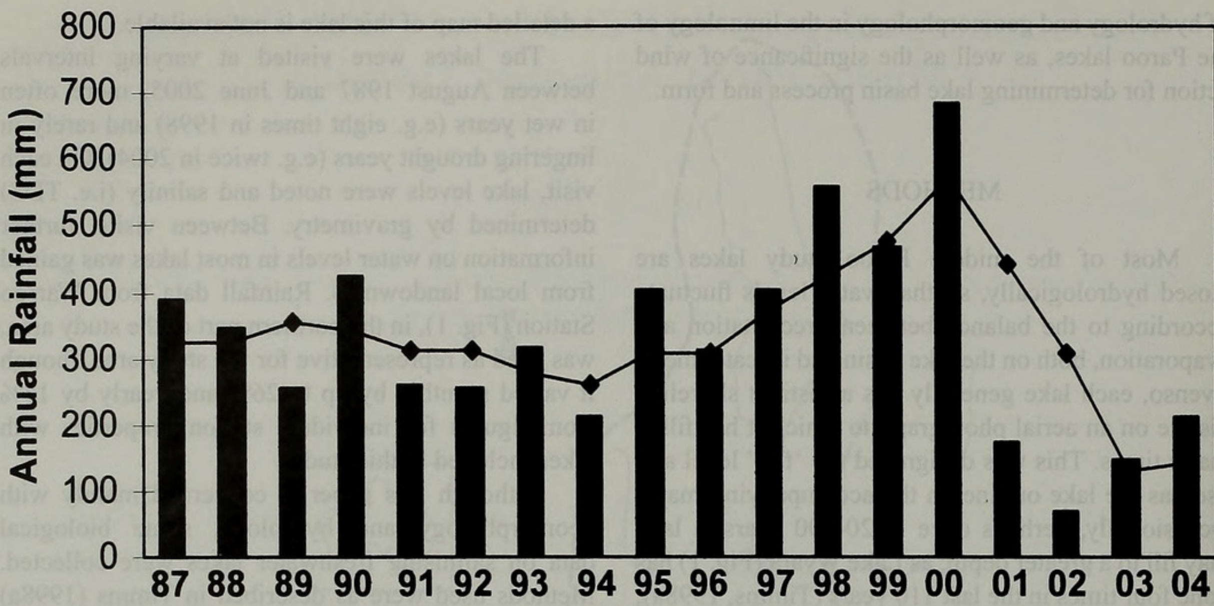

Figure 2. Variation in annual rainfall 1987 -2004 at Warroo Station, middle Paroo. Three year moving average shown by solid line.

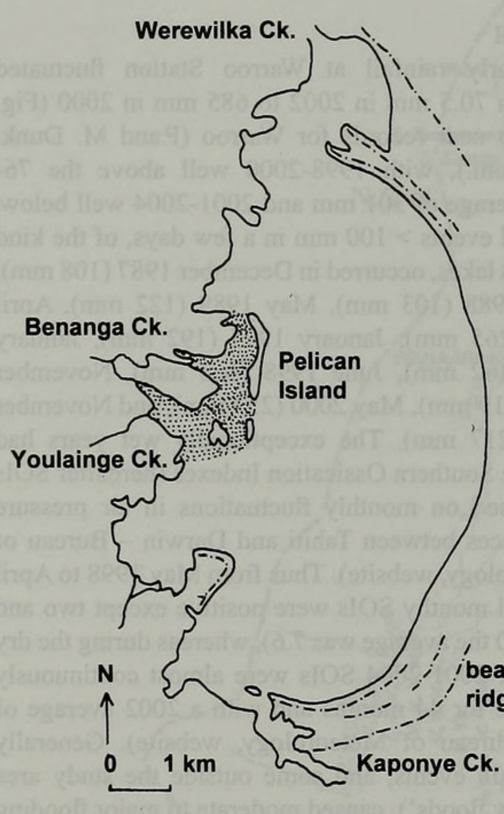

Figure 3. Lake Wyara showing the main inflowing creeks, beach ridges and the depositional area (stippled) behind Pelican Island. After Timms (1998a).

Lake Wyara

Lake Wyara is the largest of the lakes studied, with an area of 3400 ha. It is D-shaped with the longest axis N-S of 8.5 km and width 4.5 km (Fig 3). The eastern shoreline is evenly curved, with well developed beaches and spits at each end largely occluding the mouths of the two major inflowing creeks. There is an ancient lunette, 400-700m east of the average shoreline, which is hardly visible on the ground but noticeable on satellite images. The western shore is irregular but smoothed somewhat with offshore islands which are inundated when water levels are high but connected to the mainland at low levels (the large island to the southwest is connected at average 'lakefull' stage while Pelican Island is isolated (Fig. 3). Details of beaches and islands are given in Timms (1998a). The catchments of Benanga and Youlainge Creeks to the middle west of the lake are severely eroded so that much clayey soft sediment has been deposited recently behind the islands (i.e. over the last few decades including during 1987-1996 when the lake was visited regularly – Timms, 1998a). The deepest area is ca 750m north of the southern shore; depth fluctuates widely, often up to ca 2.6m, sometimes to ca 4m, and rarely to ca 6.9 m, at which level it overflows (see Timms, 1998a, for details).

Lake Wyara fills from its own catchment (mainly from Werewilka Ck) and occasionally overflows via Kaponyee Creek to the Paroo River. It holds water most of the time (Fig. 4) but dries in moderate to major droughts and has overflowed just four times

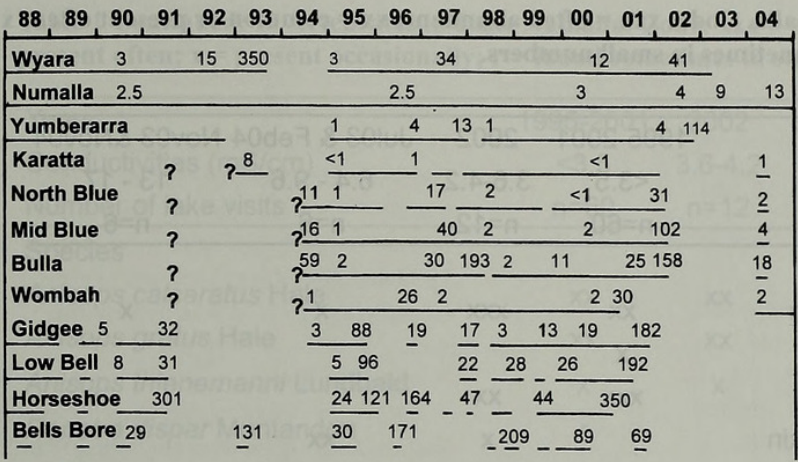

Figure 4. Comparsions of wet (black line) and dry periods (blanks) of Paroo lakes. Some salinities (TDS in gL^{-1}) are given.

in the last 118 years. Details are provided in Timms (1998a). Periods of being full and dry are strongly correlated with pulses of rainfall-drought explained by the SOI (r = 0.622, p> 0.001, n =34). Salinities vary greatly from almost fresh to crystallising brine.

Lake Numalla

Lake Numalla is the second largest lake (A = 2900 ha, Timms, 1999, 2001a) of the middle Paroo (Figs 1 & 5). It lies near the edge of the Paroo floodplain along Boorara Ck and is connected to the main river by a distributary channel of Carwarra Ck.

