Geology, geomorphology and hydrology of the Lake Bathurst drainage basin, New South Wales

By Robert S. Abell

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SUMMARY

Lake Bathurst drainage basin has an area of 115 sq. kms and lies within the Southern Tablelands of New South Wales. The bedrock geology consists of deformed Palaeozoic sediments intruded by granite ("Lake Bathurst Granite"). In situ deep weathering of bedrock is widespread and equates with an early-mid Tertiary landscape. Palaeogene rocks are represented by fluvial and colluvial sediments cemented to ferricrete and silcrete, while Eocene basalt is capped by bauxite. There is no evidence for a Neogene sequence. The Quaternary is represented by fluvial, colluvial, lacustrine, strandline and aeolian sediments variably modified by pedogenesis. Drilling indicates this sequence exceeds 40 m in thickness and has a minimum age coincident with the first palaeomagnetic reversal at 780,000 yrs BP.

The drainage basin lies along the watershed separating the Wollondilly and Shoalhaven catchments and is an elevated remnant of the ancient Shoalhaven Plain. It probably originated in the Late Tertiary by drainage disruption caused by lowering of the base level of the Shoalhaven river and partial capture of the headwaters of Mulwaree creek. Alluvial aggradation by Mulwaree creek across this area of indefinite drainage was probably the main process leading to basin closure. Quaternary climate change is reflected in a complex basin morphology. Smaller lakes are separated by wave-built sand barriers in and around Lake Bathurst and clay-rich lunettes at the at the eastern margin of the Morass. The highest palaeoshoreline at approximately 680m above sea level is taken as evidence for a Late Quaternary megalake. Modern landscape processes are attributed to anthropogenic occupation. Removal of the natural tree cover has caused dryland salinity, gully erosion and incipient slope instability.

The hydrology of the basin has been investigated since 1981. The Morass is an ephemeral "flow-through" lake fed mainly by runoff; it is in hydraulic connection with Lake Bathurst through a 1km wide sand barrier. Converging groundwater flow paths, perched groundwater seepages and maintenance of water over long periods indicate Lake Bathurst is an internal discharge area. Water levels in the lakes respond synchronously to seasonal variation in climate but during sustained dry periods it is probable that Lake Bathurst will retain water for longer than the Morass. Hydrochemical data shows Lake Bathurst is a NaCl rich water and is consistently ten times more saline than the Na-HCO_3-Cl water in the Morass. The groundwater hydrology is essentially an interaction between aquifers in unconsolidated Cainozoic sediments and the lakes. In most cases groundwater recharge is directly from rainfall. The monthly water balance data (1987-1994) shows most recharge is accomplished in winter months when rainfall exceeds evaporation. The close juxtaposition of these saline and freshwater wetlands with their contrasting ecologies is an unusual occurrence in the tableland areas of New South Wales.

INTRODUCTION

Lake Bathurst was known to the aboriginals as "Bundong". European discovery was by the surveyor, explorer and settler James Meehan on 3rd April 1818 two years prior to the discovery of Lake George (Cambage 1921). In his field book Meehan gives the first description of the area:

"The plain and marshes are open to the eastward, and on the west is a large lake exceeding ten miles in circuit, the water from the marshy lagoons empty themselves into the lake at which place the land is sandy and swampy, with some Gum trees and Honey Suckle growing. The quantity of ducks and other wild water fowl on the lake and marshes are beyond description" (Cambage 1921).

The lake was named "Bathurst Lake" by Meehan after Earl Bathurst, Secretary of State for the Colonies. He further described the lakes as:

"On the N.W. side are several trees growing in the water that are dead, which makes me conclude the lake extends its former limits. There is no discharge whatever from the Lake but receives the water off a good deal of the surrounding country. There are some islands formed in the lake, and several clumps of rocks, which are all granite dispersed over it, that I am certain, were at some time united to the main. It has a very picturesque appearance" (Cambage 1921).

Lake Bathurst and the Morass form part of a chain of small naturally occurring lakes that can be traced along the Main Divide from Victoria to Queensland. Many of the lakes and their closed catchments appear to have originated through drainage modifications associated with long term landscape evolution of the Eastern Highlands (Ollier 1978). These lakes also occur within small Cainozoic depositional basins which preserve important records of continental sedimentation and associated microrelief. Field studies and drilling, have added considerably to an understanding of the lithostratigraphic and palaeoclimatic record over tens of thousands of years across the Southern Tablelands of New South Wales (Singh & Geissler 1985 ; Dodson 1986 ; Taylor & Walker 1986 ; Harrison 1989 ; Wasson & Donnelly (1991) and Nott & Owen 1992) .

Apart from Lake George (Jacobson et al .1992) and Lake Goran (Hamilton 1992) suprisingly little attention has been focussed on the hydrology of these small catchments. Changing water levels observed in most of these lakes are taken to be sensitive indicators of modern seasonal and longer term climatic fluctuations. On a time scale of decades these hydrologic records monitor major drought events and may be useful in prediction across regions of southeast Australia. However more emphasis is needed in evaluating the occurrence of groundwater in the surficial and fractured rock aquifers in these small catchments.

Judging by the sparse literature references to Lake Bathurst and its catchment, it appears that its scientific potential has probably been overshadowed by an assumption that its origin is analagous with Lake George. Nevertheless, at an early stage Griffith Taylor (1907 and 1958) noted that the origin of Lake Bathurst (an alluviated river valley) and Lake George (a fault - angled depression) were dissimilar and later Jennings et al. (1964) briefly confirmed an alluviation model for Lake Bathurst. Apart from these cursory references, the only other published material is a study of the life history of the ostracod M. henricae (Marten et al. 1985).

The investigation of the Lake Bathurst drainage basin by AGSO (formerly the Bureau of Mineral Resources, Geology and Geophysics) began in 1981 with a program of monthly monitoring of water levels tied into a benchmark on the western side of Lake Bathurst. In 1982, the Australian Survey Office completed at a scale of 1:10,000 a series of black and white orthophoto maps of the drainage basin and a detailed bathymetric map of Lake Bathurst and the Morass. During 1982 colour aerial photography at a scale of 1:36,000 was flown and eight core holes were drilled by AGSO for stratigraphic and long term groundwater level monitoring. During 1983, geomorphology students from the Australian National University investigated the Late Quaternary history of the catchment, with summary results of the fieldwork given in Gillieson (1984). The lake monitoring program expanded in 1987 to include the Morass and an additional benchmark was installed on the eastern side of Lake Bathurst by the Australian Survey Office. In 1989, a basin-wide study of the Cainozoic history and hydrogeology was attempted which is reported in a student thesis (Hawkes 1989). Two further stratigraphic drillholes were completed near the eastern margin of the Morass in 1990 which provided material for a preliminary magnetostratigraphic investigation (Svetlitskaya et al. 1992).

Lake Bathurst and the Morass represent a large but diffuse archaeological site. Aboriginal stone artifacts commonly occur at the surface in association with sandy deposits which have been disturbed by rabbits marginal to the lakes. The wooded pristine nature of the catchment has been strongly altered by clearing leading to pastoral activity. Much of the scenic beauty is focussed on Lake Bathurst which is a rare drought - proof lake providing a sanctuary for bird life when other nearby lakes dry out. It is largely this aspect that has led to the lakes being identified as a significant inland wetland system in New South Wales (ANCA 1992). This report aims to compile and interprete the geological and hydrological data that will form a scientific framework for further Quaternary studies and long term catchment management on the Southern Tablelands of New South Wales.

MODERN ENVIRONMENTAL SETTING

Lake Bathurst drainage basin lies within the Southern Tablelands of New South Wales at latitude 35° 05' South and 149° 45' East. It has an area of 115 sq. kms and is situated east of the Main Divide about 30 km south of Goulburn and 15 km east of Lake George (Fig 1). Access to the area is via Tarago by main roads from Goulburn or Bungendore. A network of secondary roads and tracks opens up the more remote parts of the catchment.

A cool temperate continental climate typifies a drainage basin situated close to the Main Divide. Climate is moderated during summer months by southeast humid onshore sea breezes that bring temporarily cooler or more humid conditions due to proximity to the coast (approx 80 km). Annual rainfall averages about 700 mm / year with minimal seasonal pattern. The annual mean ranges of temperatures are determined largely by elevation. Mean monthly temperature ranges are 7-27° C in summer and 1-16° C in winter. The persistence of a scattering of small stands of snow gums (E. pauciflora) around the lakes is a sign of cold air drainage over several winter months of the year.

The Lake Bathurst drainage basin lies within a regional drainage system directed to the Tasman Sea. The basin is a narrow north northeast trending area of internal drainage (19 km long and 11 km wide) straddling the watershed between the Shoalhaven and Wollondilly catchments (Fig 2). Major relief in the area is also afforded by the Mulwaree fault scarp which is separated from the drainage basin by Mulwaree creek flowing sluggishly northward parallel to the escarpment to join the Wollondilly river near Goulburn. Relief within the basin is moderate with the higher ground underpinned by Palaeozoic bedrock. Elevation generally ranges from 680-700 m ASL (above sea level) but extends up to 830m at Percy Hill (Fig 3). A series of wavebuilt ridges reaching up to 680 m ASL divides Lake Bathurst from the Morass (two smaller lakes to the east). The larger and northern-most of the Morass lakes is in part cut off from the other by a lunette on its eastern shore which has a crest level peaking at 687 m ASL. A wave-constructed ridge of sand hinders drainage from Chain O Ponds creek into the southern part of Lake Bathurst. To the west, a broad, slightly terraced barrier (sill height 678.3 m ASL) of sand and gravel separates Lake Bathurst from Mulwaree Creek. The ill-defined drainage network within a catchment of depressed relief is directed towards the lakes.

The landscape units summarised in Table 1 are based on information contained in Gunn et al. (1969); the arbitrary division of the units into erosional and depositional domains approximates to the 690 m contour (Fig 3). Sheep and cattle grazing is the dominant form of land use where large properties have remained intact. Signs of encroaching development within the catchment are evident from rural subdivision and recent exploitation of sand and clay resources to service building and construction demands from the continued urban growth of Canberra and Queanbeyan.

	DEPOSITIONAL	EROSIONAL
Landforms	Plain; microrelief of lunettes, barrier ridges and lakes; Quaternary lacustrine, strandline and alluvial sediments.	Undulating / hilly terrain; Palaeozoic bedrock of folded sediments / granite; Tertiary basalt; variable deep weathering; colluvial mantles on hillslopes; gully erosion.
Soils	Red gravelly loams at lake margins and wave-built barriers; alluvial soils along drainage lines and Mulwaree Creek .	Lithosols along ridges and hilltops ; patchy and poorly differentiated podzolic soil profiles
Vegetation	Cleared; secondary grassland (some improved pasture); patches of open savannah woodland.	Dry schlerophyll woodland (locally dense on higher slopes); patches of savannah woodland on lower slopes interspersed with natural grassland; pine plantations (wind breaks).

TABLE 1 Landscapes in the Lake Bathurst drainage basin

REGIONAL GEOLOGY

The study area lies within the southern part of the Lachlan Fold Belt (Fig 4). Strongly deformed Palaeozoic sediments consist of Upper Ordovician quartz turbidites unconformably overlain by Late Silurian shallow marine sediments and acid volcanics cut later by Early Devonian acid and basic intrusions. Permo-Triassic sediments of the Sydney Basin resting unconformably across the Palaeozoic sequence may have extended further west but are now mainly confined to an erosional margin of resistant sandstone east of the Shoalhaven River. A long period of stability and subaerial weathering through the Mesozoic led to the local region attaining a low relief landscape (the Shoalhaven Plain of Craft 1928) by the end of the Cretaceous. The Lake Bathurst drainage basin appears to lie within a palaeorift zone (a southern extension of the Hill End Trough) that has been later rejuvenated in part by Cainozoic movement along the Shoalhaven Fault and Mulwaree Fault further to the west . During the Early Tertiary, widespread alluvial deposition and basaltic activity occurred followed in the Quaternary by fluvial, colluvial, lacustrine and aeolian sediments variably modified by pedogenesis.

DRAINAGE BASIN GEOLOGY

The geological map of the basin shows a deformed and weakly metamorphosed Palaeozoic sedimentary sequence intruded by granite (Fig 5). The oldest surficial sediments are patchy outcrops of silicified and ferruginised quartz pebble and lithic conglomerate of presumed Early Tertiary age. Eocene basalt locally weathered to bauxite crops out at the extreme northeast margin of the basin. A basin fill of Quaternary age consists mainly of lacustrine clay interspersed with wave-built barrier and lunette deposits of sand and clay grading marginally into alluvial and colluvial sediments. A tract of alluvium associated with Mulwaree Creek borders the western margin of the basin. Additional geological information is available from the stratigraphic bores drilled in the basin by AGSO (Fig 6).

Palaeozoic sediments and Volcanics

On the Braidwood 1:100,000 geological sheet (Felton & Huleatt 1971), Palaeozoic sediments in the basin are shown as undifferentiated Ordovician metasediments except for a belt along its western margin which is assigned to the Late Silurian Mt Fairy Group (De Drack Formation). Limited field checking of lithologies suggests that perhaps the Late Silurian sequence is more extensive although its recognition is hampered by deep weathering, lack of marker units and fossils . The geological structure of the sediments is reflected in the north northeast alignment of broad ridges later infilled with surficial sediments immediately east of Lake Bathurst and to a lesser extent south of Kywong Station. The few good exposures examined suggest isoclinal folding in which bedding and cleavage are subparallel. The main rock type exposed is pure massive quartz sandstone with interbeds of dark grey shale and minor chert. The sandstone which tends to resist weathering is pale grey to white when fresh; some float is armoured with silica giving the appearance of silcrete. Local contact metamorphic effects due to granite intrusion are evidenced by hornfelsing and the growth of small needles of andalusite-cordierite in slates exposed in a quarry at MR 427/158. A porphyritic rhyodacite is exposed along a ridge at MR 424/177 and in drillhole C346. (All map references in the text are given in terms of the metric grid on the 1:25,000 topographic base maps covering the drainage basin - KOORINGAROO, LAKE BATHURST, WINDELLAMA and BORO sheets).

" Lake Bathurst Granite".

Tor-like knolls, bouldery outcrops and rocky promontories of felsic granite form negative relief along the western side of the drainage basin and also bedrock to Lake Bathurst. The distribution of the granite and its probable extent beneath surficial sediments is shown in Figure 5. The two main rock types in the "Lake Bathurst Granite" are related to fractionation within a single magma body. The most readily visible is a massive, pale pink, coarse grained adamellite which grades marginally into quartz feldspar porphyry. The main rock type contains rounded and fractured phenocrysts of quartz up to 0.5cm, large subhedral crystals of potash feldspar and plagioclase locally with rapakivi texture and minor biotite. Xenolithic material is sparse consisting mainly of mafic-rich bodies up to 3cm and fragments of vein quartz up to 25cm .The rock is cut by occasional pale green veinlets of quartz-epidote. A roof pendant remnant preserved at MR 473/209 contains rounded inclusions of biotite-rich hornfels up to a metre across veined by adamellite and cut by aplite (Plate 1). The fine grained leucogranite phase tends to occur towards the margin of the intrusion where it is exposed as small bosses showing well-jointed blocky outcrops with sharp and gradational contacts with the coarse grained phase (Plate 2). The rock is composed of equigranular quartz and feldspar and is mafic-poor. Aplites with variable orientation are also thought to be a leucocratic segregation within the magma body. The "Lake Bathurst Granite" is considered to be of Early Devonian age and regarded as a northern extension of the I-type Bega Batholith (Felton & Huleatt 1971 and Chappell et al. 1991).

Lichen growth (Xanthoparmelia , Flavoparmelia and Physcia sp. J. Elix pers comm 1994) on granite outcrops around and on the lake bed suggest a lengthy period of subarial exposure associated with depressed lake levels. Thin encrustations of pale grey $CaCO_3$ supporting the lichen Lecanora caesra (J.Elix pers.comm.1994) on fresh granite surfaces may be monohydrocalcite (P. De Deckker pers.comm. 1994) but detailed mineralogical and chemical analysis is needed to confirm this identification.