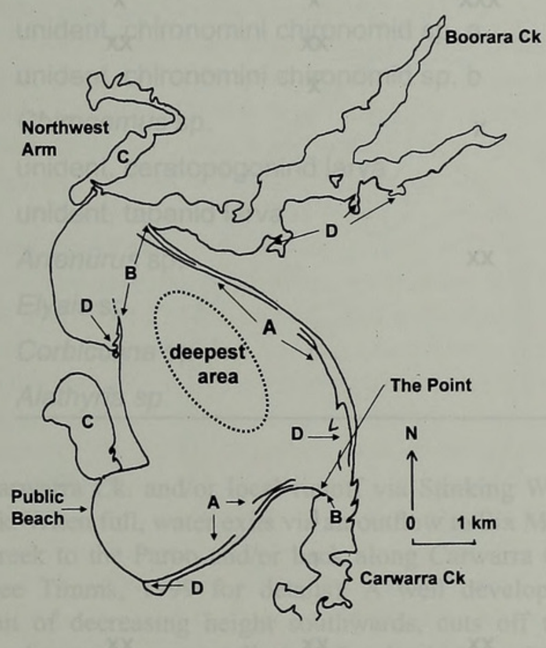

Figure 5. Lake Numulla showing beaches (A), spits (B), major occluded bays (C), and minor occluded bays (D).

Shorelines are sandy everywhere and usually gently shelving, but there are parallel beach ridges on the southern and eastern shores (marked A in Fig. 5), the inner beach inundated at higher water levels. Major spits occur at sudden changes in shore orientation (B on Fig. 5) and in two places these almost occlude two large backwaters, the Northwest Arm and a lakelet north of the Public Beach (C on Fig. 5). Smaller sandy spits partially cut off a few small bays and an incipient spit north of The Point is building out from the northeast, but has only partially occluded this corner of lake (D on Fig. 5). The lake is 6.5 m deep when full; when levels are low, as in 2002-05, creek inlets are dry, the Northwest Arm drying first, followed by Carwarra Ck. There is no lunette dune associated with this lake.

Lake Numalla held water throughout the study period (but dried in mid 2005) and besides receiving local runoff via the three northern arms, its main source of water comes from Paroo 'freshes', which reach the lake via Carwarra Ck. Water in the lake is generally subsaline (0.5 – 3 gL^{-1}), but at low water levels, salinity increases to hyposaline conditions (Fig 4) and finally becomes hypersaline (L. Fabbro in Hobson et al., 2005, recorded a conductivity of 104,000 µS/cm in May 2005). Inflowing water is of very low salinity (<100 µS/cm) and mixes poorly with incumbent water because of the embayments in the lake, so salinity can vary spatially (see Timms, 1997a).

Lake Numalla supports abundant waterbird and turtle populations (Kingsford and Porter, 1994; Hobson et al., 2005), though the invertebrate fauna is neither rich nor abundant compared with other lakes in the area (Table 1 cf Hancock and Timms, 2002; Timms, 2001b; Timms and Boulton, 2001; Timms and McDougall, 2005). As the lake naturally salinised between 2002-2005, the invertebrate fauna became less diverse and dominated by salt-tolerant species together with some typical saline lake species (Table 1).

Lake Yumberarra

This lake is a triangular-shaped, 170 ha in area and 3.4 m deep when full (Fig. 6). It lies in a depression in Quaternary alluvium at the edge of the Paroo floodplain. It is fed by Paroo floodwater via

Table 1. Invertebrates in Lake Numalla. Code: xxx = often abundant; xx = common or present often; x = present occasionally; r = found sometimes in small numbers.

Years	1995-2001	2002	Jul03 & Feb04	Nov03 &Nov04
Conductivities (mS/cm)	<3.5	3.6-4.2	6.4 - 9.6	13 - 17
Number of lake visits	n=60	n=12	n=6	n=6
Species				
Boeckella triarticulata Thomson	xx	xxx	x	x
Calamoecia canberra Bayly	x			
Calamoecia lucasi Brady	xxx	xx		
Apocyclops dengizus Lepeschkin		x	xx	
Metacyclops sp.	x			
Mesocyclops cf *woutersi* Van de Velde				xxx
Cletocamptus deitersi Richard	x	x		
Diaphanosoma unguiculatum Gurney	x			
Moina australiensis Sars		x	xx	
Moina micrura Kurz	xx	xx		
Bosmina meridionalis Sars	r			
Daphnia carinata s.l.King	r			
Ceriodaphnia cornuta Sars	r			
chydorids (mainly *Alona* spp.)	r	r		
Heterocypris sp.		r	x	xx
Mytilocypris splendida (Chapman)			x	x
Asplanchna sieboldi (Leydig)	x	x	x	x
Brachionus calyciflorus Pallas	x	xxx	x	x
Brachionus ibericus Ciros-Perez et al.			xx	xx
Filinia australiensis Koste			x	
Filinia cf pejleri Hutchinson		x		
Hexarthra sp.	x			
Keratella sp.	x			
Macrobrachium australiense Holthuis	xx	xx		
Cherax destructor Clark	r			
Cloeon sp.	x			
Tasmanocoenis tillyardi (Lestage)	x			
Xanthoagrion erythroneurum Selys	x			
Diplacoides spp.	r			
Hemianax papuensis (Burmeister)	r		r	
Hemicordulia tau (Selys)	r		r	
Austrogomphus sp.	x			
Agraptocorixa eurynome Kirklady	xx	xx	xx	xx
Agraptocorixa parvipunctata Hale	x	x		x
Micronecta sp.	xxx	xxx	xxx	xxx

Table 1 Continued: Invertebrates in Lake Numalla. Code: xxx = often abundant; xx = common or present often; x = present occasionally; r = found sometimes in small numbers.

Years	1995-2001	2002	Jul03 & Feb04	Nov03 &Nov04
Conductivities (mS/cm)	<3.5	3.6-4.2	6.4 - 9.6	13 - 17
Number of lake visits	n=60	n=12	n=6	n=6
Species				
Anisops calcaratus Hale	xx	xx	x	x
Anisops gratus Hale	xx	xx	xx	xx
Anisops thienemanni Lundbald	x	x	x	
Ranatra dispar Montandon	r			
Naucoris congrex Stal	r			
Limnogonus sp.	r			
Oecetis sp.	r			
Triplectides australicus Banks	r			
Allodessus bistrigatus (Clark)	r			
Antiporus gilberti Clark	r		r	
Berosus munitipennis Blackburn	r			
Berosus australiae Mulsant	r	r	r	
Enochrus eyrensis (Blackburn)	r		r	
Hydaticus christi Nilsson		r	r	
Rhantus suturalis (W. MacLeay)	r			
Sternopriscus multimaculatus (Sharp)			r	
unident. tanypodine chironomid	x		x	x
unident. chironomini chironomid sp. a	r		xx	x
unident. chironomini chironomid sp. b	x	x		
Chironomus sp.	x	x		x
unident. ceratopogonind larva	x			x
unident. tabanid larva	r			
Arrenurus sp.	x		r	
Elyais sp.	x		r	
Corbiculina sp.	x	r		
Alathyria sp.	r			

Carwarra Ck. and/or local runoff via Stinking Well Ck. When full, water exits via an outflow to Six Mile Creek to the Paroo and/or back along Carwarra Ck (see Timms, 1999 for details). A well developed spit of decreasing height southwards, cuts off the southeastern corner totally (at 0.5 m depth) to partially (at 2 m depth). No enhanced sedimentation in the main lake was detected. A lunette only 1.5m higher than the full shoreline flanks the eastern shore.

Lake Yumberarra had three filling-drying cycles during the 17 years of study. It usually fills from Paroo floods, but can fill from local runoff, as it did in July 1998 (see Timms and McDougall, 2005). The lake is usually fresh, but it naturally salinises as it dries. During such periods it gains some saline species, but some salt-tolerant freshwater species persist (see Timms and McDougall, 2005).

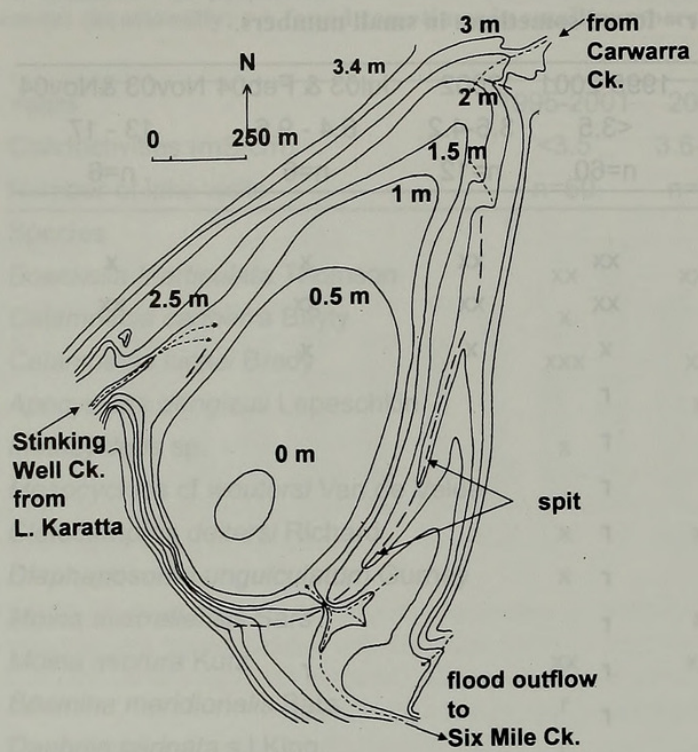

Figure 6. Bathymetric map of Lake Yumberarra. Contour intervals 0.5m. Map based on Fig 1 in Timms & McDougall (2005). Key: beach ridges – long dashes; creek channels – short dashes.

Lake Karatta generally fills from local runoff via Stinking Well Creek, but occasionally Paroo floodwater reaches it via Lake Yumberarra (details in Timms, 1999). During the wet years of 1998-2000 it remained full, but soon dried in the 2002 drought (Fig. 3). At other times it may partially fill and soon dry, as in 1997 and 2004 (Fig. 3). Water is generally fresh, but in 1993 it was hyposaline.

North Blue Lake

North Blue Lake on Rockwell Station is elongate oval shaped, 205 ha in area and up to 2.3 m deep when full, but usually depths are < 1m (Fig. 8). The long axis runs NNW-SSE. This lake is the first in a series (North Blue, Mid Blue, Bulla, and sometimes Lake Wombah) fed by Number 10 Creek, a major drainage line about 25 km long and partially blocked by dunes south of each lake. The indistinct shoreline varies from ~2 to 3 m above the deepest point. The western shore is partly cliffed and the eastern shore has a gypseous lunette highest in the southeast. The eastern shore has well-defined beaches, decreasing in height from north

Lake Karatta

Lake Karatta is hourglass-shaped, aligned N-S, 57 ha in area and near 1.2 m deep when full (Fig. 7). The basin lies in Quaternary alluvium at the edge of the Paroo floodplain. At the constriction, marked by two long spits, it receives a deeply incised Stinking Well Ck., the channel turning to the south, shallowing and eventually dividing. A small channel connects the two parts of the lake near the eastern shore (Fig. 7). The lake overflows to the northeast when it is >1.25 m above the deepest point in the southern basin. The lake basin contains much recent sediment, largely clays in the centre of the southern basin and loams and sands nearer the creek mouth. This recent sediment is 42 cm thick in the southern basin and > 1 m thick near the creek mouth (corer could not penetrate coarser bottom sediments). There is a broad, low lunette up to 1 m high abutting much of the eastern and southeastern shoreline.

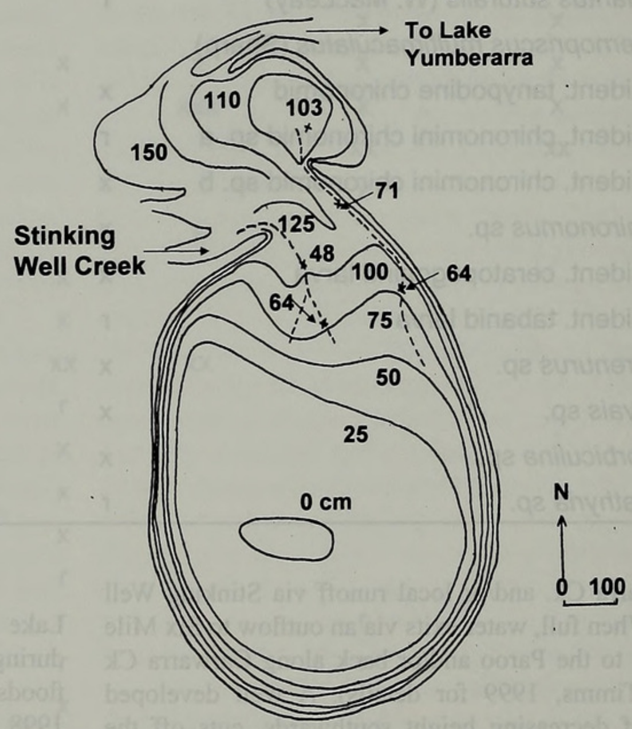

Figure 7. Bathymetric map of Lake Karatta with position of creek channels and spot heights in these above lowest point in the lake. Contour intervals 25 cms. Key: creek channels – short dashes.

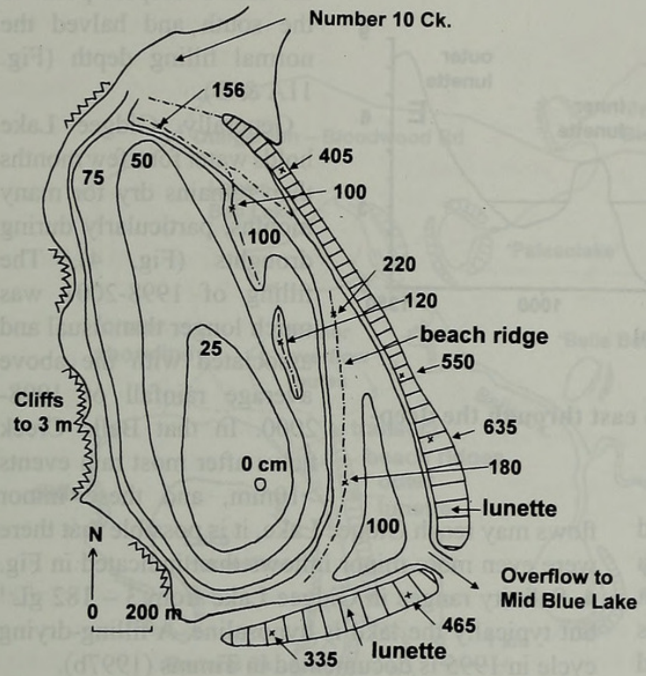

Figure 8. Bathymetric map of North Blue Lake with heights of the lunette dune on the eastern and southern shores and location of cliffs on the western shore. Contour intervals 25 cms. Key: beach ridges – dot and dashed lines.

to south; one cuts off the southeast corner of the lake. Lake sediments are deep muds which, when dry, are readily moved in dust storms and partially redeposited in the lee of samphires (*Arthrocnemum halocnemoides* Nees) in the littoral zone, on the beaches and beyond. Other data are given in Timms (in press a).

North Blue Lake held water for most of 1994-early 2002, but dried briefly three times. It also held some water in mid 2004 (Fig 4). Salinity varied from fresh to 31 gL^{-1}, with a median salinity of 4.2 gL^{-1}. Details are given in Timms (in press a).

Mid Blue Lake

The next lake downstream on Number 10 Creek is Mid Blue Lake which is also oval-shaped, but slightly bigger (at 210 ha) and considerably deeper when full (3.4 m). The bathymetric map (Fig. 9) is not as detailed as other maps, but together with the transect (Fig. 10), is sufficient to show relatively steeply shelving shores above the 1 m contour, a inner lunette system ending both north and south in a beach system and a massive outer lunette system. The lake has largely retreated from the occluded parts in the southeastern and northeastern corners. Much of the western shoreline is cliffed soft sandstones cemented by carbonates; on the transect (Fig. 10) these rocks are exposed in the shore zone and beyond this to at least 300m from the western cliffs where they are buried by 30-50 cm of grey mud.