Basic rocks

An elongate, north trending dolerite intrusion is exposed at the foot of a ridge on the eastern shore of Lake Bathurst (MR 469/169). According to Hawkes (1989) the rock displays ophitic texture with the mafics altered to amphibole and chlorite. Contacts are not exposed but it is probable that the intrusion post dates the "Lake Bathurst Granite". Similar dykes of mid to late Devonian age are known to intrude Early Devonian granites on the Araluen 1:100,000 sheet to the south (Wyborn & Owen 1986).

Tertiary

Prior to the Late Eocene there is ample evidence of widespread alluviation across the Shoalhaven Plain (Ruxton & Taylor 1982) and the Shoalhaven Valley (Nott 1992 and Nott & Owen 1992). Following alluviation, basalt flows covered substantial areas of the plain and are now left as erosional remnants capping hills. There is also visible evidence throughout the Shoalhaven Plain of deep weathering of Palaeozoic bedrock and duricrust formation which continued into the mid-late Tertiary.

Sediments

There is no definite field evidence for Tertiary sedimentation in the drainage basin. However it is likely that pre-basaltic fluvial and colluvial deposition is evidenced by extensive exposures of ferruginous and locally silicified quartz-rich pebble and lithic conglomerate. It is probable that they are equivalent to patches of similar sediments exposed along the crest of the Lake George escarpment and elsewhere on the CANBERRA 1:100,00 sheet (Abell 1991) which are considered to be Early Tertiary or older. Palaeomagnetic reversal studies from sediments in C348 have detected the Matuyama-Gauss transition at 1.6 Ma with the possibility that the bottom of the sequence may reach into the Pliocene (Gillieson 1984). However further work on fresh core material at a finer sampling interval is needed to fully confirm the existence of a late Tertiary signature in the basin fill sequence.

Basalt

Scattered outcrops of rubbly basalt occur at an elevation of 700-710 m ASL in the northeastern part of the drainage basin. The extent of the outcrop is readily outlined on colour aerial photography by the distribution of chocolate brown soils. Fresh outcrop is scarce; the best being in a creek north of Hedley Park Station at MR 532/237. The basal contact is not exposed but mapping indicates the basaltic flow lies on weathered Palaeozoic sediments and locally silicified quartzose sediments (silcrete). A minimum thickness of 20 m is estimated from the difference in topographic elevation within the outcrop area. According to Hawkes (1989) the rock is a dark grey microcrystalline olivine basalt with rare centimetre-sized amygdales infilled with calcite and/or zeolites. Thin sections show the presence of pyroxene-plagioclase intergrowths with olivine altered to iddingsite and accessory iron oxides. The low K tholeiitic nature of the basalt places it as part of the Nerriga Volcanic Province (Wellman & McDougall 1974). Outcrop near Hedley Park Station has been isotopically dated by K - Ar to a late Eocene age of 43 Ma (Ruxton & Taylor 1982). The lobed outcrop pattern of basalt and bauxite suggest extrusion along drainage lines which were originally part of the palaeoheadwater system of Mulwaree Creek. Outliers of bauxite may be indicative of a formerly more extensive cover of basalt in the drainage basin.

Deep Weathering.

A complex and prolonged deep weathering history is evident in the drainage basin. There is widespread occurrence of in situ weathering of Palaeozoic bedrock and Tertiary basalt capped locally by bauxite. The saprolite and associated ferricrete and silcrete duricrusts represent the preservation of an older landscape equating with the more extensive Middle Shoalhaven Plain. The Mesozoic origins and Tertiary weathering history of this plain are described in detail by Ruxton & Taylor (1982) and Taylor & Ruxton (1987), while the palaeoclimatic background to the deep weathering process is given in Taylor et al. (1990 and 1992). The deeply weathered regolith in the Lake Bathurst area consists of two essential elements : saprolite and duricrust (Fig 7).

Saprolite

No complete profile of saprolite is exposed. However elements of the profile occur locally in the lower relief areas of the basin.

Deeply weathered black shales of possible Ordovician age are exposed in a quarry on Leahys Lane at MR 499/134. The profile shows a pallid zone of greyish-white kaolinite grading up into ferruginous mottling capped locally by ferricrete and overlain abruptly by a pale brown lithosol 50cm thick. Fresh bedrock is exposed in the bed of the quarry. Oygen-isotope studies on kaolinite from a similar profile developed in deeply weathered Palaeozoic metasediments north of Braidwood suggest an Early Tertiary age for a weathering process operating in a cool wet climate (Bird & Chivas 1993).

The upper part of a saprolitic profile is exposed in an erosion gully south of Tarago Tip (MR 460/142). Here a ferruginous mottled zone of sandy clay typical of granitic saprolite is in sharp contact with an organic-rich alluvial soil 50 cm thick.

Within an earth dam spillway on Bonnie Doone property at MR 513/193, a 2 m section shows a strongly ferruginised sandy mottled zone in sharp contact with ferricrete (with rubbly upper surface) overlain by a thin alluvial soil

In an erosion gully close to the Tarago-Mayfield road at MR 443/156, a well exposed profile (from the base) consists of weathered granite grading up into a 2-3m thick sandy mottled zone. The saprolite is in sharp contact with ferricrete 20-30cm thick which in turn is overlain by a quartz sand (Quaternary strandline deposit) supporting a 50 cm thick soil. The kaolinitic pallid zone appears absent from the profile.

A composite profile of saprolitic basalt occurs near Hedley Station. According to Taylor & Eggleton (1984) the profile consists of fresh basalt grading up into a zone of kaolinitic basalt and then into a mottled zone containing gibbsite and minor haematite. The profile is capped by bauxite. Remnant palaeomagnetism indicates a Mid Tertiary age for this profile (Taylor & Ruxton 1987) with a weathering process operating under a wet, cool to cold climate.

Duricrust

Three types of duricrust: ferricrete, silcrete and bauxite have been mapped in the drainage basin (Fig 5). The various types of duricrust are distributed in close proximity and are commonly associated with deeply weathered Palaeozoic bedrock and Tertiary basalt.

Ferruginous duricrust (ferricrete) commonly outcrops across the more elevated slopes in the eastern half of the drainage basin (Fig 5). Lack of outcrop within and adjacent to the lakes area suggest it is probably covered by younger Quaternary sediments. Ferricrete forms minor relief features in the landscape such as benching close to drainage lines or residual hills (inverted relief); it supports a distinctive reddish-brown soil evident on colour aerial photography which assists in mapping its distribution in the landscape. Ferruginous duricrusts unconformably cap weathered Palaeozoic bedrock profiles and locally may be associated with silcrete. Thickness varies from a thin veneer (a few cms) up to 2m . Ferricrete occurs as dense, massive hydrated ironstone but more often as iron-cemented transported material (alluvial and colluvial sediments) deposited on older saprolite. Good exposures of ferricrete occur within a kilometre radius of Bonnie Doon Station (MR 508/181). Here brownish-yellow ferricrete containing a framework of poorly sorted, subangular and rounded clasts of vein quartz set in a sandy quartz-rich matrix and cemented by hydrated iron oxide (probably goethite-limonite) represents a prior fluvial sediment. Other outcrops may show poorly sorted lithoclasts of quartzite and shale suggesting a colluvial origin for the transported material (Plate 3). While the source of iron is clearly from the underlying deep weathering profile, the process of concentration to form ferricrete is less certain - the probable explanation is the carriage of iron in solution by laterally moving groundwater which on reaching the oxidising environment at the surface accumulates and cements the regolith (Ollier 1991). In the drainage basin ferricrete seems to be an indicator of landscape antiquity as there is no evidence that it is forming in the modern landscape. Similar rocks in the Middle Shoalhaven Plain have been palaeomagnetically dated as Mid Tertiary (Taylor & Ruxton 1987), while in the Bungonia area ferricretes are overlain by Late Eocene basalt (Wray et al 1993). However ferricrete is not related to any regional geomorphic surface and its formation may be continuous over a long time scale.

Silicified duricrust (silcrete) has been described in detail on the Middle Shoalhaven Plain by Taylor & Ruxton (1987). In the local landscape area silcrete occurs at elevations ranging from 670-700 m ASL. In the more elevated parts of the catchment silcrete is associated with ferricrete and a pavement outcrop is well exposed near the eastern rim of the catchment at MR 527/162. Here, the silcrete is a hard, pale grey rock consisting of a framework of mainly rounded quartz vein pebble clasts set in a sandy matrix and cemented by silica. The north west elongation of the outcrop suggests silicification of sandy alluvium along a palaeoheadwater channel of Mulwaree Creek. Similarly silcrete locally exposed in the vicinity of Hedley Park Station (Fig 5) may represent silicification of sandy alluvium in sub basaltic deep leads. A thin discontinuous sheet of silcrete is exposed at the southern margin of Lake Bathurst (approx. MR 450/163). Access to the outcrops is best achieved during periods of low lake level. Silcrete at this locality is not associated with ferricrete or a deep weathering profile appearing to drape directly across fresh granite ("Lake Bathurst Granite") although contacts are not exposed. The rock is white-creamy coloured consisting of the usual silica cemented quartzose framework of sand and pebble clasts. However many outcrops show large concentrations of subangular lithic clasts of quartzite suggesting a local derivation from surrounding Palaeozoic bedrock areas (Plate 4). For those silcretes associated with ferricrete and perhaps basalt, acid humid weathering conditions (low pH) seems to be a prerequisite for the release of silica into the environment. Silica mobility in ground or surface water and later its precipitation in surficial sediments is determined by sites of internal or impeded drainage. Nott (1992) demonstrates a minimum Early Tertiary age for silcrete in the Shoalhaven River Valley, while Taylor & Ruxton (1987) consider the silicification process operated intermittently from early Mid-Tertiary to latest Tertiary. However, the absence of a saprolitic profile and close association with sediments on the bed of Lake Bathurst suggests that silcrete here may have formed at an even younger time, perhaps in the Quaternary.

Residual duricrust (bauxite) formed by in situ weathering of basalt caps hills and ridges in the north east part of the catchment. In some cases the basalt has been completely weathered leaving a bauxitic profile directly overlying Palaeozoic bedrock.The elongate nature of the outcrops and associated inverted relief not only outline the form of the original basalt flow but indicate post basaltic landscape inversion .In the vicinity of Hedley Park Station residual outcrops of rubbly, reddish-brown pisolitic bauxite are typically exposed at a small hill at MR 535/233 and along south west trending ridges at approx MR 525/220 and MR 530/215. The typical rock type consists of ironstone pisolites reaching up to 3cm in diameter set in a reddish-brown ferruginous matrix dominated by hydrated iron oxides and gibbsite (Plate 5). Thickness is variable but may reach 3 m. In a shallow road cutting at MR 516/223 pisolitic bauxite (with some re-worked pisolites) appears to grade downwards into a fragmented (slaggy) weathered basalt flow. Ruxton & Taylor (1987) give a mid to late Tertiary palaeomagnetic age for bauxitic weathering in the Middle Shoalhaven Plain.

Quaternary

About 60% of the bedrock in the drainage basin is covered by Quaternary sediments. The sedimentation pattern is largely controlled by climatic changes related to Pleistocene glacial-interglacial cycles. Colluvial and alluvial deposits are generally confined to more elevated parts of the drainage basin ; the former accumulating in a cold arid environment. Wave-built barrier, lacustrine and aeolian deposits result largely from changes in the levels of Lake Bathurst and the Morass. Patches of ferruginous weathering in the sediments are indicative of long periods of subaerial exposure and landscape stability in the Quaternary. The sediments and associated landforms are described in terms of morphostratigraphic units. Some of these units are composite features eg. wavebuilt barriers and lunettes, and relationships between them are poorly defined; their age is also limited by a lack of an absolute chronology. Subsurface information from drillholes (Figs 5 and 6) reveal in excess of 40m of sediment infill which has been dated with some confidence to at least the first palaeomagnetic reversal at 780,000 yrs BP (Gillieson 1984; Svetlitskaya et al 1992).

Early Quaternary Sediments (Qs)

A logged sequence of white, friable silt and sand reaching a thickness of over 20 m in bores C348 and C376 (Fig 5, section A-B and Fig 6) may represent evidence for at least an early Quaternary depositional facies in the basin. Two samples of sandy silt from C376 (depth intervals 29.6-29.9 m and 34.6-34.9m) were analysed using petrographic, XRD, sedimentological and SEM techniques. Silica as quartz is the primary constituent with minor proportions of kaolinite and feldspar. Angular to subrounded quartz grains containing inclusions are locally embayed and fractured. Zircon is present as an accessory. Based on grain size parameters outlined in Reineck & Singh (1973) and Leeder (1982) there is a strong aeolian signature in the sediments. This is indicated by little vertical variation in grain size (median diameter 2.94-2.84ϕ); a standard deviation of 0.75-0.78 typical of moderate sorting and a strong coarse skewness (- 0.73-0.66) with coarse-grained tail generally absent. A preliminary SEM analysis of quartz grains and their surface features (Krinsley & Doornkamp 1973) shows angular grains with rounded edges, upturned cleavage plate and smoothed grain surfaces. However silica precipitation (quartz crystal growth) on upturned plates and possible solution pitting may be related to diagenetic effects. The angularity of the grains and V-shaped etch markings on grain surfaces suggests that mechanical action also occurred probably in a subaqueous (lacustrine) environment. The preliminary analysis of these sediments suggest diverse environments existed during the Early Quaternary history of the basin perhaps represented by the "Lake Bundong" phase (see Geomorphology section p.18).

Colluvium (Qc)

Colluvial deposits commonly mantle steep slopes bordering the south west margin of Lake

Bathurst and hills at the southern margin of the catchment notably below Percy Trig (MR 485/116) The colluvium shows some pedogenic differentiation and comprises screes of cemented angular quartzite clasts derived from underlying bedrock. Colluvial deposition is believed to reflect slope instability during cycles of dry, cold conditions in the Pleistocene. At present the deposits have stabilised under a vegetation cover but in some cases creek dissection has locally reworked the deposits to form alluvial fans at the foot of the slopes. In the Bungonia area a few kilometres to the north west of the drainage basin, a U-Th date of 27,000 ±11 yrs BP provides a minimum age for colluvial deposition while stratigraphic techniques suggest the deposits may be older than 50,000 yrs BP (Wray et al 1993).

<u>Alluvium</u> (Qa)
Alluvium occurs in flat swampy floodplain embayments on the southern margin of Lake Bathurst and east of the Morass. The embayments show the characteristics of a stagnant alluvial plain with swampy conditions evidenced by reedy vegetation and dark grey alluvial soils. Low gradient, intermittent and underfit creeks cross the floodplains and only incise their courses to form younger narrower meander floodplains adjacent to the lakes. Colour aerial photography shows that more permanent drainage eg. Chain O Ponds Creek cuts across older strandline ridges to build sandy deltas onto the surrounding lake beds. Alluvium grades into colluvium at boundaries formed by a marked change in topographic slope. Marginal to the lakes, alluvial deposits grade gently into strandline and lacustrine sediments. The best known exposure of alluvium is in an erosion gully south of Tarago tip where a 50 cm thick overbank deposit of dark grey organic silt and clay containing calcareous nodules rests abruptly on saprolite. The nodules appear to have weathered out from the alluvium and lie in heaps in the upper reaches of the gully (Plate 6). According to Wray et al (1993), U/Th analysis of pedogenic carbonate in the Bungonia area yield ages ranging from 8-18,000 yrs BP. No information presently exists on the age of the calcareous nodules in the Lake Bathurst drainage basin.

A tract of alluvium reaching up to 500 m in width is associated with Mulwaree Creek. The low gradient nature of the drainage typifies a headwater system that has undergone diversion in its upper reaches.The sluggish drainage forms disconnected pools in prolonged spells of dry weather. Remnant terraces in the vicinity of Lake Bathurst village attest to a former but more extensive floodplain. The thickness, composition and age of the alluvial sediments has not been studied but it is expected that the sequence may range into the Tertiary.