Mid Blue Lake contained water continuously from 1994 to early 2002 and again in mid 2004. Its mean salinity (4.1 gL^{-1}) was similar to that in North Blue Lake, but the maximum salinity of 103 $gL^{-1}$was much higher. Further data are given in Timms (in press a).

Lake Bulla

Lake Bulla is a complex lake, with a western basin connected to extensive waterways backed up inflowing creeks and with many gypseous lunettes on its northern, eastern and southern shores. It is 420 ha in area and up to 4.8 m deep when full. Generally it is the final lake of the series on Number 10 Ck., as there is a dune system totally blocking the creek southwestwards. It receives water in the same pattern as the two lakes upstream (Fig.4), but has a greater salinity range (2 - 262 gL^{-1}), higher median salinity (9.8 gL^{-1}) and slightly shorter wet period. See Timms (in press a) for further data.

Lake Wombah

Lake Wombah is the largest of the Rockwell-Wombah system at 740 ha and 2.3 m deep. It is connected to the Paroo River and, like Lake Numalla, receives Paroo floodwater, but unlike Numalla, has limited beach and spit development. The western and northern shoreline is cliffed (up to 7.5 m high),

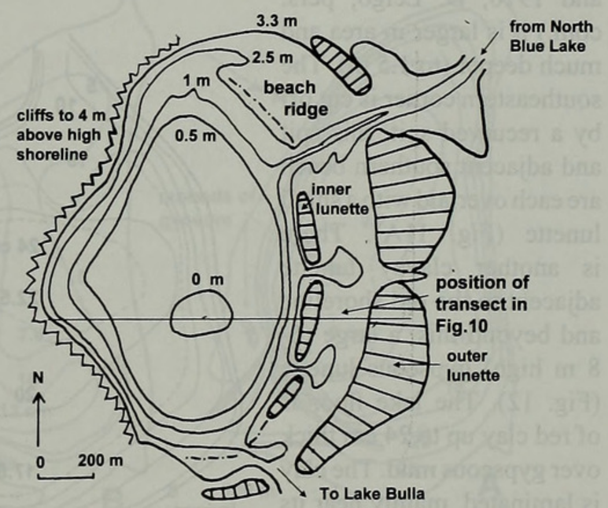

Figure 9. Incompete bathymetric map of Mid Blue Lake together with position of lunettes on eastern shore and cliffs on the western shore. Contours at 0, 0.5, 1 and 2.5m. Key: beach ridges – dot and dashed lines.

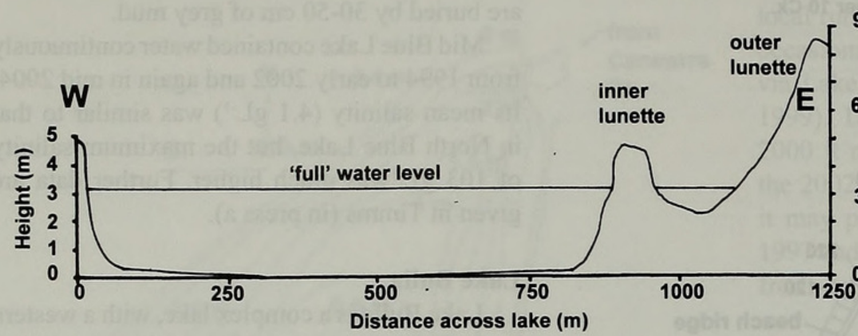

Figure 10. Transect across Mid Blue Lake west to east through the deepest portion

while the eastern shoreline abuts subdued inner and outer lunettes. Because Wombah fills mainly from the Paroo and not Number 10 Creek, it has different fluctuations in water levels than the Rockwell Lakes (Fig. 4), though salinity range (1 – 30 gL^{-1}) and median salinity (4.9 gL^{-1}) are similar. It dries more regularly than Lake Numalla, because it is less than a third its depth. Timms (in press a) presents more data on this lake.

Gidgee Lake

Gidgee Lake is an oval-shaped lake with a N-S major axis lying in a depression east of a dune system and connected by a channel to Bells Creek (Figs.11 & 12). In normal fillings it is160 ha in area and ca 5 cm deep, but in unusually large fillings (as in 1974 and 1976, D. Leigo, pers. com.) it is larger in area and much deeper (to 1.5 m). The southeastern corner is cut off by a recurved spit; this spit and adjacent southern beach are each overlaid with a small lunette (Fig. 11A). There is another clayey lunette adjacent to the old shoreline and beyond this, a large (5-8 m high) gypseous lunette (Fig. 12). The lake floor is of red clay up to 24 cm thick over gypseous mud. The clay is laminated, mainly near its base with the thick upper part believed to have been deposited in either of the big 1974 or 1976 fillings (D. Leigo, pers. com.). Recent sedimentation has moved the lake's deepest point to the south and halved the normal filling depth (Fig. 11A & B).

Generally, Gidgee Lake holds water for a few months then remains dry for many months, particularly during droughts (Fig. 4). The filling of 1998-2001 was much longer than usual and associated with the above average rainfall of 1998-2000. In that Bells Creek flows after most rain events >10mm, and these minor flows may reach Gidgee Lake, it is possible that there were even more minor inflows than indicated in Fig. 4. Salinity ranges in Gidgee Lake from 3 – 182 gL^{-1} but typically the lake is hyposaline. A filling-drying cycle in 1995 is documented in Timms (1997b).

Lower Bell Lake

At Lower Bell Lake, the 23 km long Bells Creek is blocked by a large dune advancing from the northwest. The lake is wedge-shaped with the main axis SW-NE and the creek entering in a wide channel at the southeastern corner (Figs 12 & 13). When full, the lake is 185 ha in area and about 30 cm deep. There is a bar across the mouth of Bells Creek; this is part of a beach system extending across the southeast

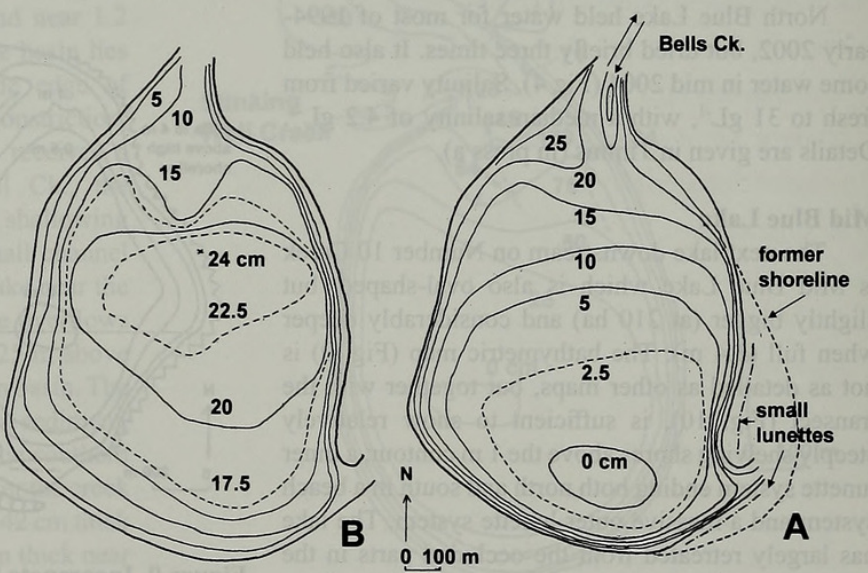

Figure 11. A, Bathymetric map of Gidgee Lake with main contour intervals at 5 cm. B, map showing extent of recent sedimentation in Gidgee Lake. Main contour interval 5 cm.