<u>Wave-built sand barriers</u> (Qbs)
Lakes in the drainage basin are divided by a series of parallel north northeast trending wave-built sand barriers. The complex morphology and topographic detail is defined on the 1: 36,000 scale colour photography (1982) and 1: 10,000 scale orthophoto maps (1983). In general, these barrier sediments consist of a Late Quaternary sequence of medium to coarse grained sand and pebble gravel of granitic and metasedimentary origin. The barriers are essentially quartz sand lunettes that have been subsequently modified by processes associated with post Late Quaternary megalake recession.

At the western margin of Lake Bathurst a broad barrier straddles an old headwater tributary valley of Mulwaree Creek (now a windgap). The barrier is about 1km in length , 0.5 km in width and has a crest elevation of 678.3m ASL; it is asymetric having a gentle westerly slope and steeper (trimmed) eastern slope. The crest of the barrier is outlined by a remnant stand of snow gums (Plate 7). The modern course of Mulwaree Creek has incised into the barrier on its western side. Part of the sedimentary sequence is exposed in a disused quarry at the southern end of the barrier at MR 428/179. Here, poorly to well sorted gravel is interbedded with varying amounts of well sorted medium to coarse grained sand showing smallscale cross stratification dipping at up to 10^0 towards the lake. Flattened clasts of sandstone and shale and more rounded clasts of black slate, acid porphyry and milky quartz up to 10 cm in diameter suggest a local derivation (perhaps reworked colluvium) from nearby Palaeozoic sediments. The subsurface lithologic data is depicted in drillhole logs C346 and C347 (Fig 6), while a simplified representation of the lithofacies showing an interfingering of floodplain silt and clay (associated with Mulwaree Creek) and wave-built barrier sand and gravel (associated with lacustrine processes) is given at Fig 8. Drillhole data indicate that the bedrock topography underlying the barrier slopes to the west. However further work is necessary to define the course of the palaeotributary of Mulwaree Creek.

The trimmed eastern margin of the barrier is attributed to lake shore abrasion at times of high lake levels in the late Quaternary. A series of palaeostrandlines at 1.5, 5, 8, and 11m above the lake floor have been defined by Gillieson (1984). A radiocarbon date of 810 ± 70 yrs BP from a slopewash deposit at 1.5m provides a minimum age for the barrier, while progressively older dates of 1,300 ± 80 yrs BP and 43,000 ± 150 yrs BP (approximating the upper limit for the radiocarbon method) have been obtained from higher parts of the barrier (Gillieson 1984, Hawkes 1989, this study and see also Fig 8). Interpretation of these dates needs caution as the palaeostrandlines have been degraded by erosion gullying, sand mining and groundwater discharge. Judging by the well developed red gravelly loam, the upper surface of the barrier has had a lengthy exposure to subarial processes and maybe much older than 43,000 yrs BP and perhaps equivalent in age to the Winderadeen Embankment at Lake George. This sequence of palaeoshorelines can be traced around the northern shores of Lake Bathurst. They are evident as subparallel air photo lineations which are depicted in simplified form at Fig 5. The highest shoreline approximates to the 680 m contour and also fixes the lakeward limit of remnant stands of snow gum. The remains of this oldest shoreline is represented by a series of small "bays" and "headlands" cliffed into resistant outcrops of granite. Strandlines at progressively lower elevations have limited topographic expression and are denoted by the growth of reedy vegetation on a sandy substrate often impregnated with rabbit burrows. They consist of well sorted medium to coarse quartz sand derived initially from surrounding granite and subsequently reworked by wind and current action during lake stillstands.

Lake Bathurst is divided into two parts by a low relief sand barrier that extends from the southwestern shore to link up with spurs of granitic bedrock at the northern side of the lake (Fig 5). The topography reaching a general height of 674 m ASL is outlined on the 1:10,000 orthophoto maps (1982). In normal lake conditions much of the barrier is submerged. The only evidence for its existence being a grass covered sand bank (known locally as Rabbit Island). The morphology examined briefly during a period of low lake level (< 1.0m deep) showed a similar but less pronouced asymetry to that of the adjacent western barrier. On the western slope there is evidence of a dissected beach ridge corresponding to the 674 m contour.The airphoto lineations along the trimmed and locally embayed eastern margin outline a series of etched shorelines relating to more recent and seasonal changes in lake level. The barrier sediments consist of medium to coarse quartz sand supporting a cover of native grasses through which protrude isolated granite outcrops. The position of the barrier within the lake suggests it may be a connecting bar (similar to a tombolo) with the configuration of the granitic outcrops on the lake bed in part determining longshore sediment movement patterns.

A broad wave-built barrier separates Lake Bathurst from the Morass lakes. This linear trending barrier is 2.5 km in length and 1km in width; it stretches from a ridge of Palaeozoic sediments northwards to granitic outcrops south of Bundong Station (Fig 5). The topography of the barrier which crests locally along its eastern margin at 680m ASL is displayed on the 1:10,000 orthophoto maps (a portion of which is reproduced at Fig 9). The barrier is asymetric with a long west-facing slope rippled by four subparallel beach ridges (reconstructed by linking residual peaks) interspersed by lagoonal swales which fill after heavy rains.Along the eastern shoreline some barrier trimming has occured, but otherwise the absence of palaeoshorelines emphasises the ephemeral nature of the Morass. Shallow alluvium deposited in an overflow channel cuts across the beach ridges and indicates a linkage between the Morass and Lake Bathurst during flood peaks. Palaeoshorelines etched into the lower western margin of the barrier are evidenced as closely spaced lineations on aerial photography. They relate to lake changes over the last few hundred years and occur as subtle changes in vegetation and topography. The barrier is a composite sedimentary feature. The highest and probably oldest beach ridge which predates the late Quaternary is embayed by the Morass and remains as residual peaks reaching just above 680m ASL (Qbs_1). Localised outcrops of unconsolidated, poorly sorted pebble gravel comprise mainly subrounded and flattened clasts of quartzite/siltstone up to 10 cm diameter derived locally from Palaeozoic metasediments appear reminiscent of a storm beach deposit. A section through part of this beach ridge is exposed in and around Bundong Tip (MR 480205). where the loose gravel supports an unstructured red loamy soil profile. Finer materials with incipient soil profiles ranging from poorly to well sorted, medium to coarse quartz sand progressively characterise lower beach ridges westwards. The subsurface lithology of the barrier is known from only one drillcore (C348; see Fig 6). The top 16m of the core shows four sand and gravel intervals interspersed with thinner clay and silt. This lithostratigraphic sequence suggests the quartz sands are indicative of phases of barrier construction while the clay layers represent lacustral conditions and perhaps linkage between Lake Bathurst and the Morass (Fig 10). Below 16 m a thick sequence of silt, sandy silt and fine to medium grained sand (Qs) represents a poorly defined Early Quaternary lacustrine and aeolian history in the basin. The mode of construction of the barrier is poorly understood. The width of the barrier suggests it has formed by processes of lateral and vertical accretion. It is possible construction was dominated by wind driven currents reworking sediments of lacustrine and colluvial origin, perhaps following a sedimentation model proposed for the Winderadeen embankment at Lake George (Lees & Cook 1991) or alternatively a tombolo-type process whereby longshore drift has moved sediments progressively northwards linking a prominent ridge of Palaeozoic sediments with granitic rocks south of Bundong HS (see Fig 5).

The present day morphology of the barrier probably relates to the Late Quaternary mega lake phase which occurred prior to 25,000 yrs BP (Macumber 1991). At this time Lake Bathurst was joined to the Morass; the extent of the megalake approximating to the 680 m ASL contour.