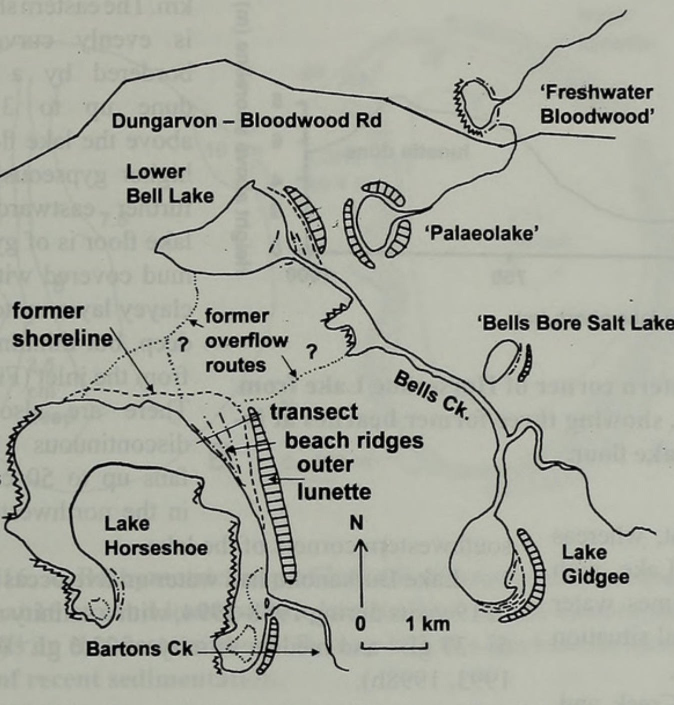

Figure 12. Map showing streams and lakes in the vicinity of the terminus of Bells Creek.

corner of the lake. The rudiments of another beach further into the lake and at lower elevation is marked by two low gypseous mounds and slight elevations in the lake floor as evidenced in the bathymetric map (Fig.13 A). The lake basin extends further east, is marked by some minor beach/ dune systems near Bells Creek, and is bordered by a large gypseous lunette (Fig. 12). The lake is floored with gypseous muds, covered by laminated red clays up to 13 cm deep and alternating with layers of small gypsum crystals. The bar and associated beach is composed of at least 1m of gypsum. There is a large (5-8 m high) gypeous lunette lying to the east of the lake

Lower Bell fills less often than Gidgee Lake and tends to dry sooner after filling. It is dry for many months to years. Salinity regime is similar to, but slightly more saline than, that of Lake Gidgee (Fig. 4). Like Gidgee Lake, it filled well beyond its normal shores in 1974 and 1976, so that it was possible to water ski on, and between, both lakes (D. Leigo. pers. com.). Events during a filling-drying cycle in 1995 are given in Timms (1997b).

Horseshoe Lake

Horseshoe Lake (A = 746 ha) has a flat floor with slightly deeper parts at the southern end of each arm (Fig.12), and a mound of sediment at the mouth of Bartons Creek partly occluding the southeastern portion. This mound is interpreted as an alluvial fan rather than a delta, as it has the profile and plan of a fan and is believed to form subaerially as the lake fills. Water depth is rarely > 30 cm. Besides a typical gypseous lunette on the eastern side and cliffs on the western shore, parts of the shoreline are backed by beach ridges. The most significant of these are in an area of the lake now abandoned in the northeastern corner (Figs 12 and 14), where there are three ridges increasing in average height landwards. There is no marked vertical differentiation in the bottom sediments, but those of the alluvial fan of Bartons Creek are more silty and give the appearance of recent deposition. Lake Horseshoe now never overflows, but two former pathways are evident to Lower Bell Lake (Fig. 12). Better evidence for a drainage change in this area is seen nearby at Palaeolake and Freshwater Lake (Fig. 12) – once Palaeolake with its older gypseous lunettes was

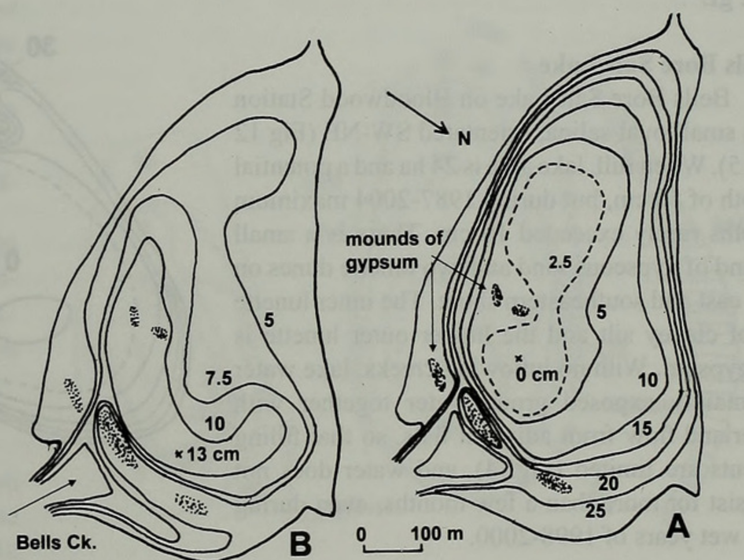

Figure 13. A, Bathymetric map of Lower Bell Lake with main contour intervals of 5 cm. Mounds of gypsum shown dotted. B, map of Lower Bell Lake showing extent of recent sedimentation. Contour intervals at 5, 7.5 and 10 cm.

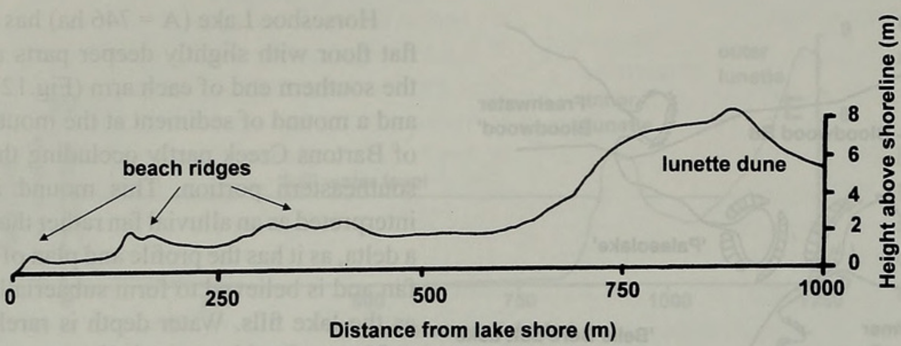

Fig 14. Transect through the northeastern corner of Horseshoe Lake from the lake shore to the gypseous lunette, showing three former beaches at increasing elevation above the present lake floor.

the only ponding place in this catchment, whereas now, water ponds mainly in Freshwater Lake, with its younger inner clayey lunette. Sometimes water flows on to Palaeolake, creating an unusual situation of water abutting an older gypeous lunette.

Horseshoe Lake fills from Bartons Creek and, like Lower Bell Lake, did not overflow during the study period. Filling is even more intermittent than for Lower Bell Lake, and prevailing salinities higher, so that meosaline – hypersaline conditions mostly prevail (Fig. 4). Salinities often increase along the axis of the lake from the inflow of freshwater to the southeastern corner to the blind southwestern corner, e.g. in July 2001, the gradient was 64 to 182 gL^{-1}.

Bells Bore Salt Lake

Bells Bore Salt Lake on Bloodwood Station is a small oval salina, orientated SW-NE (Fig 12 & 15). When full, lake area is 24 ha and a potential depth of 50 cm, but during 1987-2004 maximum depths rarely exceeded 10 cm. There is a small island of gypseous sand and two lunette dunes on the east and southeastern shore. The inner lunette is of clayey silt and the higher outer lunette is of gypsum. With no inflowing creeks, lake water is mainly exposed groundwater together with overland flow from adjacent flats, so that filling events are limited (Fig. 4), and water does not persist for more than a few months, even during the wet years of 1998-2000.

Lake Burkanoko

Lake Burkanoko on Wangamanna Station is oval shaped with a N-S major axis and is 280 ha in area and ca 40 cm deep when full (Fig. 16A). It is the terminus for a creek flowing from the northeast for about 11 km. The eastern shoreline is evenly curved and bordered by a lunette dune up to 330 cm above the lake floor and higher gypseous lunette further eastwards. The lake floor is of gypseous mud covered with a red clayey layer up to 10 cm deep, but thinning away from the inlet (Fig 16B). There are also short, discontinuous alluvial fans up to 50 cm deep in the northwestern and southwestern corners of the lake.

Lake Burkanoko had water on five occasions out of 19 visits during 1988-1994, with a salinity range of 6 – 37 gL^{-1} and median salinity of 22.6 gL^{-1} (Timms, 1993, 1998b).

Lake Barakee

One of many small salinas on Barakee and adjacent Goonery Stations, Barakee Lake (Fig. 17A) is a small oval salina (A = 90 ha) with a N-S axis, lying between western cliffs up to 5 m high in a transgressive dune and two lunettes to the east.

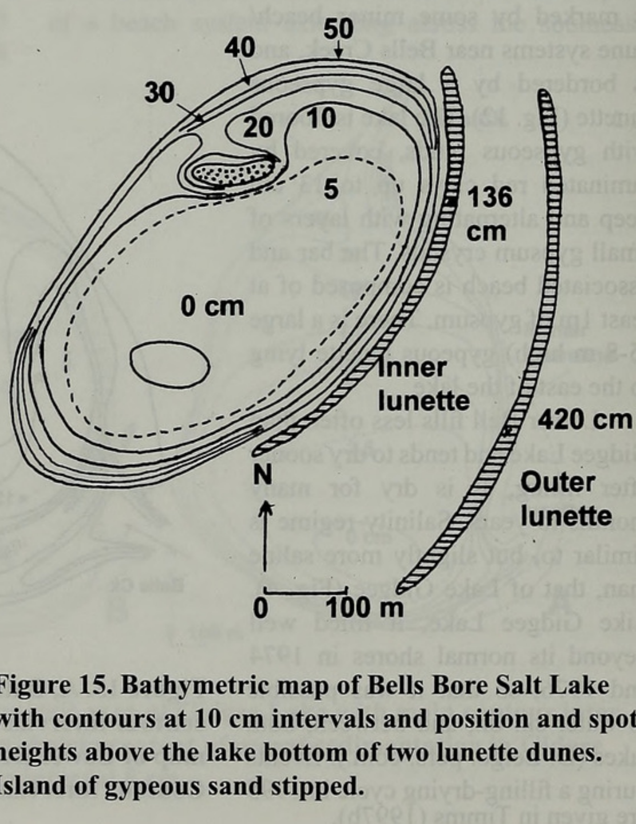

Figure 15. Bathymetric map of Bells Bore Salt Lake with contours at 10 cm intervals and position and spot heights above the lake bottom of two lunette dunes. Island of gypeous sand stipped.

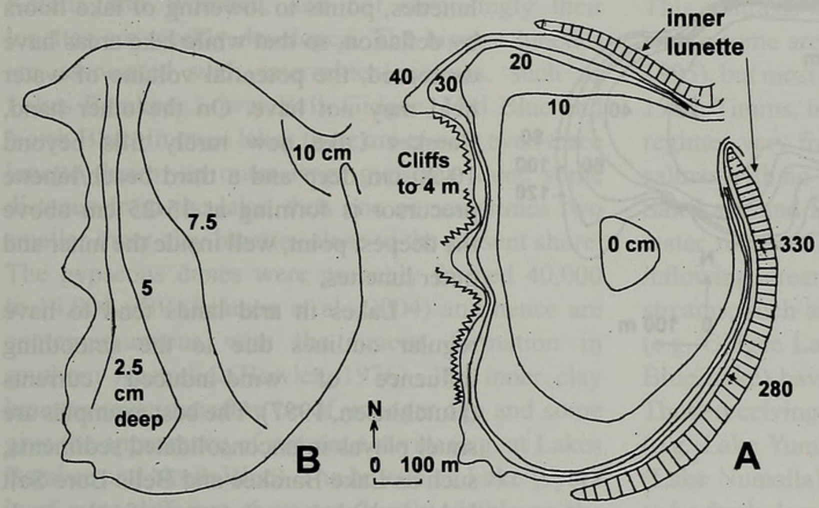

Figure 16. A, Bathymetric map of Lake Burkanoko with contour intervals at 10 cm and location of a lunette dune on the eastern shore and cliffs on the western shore. B, map of Lake Burkanoko showing extent of recent sedimentation.

The inner lunette of clay is much dissected and with a present day maximum height above the lake floor of ca 3 m, while the outer lunette of gypsum is much larger and higher, to ca 9 m. The lake has a 'shoreline' 50 cm above the lowest point, but when it contains water, depth rarely exceeds 10 cm. There is a boomerang-shaped beach in southeast sector reaching 23 cm above the lake floor. Superficial sediments are of recently deposited red silty clay up to 25 cm deep beneath the beach, and generally 15 cm deep in the centre of the lake and thinning to < 5 cm towards the margin (but deeper at the edges due to fans from the lake edge (Fig. 17B)).

Lake Barakee had water on eight occasions out of 20 visits during 1988-2004, with a salinity range of 23 – 218 gL^{-1} and median salinity of 115 gL^{-1} (Timms, 1993, 1998b).

Taylors Lake

Taylors Lake on Ballycastle Station is a relatively deep (1.2 m) hypsosaline lake in a hollow among dunes (Fig 18), probably made smaller by an advancing transgressive dune from the northwest. The lake is orientated SW – NE and has an area of 62 ha. It receives a major stream (about 4 km long) which has built a multi-channelled delta on the southern shore of the lake. Superficial examination this delta suggests it is composed of sands and gravels. There is a small lunette to the east (not shown on Fig. 18).

During 1988-2004, Taylors Lake had water 18 times on 20 visits, with a salinity range of 0.7 – 9.1 gL^{-1} and median salinity of 2.1 gL^{-1} (Timms, 1993, 1998b). Despite usually having water, the lake dried in late 2002 and has not held water since (T. Nielson, pers. com.).

DISCUSSION

Geomorphology

Aeolian deflation is a major force in lake geomorphology in arid lands (Shaw & Thomas, 1989; Timms, 1992), and the Paroo is no exception. Some playas such as Bells Bore Salt Lake and Barakee Lake are simply hollows in the Quaternary sandscape deepened by wind. Timms (1993) lists further examples in the Paroo and inspection of topographic maps suggests many other lakes were formed in this way. Blockage by dunes as they move transgressively across the land has formed many others, notably Lower Bell Lake

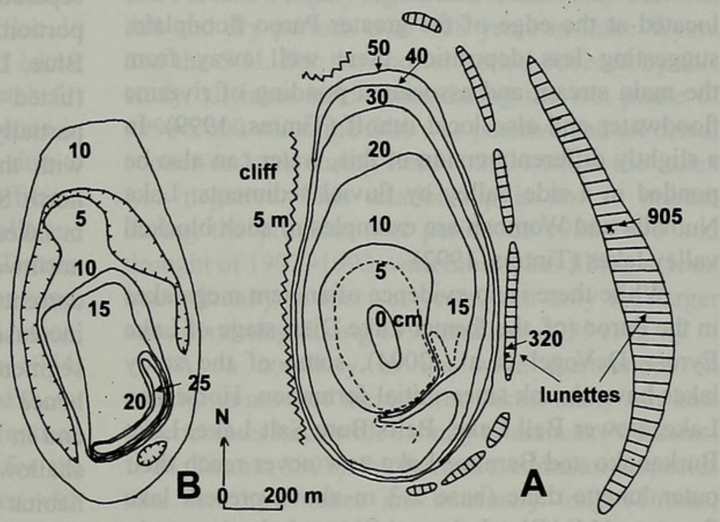

Figure 17. A, bathymetric map of Lake Barrakee with contour intervals of 5 cm and location of lunette dunes on the eastern side and cliffs on the western shore. B, map of the extent of recent sedimentation in Lake Barakee. Note the 5 cm depression contour, indicting recent deposition of sediment is least within this contour.