Remnants of the highest part of the barrier (the gravel beach ridge) escaped lake inundation and remained exposed to subaerial soil forming processes (red loam). The younger and lower beach ridges across the shallow western slope formed progressively during the post Late Quaternary mega lake recession. Subsequent landscape modifications are evidenced by beach ridge dissection, lagoonal and alluvial deposition and shallow pedogenesis. The age of the barrier is uncertain but probably pre dates the Brunhes - Matuyama transition at 780,000 yrs BP (the currently referenced boundary after Spell & McDougall 1992) as measured from the first reversal of polarity at 22m depth in laminated lake clays in drillhole C348 (Gillieson 1984, see also Fig 6).

At the southern end of Lake Bathurst the barrier is less evident. Here, a gentle north facing sandy slope culminates in a remnant beach ridge capped by aeolian sediments supporting a leached podzolic soil, probably an equivalent of the 680m beach ridge further north. A section through part of this profile is in a shallow road cut at MR 455/146. East of Chain O Ponds Creek at MR 460/154 a low ridge of coarse sand supporting a remnant stand of snow gum represents a southerly extension of the 678m beach ridge. Other minor beach ridges at lower elevations in this general area maybe traced from vegetation changes on aerial photos. The barrier has been breached by Chain O Ponds Creek with the redeposition of the barrier sediment onto the lake bed as a deltaic fan. The toe has been reworked into a spit by the eastward drift of the sediments. Unfortunately the natural landforms across the barrier have been partially obliterated by sand extraction and the Tarago waste disposal area. Until recently the barrier sediments were exposed in a pit at MR 458/148 (now landscaped for native plant regeneration by the local Shire Council). At this locality, Felton & Huleatt (1977) describe the sediments as lenticular bodies of coarse sand with occasional pebble trains showing medium scale low angle cross stratification representing a wave built bar with a strong fluvial influence. The apparant lack of gravel suggests the barrier was deposited under less energetic conditions perhaps being a function of its protected position at the southern margin of Lake Bathurst.

<u>Clay-rich lunettes</u> (Qls)

Two large clay-rich lunettes occur parallel to the eastern margin of the Morass (Fig 5). They have the distinction of being among the most easterly in the Southern Tablelands of New South Wales. Their morphology follows descriptions outlined in Bowler (1968 and 1983). They are crescentic in shape (concave to the west); show a decrease in height towards their northern and southern extremities; have steeper windward slopes (in part trimmed by past high lake levels) and gradual east-facing lee slopes; a morphology with opposite asymmetry to the wave-built sand barriers (Fig 11).

The inner lunette bordering the northern Morass is the best developed in the basin. A smoothed grassed surface rises gradually to a crest of 688 m ASL (approx. 14 m above the Morass lake bed) and it has a maximum width of 500 m. Soil development is extensive as evidenced by a reddish-brown loam exposed in a landslip along the west-facing margin of the lunette; surficial weathering reaches to a depth of 7.5 m as logged in drillhole C376. The lithology in this drillhole consists of a 12m thickness of clay and silty clay. Two phases of lunette construction are possibly indicated by a 2 m interval of carbonaceous silt/fine sand at a depth of 7.5 m (approx. 680 m ASL - see Fig 6) suggesting a high water level phase in the Morass temporarily existed across a lower, earlier lunette. A minimum radiocarbon date for this interval given as 22,000 ± 450 yrs BP (ANU

9364) provides tentative evidence for the Late Quaternary megalake phase within the lunette sequence.This inner lunette extends southwest and divides the Morass into two lakes. Here, the lunette appears to have been eroded and instead has become modified into a low emergent strandline embankment (675 m ASL) of coarse sand covered by reeds giving the appearance of a wave-built barrier. During very wet winter seasons this barrier is breached and may in part be covered by water to reunite the Morass into a single lake.

The less obvious outer lunette at the eastern margin of the southern Morass has a similar morphology but culminates at a lower elevation of 685 m ASL (approx. 11m above the Morass lake bed). This lunette is attenuated by alluvium from creeks feeding into the southern end of the Morass.It is also joined to the inner lunette by a sand barrier corresponding to the 678 m contour which has been breached by a creek flowing into the northern end of the Morass (MR 495/187). A reddish-brown loamy soil is exposed in a landslip face on the western side of the road at MR 496/182 ; otherwise details of lunette lithology are unknown.

The age of lunette construction in the Lake Bathurst drainage basin is unclear. In the local region the main period of aeolian activity post dates the Late Quaternary megalake phase (> 25,000 yrs BP) and also follows on from the last Glacial Maximum (approx. 20 Ka). According to Bowler (1973) most lunettes in southeast Australia became inactive in Late Quaternary time; radiocarbon dates indicating widespread formation between 17,000 and 15,000 yrs BP. However radiocarbon dates from fine sandy deposits from Fernhill gully at neighbouring Lake George, show that periodic instability to wind of lake margin deposits persisted over a longer time interval of 23,000 - 2,000 yrs BP (Coventry & Walker 1977). In the Shoalhaven river catchment, Late Pleistocene - Early Holocene source bordering dunes were active between 19,000 - 6,000 yrs BP (Nott & Price 1991). The radiocarbon date of 22,100 ± 450 yrs BP obtained from within the lunette sequence at the Morass suggests the youngest aeolian clays post date the Late Quaternary megalake phase in the drainage basin and hence fit into the chronology established for aeolian activity in the Southeast Highlands of New south Wales (see above). Remnant podzolic soils in aeolian clays on the inner and outer lunettes also suggests pedogenesis post dates the Late Quaternary megalake phase. The lunettes around the Morass are considered to have formed initially by deflation of lake bed clays by predominantly westerly winds. They represent a relict landform providing evidence that more than one at least seasonally dry phase was associated with the development of the Lake Bathurst drainage basin during the Late Quaternary.

Lacustrine and lagoonal sediments

Dark grey clay and silty clay underlie flat terrain in and around Lake Bathurst and the Morass (Fig 5). These sediments grade laterally into deltaic and lake barrier sands and bordering clay lunettes. Locally, on the northern and southern Morass low mounds of sand (< 1m elevation) may represent remnants of earlier sand lunettes now reduced to "sand islets". These features which become exposed at low lake levels are nesting habitats for birds. Calcareous nodules of probable pedogenic origin occur locally in the clays. Bordering areas of dry lake bed support a thick covering of the herbs Selliera radicans and Ranunculus sp. aff. papulentus (E.Canning pers. comm. 1994). The full thickness of the lacustrine sequence is unknown although a drillhole (C349) intersected 7m of clay at the eastern margin of Lake Bathurst.

A clay plain (shown as alluvium on Fig 5) east of the northern Morass is bordered on its eastern side by a narrow strip of unconsolidated sand and gravel. These sediments form a low, northwest trending embankment < 2m in elevation and corresponding to an approx. height of 680 m ASL. The embankment is breached by creeks leading into the southern Morass (see 1:36,000 colour aerial photos). Drillcore from C375 shows the plain is underlain by at least 8 m of lacustrine clay and clayey sand. This large lagoonal - type embayment and marginal palaeoshoreline may represent evidence for the maximum known extent of the Late Quaternary megalake in the basin.

Thin layers of grey-black clay are also preserved in small lagoonal depressions perched within and behind sandy beach ridges around Lake Bathurst and behind clay lunettes at the Morass (Fig 5). Clay-filled deflation hollows also occur on granitic bedrock (MR453/197). These lagoonal clay pans fill with water after heavy rains or when water levels in Lake Bathurst and the Morass are high.

A preliminary palynological scan of three clay samples from drillhole C349 suggests at least a Holocene age for these lacustrine sediments . The pollen assemblage indicates the presence of open vegetation (Graminae, *Podocarpus*, Restionaceae, *Casuarina*, Chenopodiaceae, Asteraceae sp.) and swamp taxa (*Halongis* sp) at the time the sediments were deposited. There is no evidence within the sampled interval (3.5 - 9.6m) of *Nothofagus* pollen or other taxa suggesting the presence of pre-Quaternary sediments (E.M Truswell pers. comm.1982).