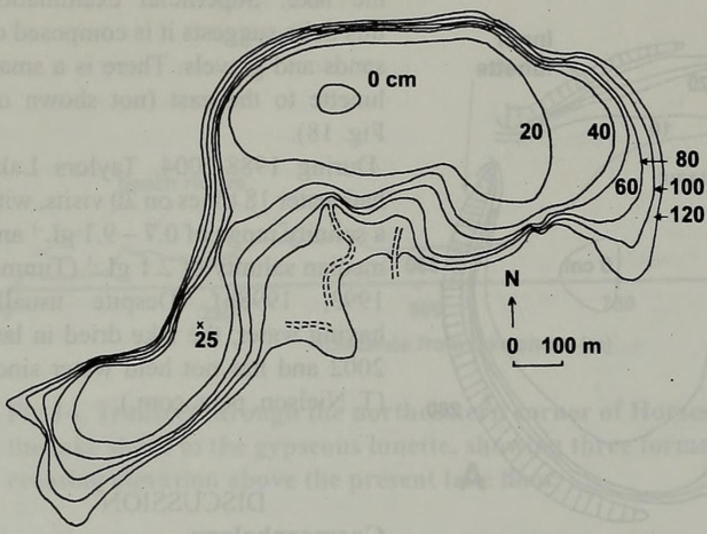

Figure 18. Bathymetric map of Taylors Lake. Contour intervals 20 cm.

where a large transgressive dune from the northwest has blocked Bells Creek. Other examples include the lakes on Number 10 Creek on Rockwell Station – here the creek line has been totally occluded south of Lake Bulla and partial blockages south of Mid Blue Lake and North Blue Lake accounts for these lakes. Gidgee Lake, Lake Burkanoko and Taylors Lake are three further examples and Timms (1993) lists others. For some lakes, however, the initial formative process is not wind. Lake Wyara lies on a Tertiary fault (Timms, 1998a) and Lakes Yumberarra and Karatta are 'embankment lakes' (Timms, 1992) located at the edge of the greater Paroo floodplain, suggesting less deposition there well away from the main stream and associated ponding of riverine floodwater and also local runoff (Timms, 1999). In a slightly different version of this, water can also be ponded in a side valley by fluvial sediments; Lake Numalla and Wombah are examples of such blocked valley lakes (Timms, 1992).

While there is no evidence of ancient megalakes in the Paroo (cf. the former Lake Dieri stage of Lake Eyre - DeVogel et al., 2004), some of the study lakes have shrunk since initial formation. Horseshoe Lake, Lower Bell Lake, Bells Bore Salt Lake, Lake Burkanoko and Barakee Lake now never reach their outer lunette dune (base 2-3 m above present lake floor), and Mid Blue Lake and Gidgee Lake do so only rarely. In both of these lakes the innermost lunette is truncated, which is believed to have happened in the exceptionally high water levels during 1974 and/or 1976. Horseshoe Lake has abandoned beaches with intervening lake floors up to 2m above present lake floor and stepped downwards towards the present lake floor (Fig. 14). This, and the high base of lunettes, points to lowering of lake floors by deflation, so that while lake areas have decreased, the potential volume of water held may not have. On the other hand, Barakee Lake now rarely fills beyond 10-20 cm deep and a third beach/lunette precursor is forming at 15-25 cm above the deepest point, well inside the inner and outer lunettes. .

Lakes in arid lands tend to have regular outlines due to the smoothing influence of wind-induced currents (Hutchinson, 1957). The best examples are small playas in unconsolidated sediments, such as Lake Barakee and Bells Bore Salt Lake, which are almost perfectly oval-shaped. Both have an ellipiticity (E = (L-W)/L) of 0.5, within the range of playas in Western Australia, but a little more than the 0.33 average (Killigrew and Gilkes, 1974). The eastern shores of most other lakes are smoothed, the most striking example being Lake Wyara (Fig. 3) probably because it is the largest lake so wave action and currents are strongest. With winds largely bidirectional (southeasteries and northwesterlies are strongest winds) (Bureau of Meteorology, website) and sandy shorelines, lake segmentation would be expected (Zenkovitch, 1959; Lees, 1989) and indeed Lake Karatta is divided into two lakelets and Lake Numalla has two major cut-off lakelets, many separated bays and an incipient cut-off southeastern portion. In other lakes, such as Yumberarra, North Blue, Lower Bell, and Gidgee (Figs. 6, 8, 13, 11) (listed in decreasing stage of development), the partially occluded southeastern part is well developed, with the major spit development always from the north. Significantly, these partial occlusions are found in lakes with a N-S axis which facilitates action by northwesterly winds to generate southerly-flowing currents on the southeastern shore. These occlusions increase habitat diversity, for in Lake Numalla, the segmented lakelets maybe of different salinity and hence invertebrate composition (Timms, 1997a) and in Lake Yumberarra the increased shoreline and shallow waters of the occluded bay increase bird habitat (Timms and McDougall, 2005).

Like most intermittent lakes in southeastern Australia, almost all of these Paroo lakes have lunette dunes on their eastern shores (Bowler, 1968, 1983). Lake Numalla is the only lake without one; significantly it is mostly fresh and nearly permanent and hence lacks the proper environment for lunette development (Bowler, 1976). The same environmental factors apply, to a lesser degree, in Lakes Yumberarra, Karatta and Wombah, and not surprisingly their lunettes are weakly developed. The biggest lunettes are associated with intermittent salinas, such as Lakes Barakee, Lower Bell, Gidgee, Mid Blue and North Blue. In most lakes there are two or even three lunette dunes: an outer large gypseous dune some distance from the lake, then one or sometimes two smaller inner clay lunettes close to the present shore. The gypseous dunes were probably formed 40,000 to 14,000 yBP (Pearson et al., 2004) and hence are contemporaneous with the lunette formation in southern Australia (Bowler, 1976). The inner clay lunettes must therefore be of younger age and some give the appearance of present activity (e.g. at Lakes Barakee and North Blue). The lunette on Lake Wyara is of quite different character (hardly visible on the ground, and no gypsum) and is possibly much older, as Lake Wyara may date back to the Tertiary (Timms, 1998a). Finally, Freshwater Lake on Bloodwood Station (Fig. 12) has only an inner clay lunette and therefore is likely to be of Holocene origin, probably because of drainage change to Palaeolake which has only a gypseous lunette (Pearson et al., 2004).

Lakes with cliffs on the western and northern shores seem to have migrated a little (at least up to 300 m) westwards. When full, waves generated by southeast and southerly winds attack the cliffs and afterwards fresh debris can be found at their bases. Further evidence of cliff retreat is provided by sloping platforms below cliffs in southern Lake Wombah and by buried rock in the littoral zone adjacent to western cliffs in Lakes Burkanoko and Mid Blue. In the Paroo, cliffs occur only in medium-sized lakes; smaller lakes lack cliffs probably because fetch for wave production is insufficient, but cliff absence in the large Lake Wyara and Numalla must be due to other factors. Perhaps in the latter there are sufficient shore sediments (sandy beaches in Lake Numalla and offshore bars and gravelly beaches in Wyara (Timms, 1998a, 1999) to protect the shore. On the other hand, large playas in Salinaland in Western Australia (Jutson, 1934) and playas in South Australia (Madigan, 1944) have cliffs on their western shores and some of them, at least, lack protective shore sediments (author, unpublished data). Perhaps the explanation for the difference lies in the difference in filling regimes, with the Salinaland lakes filling only occasionally (Van de Graaf et al. 1977). Interestingly, Jutson (1935) claims the Salinaland lakes have migrated westwards, just like some, especially Mid Blue Lake, in the Paroo.