Modern strandline deposits

Contemporary strandline deposition around Lake Bathurst involves the erosion and redistribution of lake barrier sands and gravels. A few samples of coarse sand show a composition dominated by poorly sorted subangular quartz (commonly up to 5mm) with minor lithic clasts; the presence of granitic clasts and cleaved fragments of pink-white feldspar show conclusively a granitic origin for these sands. Local concentrations of subangular quartzite pebbles along the western margin of the Morass represent reworked lithic gravel originating from remnants of the highest beach ridges at 680 m ASL. Current activity has removed the finer sandy matrix from these older beach gravels and redistributed it as sandy mounds and modern beach lines on and around the Morass.

Suitable ecological conditions at Lake Bathurst have allowed a thick growth of Ruppia megacarpa and Lepilaena sp. (E. Canning pers. comm. 1994) - submerged perennial plants that commonly grow in brackish to saline inland lakes. Lake level recession during 1993-94 exposed the plants which died off to form a brownish-white vegetation mat along the lake shore (Plate 8). Such a dense growth of Ruppia may act as a sediment trap and assist in the growth process of modern low amplitude beach ridges marginal to the lake. In other respects the plant provides a food source and nesting material for waterbirds.

GEOMORPHOLOGY

The Lake Bathurst drainage basin lies along the watershed seperating the Shoalhaven and Wollondilly catchments (Fig 2) and probably represents a higher less dissected remnant of the ancient Shoalhaven Plain. The long axis of the basin is influenced by the structural fabric of the underlying bedrock . The topographic margin is reasonably well defined by north northeast trending Palaeozoic rocks having relief commonly exceeding 750 m ASL.The sediments form hills and ridges and the granite intrusion more undulating terrain interspersed with isolated tors and kopjes. The subdued relief along the eastern catchment boundary is in marked contrast to the dissected relief of the neighbouring Shoalhaven river valley. The wide alluvial embayments with underfit creeks in the drainage basin represent the remains of former drainage associated with the palaeoheadwaters of Mulwaree Creek. Further evidence is provided by local areas of depressed relief (cols) around the southern half of the basin (Fig 11). Most prominent are the remnants of broad valleys near the headwaters of Millendale Creek (approx MR 447/103), at the western margin of Lake Bathurst (approx MR 425/184) and at the headwaters of Budjong Creek (approx MR 523/159).

Lake Bathurst is roughly triangular in outline with an area (in lake full conditions) of about 2,100 Ha. The most visible morphology is a prominent northwest trending linear scarp of quartzite at its southwest margin which maybe a structural boundary originating from some minor neotectonic movement along a branch of the Mulwaree Fault (Fig 5 and 11). The smooth crescentic shape of its eastern shoreline is attributable to persistent westerly winds promoting beach drift of sandy sediments. A simplified bathymetric map for Lake Bathurst (Fig 12) shows a bottom topography suggestive of an "infilled landscape" but providing no clear evidence for a network of palaeochannels converging on Mulwaree Creek. The undulating nature of the bottom topography on the western side of the lake relates to outcrops of granitic bedrock (Plate 9). A complex morphology of sand barriers and spits on the lake floor becomes almost completely submerged to form "depositional islands" in lake full conditions (BRAIDWOOD sheet RC 9 colour aerial photography,1976). A rectilinear patterning of surficial sediments on the lake bed is evident from 1:36,000 colour aerial photography (1982). It appears that in the vicinity of granitic bedrock, the jointed topography has initially influenced the morphology of lake shorelines and barriers ; kopjes and other smaller outcrops represent old or exhumed relief. Curved embayments associated with these features have formed by subsequent reworking of the sandy sediments. The eastern part of the lake bed is a large ovoid depression with no exposed granite. The bathymetric contours indicate this area is the lowest part of the lake basin (666m ASL) and may be erosional. Presumably, deepening of the bottom topography has occurred as sediment has been progressively removed from the lake bed to build the adjacent barrier.

The Morass lakes are pear-shaped in plan with an area (in lake full conditions) of about 565 Ha. The northern Morass is dominated by the smooth slightly curved margin of a clay lunette along its eastern shoreline while embayments are eroded into a wave-built barrier along its western shoreline (Fig 11). The southern Morass is also characterised by a smooth slightly concave margin of a clay lunette along its eastern shore and a low sand embankment where it intermittently joins the northern Morass. A structural lineament outlines the southwest trending southern margin. The bathymetric contours show the bed of the Morass lakes are shallow regular depressions free of rock outcrops. The three "terraced bed levels" of the lakes (L.Bathurst 666.2m ASL, northern Morass 672.9m ASL and the southern Morass 674.5m ASL) suggest a considerable degree of surficial sediment redistribution has taken place in the basin. Quartz sand lunettes (derived from a substrate of granite) distributed in and around Lake Bathurst imply this portion of the basin tends to hold water for long periods. Conversely, clay lunettes (derived from a substrate of sediments) marginal to the Morass are an indicator of the more ephemeral nature of these lakes which allows for fine material to to be wind transported from dry lake surfaces (Fig 11).

Pre-basin drainage scheme

An evolutionary geomorphological model espoused by Ollier (1980 and 1992) seems to have most applicability to long term landscape evolution of the Shoalhaven Plain prior to the mid Tertiary. In this model, the modern north trending drainage crossing the Shoalhaven Plain appears to have resulted by considerable reorganisation of an earlier (Mesozoic) northwest directed drainage scheme as the Eastern Highlands developed by continued warping, volcanic activity and faulting. It seems probable that by the mid Tertiary, the Middle Shoalhaven Plain was a relatively stable landscape with a partially dissected alluviated peneplain developed across deeply weathered early Palaeozoic rocks with drainage showing strong adjustment to the meridional grain of the geological structure. The course of Mulwaree Creek parallels the strike of Mulwaree Fault - a rejuvenated reverse fault (Felton & Huleatt 1977). The upper Shoalhaven River also flowed north following roughly the strike of the underlying Palaeozoic sediments and their contacts with the Braidwood Granite. The palaeodrainage at this time shows the elongate catchment of Mulwaree Creek separated from the Shoalhaven valley by a palaeowatershed (Fig 13). Mulwaree Creek would have joined the Wollondilly River to the north; its headwater system eroding back into the east facing Mulwaree fault scarp.

Drainage basin evolution

The site for Lake Bathurst was probably determined towards the end of the Tertiary through drainage disruption caused by progressive lowering of the base level of the Shoalhaven River at a rate quicker than Mulwaree Creek (Fig 14). The effects of the prolonged incision of the Shoalhaven River led to the partial capture of the headwaters of Mulwaree Creek to the west. An existing topographic difference of about 100m separates the bed of Lake Bathurst and Burrambowlie Swamp, a local base level on the Shoalhaven River. Furthermore, over comparable distances the stream gradients for Reedy and Boro Creeks are steep and uneven relative to the shallow and more even grade of Mulwaree Creek and the Shoalhaven River (Fig 15).The gradually increasing size of the Shoalhaven catchment led to drainage diversion and capture. Mulloon creek flowing north turned at a barbed junction to become Reedy Creek while the headwater encroachment of Boro and Millendale Creeks led to the progressive capture of the upper tributaries of Mulwaree Creek leaving a base level of swamps and disorganised drainage (see also Craft 1932). The separation of Lake Bathurst drainage basin from Mulwaree fault scarp by Mulwaree Creek suggests the basin is unlikely to have formed by direct tectonic processes eg. a fault dammed lake as envisaged by Craft (1928), Ollier (1978) and Timms (1992). There is no evidence of slope trimming along Mulwaree fault scarp that is attributable to lake shore abrasion or youthful alluvial fan development as displayed at Lake George (Abell 1991). At this stage evidence is lacking for drainage diversions being a direct response to upwarping or tilting. However northwest trending lineaments at Lake Bathurst and the Morass (Fig 11) indicate some minor faulting may have been a precursor to drainage basin initiation.