Hydrology

Most of the lakes of the middle Paroo are episodic, with only Lake Numalla almost permanent. This contrasts with saline lakes in southern Australia, where some are permanent (Timms, 1976; Williams, 1995), but most are seasonal (DeDeckker and Geddes, 1980; Timms, in press b). In the Paroo, filling-drying regimes vary from highly intermittent in the shallow salinas with no inflowing streams, such as Bells Bore Salt Lake and Lake Barakee, to a pattern of holding water much of the time in closed lakes with major inflowing streams, like Lake Wyara. Lakes on lesser streams, such as those on Bartons and Bells Creeks (e.g. Gidgee Lake) and Number 10 Creek (e.g. Mid Blue Lake) have intermediate hydrological regimes. Those receiving water from the Paroo fill more reliably (e.g. Lake Yumberarra) or even almost permanently (Lake Numalla). Lakes connected to the Paroo tend to be fresh, largely because, when full, they are open hydrologically, but as they dry they become closed hydrologically and naturally salinise. The other lakes are closed permanently; the most intermittent ones tend to be the most saline (generally hypersaline) while those with inflowing creeks tend to spend much of their time when holding water in the hyposaline-mesosaline range, but overall, with a large salinity range as they progress from full to dry.

Eastern and northern Australia, including the inland, is affected by the El Niño/Southern Oscillation (ENSO) phenomenon (Bureau of Meteorology, website). This influences rainfall and river flow periodicity as shown for the fillings and drying of Lake Eyre (Kotwicki and Allan, 1998). In the Paroo, there is also a highly significant relationship between full and dry periods over 118 years in Lake Wyara and the SOI. For the shorter period covèred by this study, all lakes held water during the wet phase of 1998-2000 when the SOI was positive and all dried, sooner or later during 2001 - 2004 when the index was negative. This relationship is not so intense during the previous wet period of 1988-1990 and drought of 1992 -1993, with most lakes filling at least intermittently in the wet years, and only the larger ones persisting during 1992 and into 1993 (Fig. 4).

As a corollary to the wide fluctuations in salinity in most of these Paroo lakes, many salt lake invertebrates have wide salinity tolerances (Williams, 1984; Timms, 1993). Furthermore, cumulative species lists for these lakes are unusually long (Timms, 1998a, in press a) because the lakes pass through hyposaline, mesosaline and hypersaline stages and hence have components of all faunas (Timms and Boulton, 2001). On the other hand, freshwater lakes which rarely have saline phases, e.g. Lakes Numalla and Yumberarra, have a restricted salt lake faunal component, consisting mainly of readily dispersable/

tolerant rotifers and cyclopoid copepods.

Sedimentation

Recent sedimentation in natural lakes in arid Australia has gone undocumented (Australian State of the Environment Advisory Council, 1996; Australian State of the Environment Committee, 2001), unlike that in reservoirs (e.g. Wasson and Galloway, 1986; Jones, 2003) and streams (e.g. Pickard, 1994). Either, there is none readily apparent, as in Lake Yumberarra, or lakes are too remote to know, or the problem too fragmented to be of interest (Timms, 2001c). Yet many of these Paroo lakes have suffered extensive sedimentation since European settlement, certainly during the wet years of 1974, 1976 and since. Lake Karatta, the terminus of a severely eroded stream channel, has a minimum of 42 cm of recent sediments (Fig. 7); Gidgee Lake, a side basin on Bells Creek, has up to 24 cm of clayey sediments very different to the gypseous sediments below (Fig. 11B); and Lakes Lower Bell (Fig. 13B), Burkanoko (Fig. 16B) and Barakee (Fig. 17B) have lesser amounts of recent clayey sediments. Alluvial fans and deltas are filling significant parts of Lake Wyara (Fig. 3), Taylors Lake (Fig. 18) and Horseshoe Lake, and most lakes have small fans at the entrance of every channel to the lake. These red, sticky clayey sediments originate from small catchments with severe erosion. In the lakes on Number 10 Creek, the recent sediments are friable muds which deflate during dry periods, so that there is little, if any, accumulation of recent sediments. Friable muds also floor Lakes Wyara, Numalla, Yumberarrra and in addition the Bindegolly Lakes near Thargomindah (M. Handley, pers. com.). In all these cases the inflowing stream is from a large catchment, in which isolated severe erosion of red clayey soils is masked by the less sticky grey clays transported by western rivers.

The consequences of rapid recent sedimentation are largely unknown, apart from geomorphological modification of the affected lakes (e.g. the location of the deepest point in Lake Gidgee has changed). Certainly the affected lakes hold water for a shorter period after a major fill (in Lake Gidgee's case this can be as much as a 50% shorter period), but the influence of this on their ecology is unknown. One known affect in Lake Karatta is for (the associated) greatly increased turbidity to devalue the lake as a waterbird feeding site (McDougall and Timms, 2001). Another problem is the predicted imminent connection of bird breeding islands to the lake shoreline in Lake Wyara and the consequent invasion of the islands by the predatory foxes and cats (Timms, 2001c). Beyond the lake shores, lunette building could be affected – the red clayey sediments seem not to readily deflate when dry, so that any contemporary lunette building in these lakes (e.g Lakes Gidgee, Lower Bell, Burkanoko, Barakee) is inhibited. On the other hand, lunette building could be enchanced in the lakes on Number 10 Creek by its delivery of friable sediments.

CONCLUSIONS

The middle Paroo catchment of northwest New South Wales and southwest Queensland has numerous lakes, some of which are saline or become saline as they dry. Eleven lakes have been mapped and these plus five others have been studied for periods of up to 18 years. Many lakes were formed by dunes or river sediments blocking drainage routes, some lie in dune swales, some lie at the edge of the Paroo floodplain where alluvial sediments are thinner, and Lake Wyara lies on a faultline. All developed further by deflation and owe their form to wind-induced currents and wave action shaping shorelines. Eastern shorelines are of often evenly curved and western shorelines may be indented, or smooth. Typically, lakes are flat-floored and shallow (<2 m deep), but two have maximum depths of ~ 6.5 m. Most saline lakes have shrunk, leaving double, sometimes three or more, lunette dunes on the eastern shore, and many larger ones have migrated westwards due to wave action on cliffs on the western shore. Lakes of low salinity have sandy beaches and no, or poorly developed lunettes, but may be compartmentalised by spit growth across bays. Lakes with N-S axes have the southeastern corner cut off by spits generated by currents induced by northwesterley winds. A few lakes are filling with sediment derived from the overgrazing of catchments associated with European settlement. In small eroded catchments, sediments are sticky red clays which accumulate and are filling the lakes, but if the added sediments come from large, less eroded, catchments, they are friable and present deflation can keep pace with sedimentation so that such lakes are not infilling.

Larger lakes with inflowing streams fill in El Niño years, then dry over the next few years, i.e. are episodic. Smaller lakes without surface inflows may fill a few times in wet years but dry quickly. Most lakes remain dry in La Nina years, but those with major inflowing streams get occasional small inflows which evaporate within months. Salinity regimes fluctuate between subsaline (0.5-3 gL^{-1}) and euhypersaline > 200 gL^{-1} and, while instantaneous faunal lists may be depauperate, cumulative species lists can be long. However, lakes which normally are fresh, but become saline in their final stage of drying, develop only a limited saline lake fauna.

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