Alluvial aggradation has been given as the main process forming Lake Bathurst (Taylor 1907 and 1970 ; Jennings et al 1964 and Laseron 1972). The morphology of the drainage basin at its western margin suggests the characteristics of a blocked valley lake (cf. lateral lakes of

Hutchinson 1957; Blake & Ollier 1971 and Timms 1987). In this model (Fig 16) small tributaries entering a main river can become blocked by a process of aggradation to form levees or embankments; the main river aggrading its bed at a faster rate than the tributary valleys. Over a period covering the late Tertiary and perhaps into the Early Quaternary, Mulwaree Creek still maintained headward erosion into Mulwaree escarpment ie. Crisps / Merigan Creeks which allowed continued deposition of its load across the new base level formed by the earlier capture of its headwaters. The result was backflow and aggradation across the beheaded headwater tributaries now carrying minimal runoff and sediment load to progressively form an alluvial barrier leading to a palaeolake ("Lake Bundong") and ultimately to a closed catchment. A col on the eastern valley side of Mulwaree Creek 2 km north of Tarago is the site of the barrier now modified by past climate and lake water dynamics (Plate 10). Evidence for an aggraded floodplain along Mulwaree Creek is given by the difference in elevation between Mulwaree creek (675 m ASL) and the bed of Lake Bathurst (666 m ASL) and remnant terraces (680 m ASL) along Mulwaree Creek which have been entrenched in response to base level lowering of the Wollondilly River. It is perhaps noteworthy that the Lake Bathurst drainage basin may in part parallel the evolution of marshy depressions and lagoons eg. Breadalbane Plains and Wollogorong Lagoon to the north which are also sited in an area of disrupted drainage within the headwaters of the Lachlan catchment.

A late Quaternary history as evidenced by the catchment morphology and sedimentary sequence has been superimposed on the closed drainage basin of Lake Bathurst. A late Pleistocene " lake full phase" documented for Lake George prior to 25,000 yrs BP (Coventry 1976 and Cook 1986) is not so clearly evident at Lake Bathurst. Nevertheless, local slope trimming (cliffing) around the lake is attributable to lake shore abrasion at times of high lake levels. Detrital fans of colluvial and alluvial material have developed on these .slopes during periods of lake recession. Similarly, the existence of a littoral shelf (wave cut platform) across the bedrock floor of the lake is a response to long term lake fluctuations. A radiocarbon date of 43,000 yrs BP (Hawkes 1989) indicates the western barrier has certainly existed since the Late Quaternary. It is probable that the sand lunettes were built during periods of wetter climate while deflation hollows and further east the clay lunettes are landforms relating to dry periods.Evidence for the existence of megalake phases is provided by palaeoshorelines and slope trimming coincident with the 680 m topographic contour (Fig 17). At the maximum extent of any megalake in the basin it is estimated that a minimum water depth of 12 m must coincide with at least the present sill height of the western barrier at 678 m ASL. However there are no geomorphological features in this area supporting the existence of protracted overflow into Mulwaree Creek and it is assumed hydraulic connection was by shallow groundwater seepage or periodic overland sheet flow.

It is supposed that since the Late Quaternary, high lake levels have gradually recessed to form a series of smaller lakes eg. the Morass, with the coeval construction of beach ridges and palaeoshorelines at heights below the 680 m contour. The progressive reduction in size of the Late Quaternary megalake is a response to a long term trend towards aridity also in part documented by modern water budget studies at Lake Keilembete (Bowler 1981 and Jones et al. 1993) and the hydrologic record at Lake George. Nevertheless, the morphology and hydrologic character of the Lake Bathurst drainage basin suggests a system dominated by surface water (type B basin of Bowler 1986) and lakes that rarely dry out (stage 2 hydrodynamic model of Bowler 1986).

Changes to the pristine nature of the landscape over the last 170 years are associated with European occupation. Dryland salinity (scalding) and gully erosion occur in response to tree removal and pastoral activity. Slope instability (minor landslipping) occurs along the inner lunette margin bordering the northern Morass (Fig 18). The trimmed inner margin of the barrier at Lake Bathurst is due in part to groundwater discharge and degradation through sand mining (Fig 19) .

The timing of drainage basin initiation is poorly constrained. From evidence provided by ferricrete and bauxite, the age of the prior landscape preserved in the basin dates back at least to the Mid Tertiary and probably to the Cretaceous. Ferricretes are dissected by the modern drainage and at other places covered by Quaternary sediments. Rejuvenation of Mulwaree Fault followed by partial capture of the headwaters of Mulwaree Creek preceded the formation of the drainage basin. Evidence for renewed movement along old fault lines in the region is provided by the adjacent Shoalhaven Fault which cuts an Early Miocene basalt (Wyborn & Owen 1986). From this meagre chronology it may be inferred that rejuvenation of the Mulwaree Fault and hence basin initiation is also likely to be post Miocene. At this stage there is no evidence for the preservation of Late Tertiary (Pliocene) sediments but a palaeomagnetic date of 780,000 yrs BP (Gillieson 1984) is an indicator of the length of the Quaternary sedimentary record in the basin Climatic oscillations associated with glacial episodes beginning at the end of the Tertiary may have provided the impetus for alluvial aggradation that finally led to the formation of Lake Bathurst and later the Morass. The radiocarbon date of 43,000 yrs BP from the western barrier reported by Hawkes (1989) suggests the lake basin existed prior to the last Glacial Maximum.

HYDROLOGY

The hydrologic character of the drainage basin dates from the time of its closure in the Late Tertiary- Early Quaternary. The modern humid- temperate climatic setting of the lake basin situated in the Southern Tablelands of New South Wales is reflected in a low catchment / lake area ratio (Ac /Al) of 7.5 and evaporation / precipitation ratio (E / P) of 1.9 (based on Bureau of Meteorology data 1967- 1992). The hydrology of the lakes and groundwater in the catchment has been continuously investigated since 1981.The components of the hydrologic cycle across the basin are illustrated in Fig 20. Rainfall reaching the ground may runoff the surface towards Lake Bathurst and the Morass whence it returns directly to the atmosphere by evaporation or infiltrates (after evapotranspiration losses) to the water table. Groundwater in sandy surficial sediments moves laterally in the direction of the watertable gradient where it discharges at Lake Bathurst (Fig 21). The Morass is an ephemeral lake which is in hydraulic continuity with Lake Bathurst through a wide sand/gravel barrier. In seasonally wet years, when reaching a depth of 3.4 m (676.2 m ASL) it will also overflow across this barrier towards Lake Bathurst. At the base of the surficial sediments there is assumed to be vertical leakage of groundwater into bedrock fractures which may form local semi-confined aquifers.

The hydrographs for Lake Bathurst and the Morass show they are generally synchronous in their behaviour although they appear to have different cvcles of drying out (Figs 22 and23). During the sustained dry period in the 1980s, Lake Bathurst dried out in early 1988, but the Morass retained its water through the summer months. It seems that water levels at Lake Bathurst are sensitive to major long term climate fluctuations whereas the more ephemeral Morass is responsive to shorter wavelength climatic variation eg. it dried out in 1982, when Lake Bathurst held its water. The water chemistry data shows Lake Bathurst and the Morass have salinities differing by a factor of 10. The former is a saline lake (water conductivity >1 x 10^3 microsiemens /cm) and the latter a freshwater lake (water conductivity <1 x 10^2 microseimens /cm). They present an unusual occurrence on the Southern Tablelands of New South Wales of the close juxtaposition of saline and freshwater lakes. An analagous situation in the semi arid zone of south west Queensland is provided by Lake Wyara with a salinity of 30,000 microsiemens /cm and Lake Numalla 1,700 microsiemens /cm (measured on 29/7/92) ; these lakes are also apparently separated by a sand barrier (quartz sand lunette) approximating to a width of 2 kms.

Surface water

A mean annual rainfall of 700mm and E/P ratio of 1.9 is sufficient to sustain surface water in creeks, lakes and small lagoonal depressions. The most visible expressions are provided by Lake Bathurst and the Morass that have fluctuating water levels responding to seasonal and longer term changes in rainfall patterns. Monthly water level changes measured by level and staff and salinity monitoring have been undertaken at Lake Bathurst over the period 1981-94 and at the Morass from 1987 to 1994. There are no surface runoff records in the basin. However the Morass is fed by creeks mainly on its eastern side and therefore runoff is considered a major input to the lake. In contrast, surface water input to Lake Bathurst via Chain O Ponds Creek is minimal and hence this lake must be sustained by groundwater discharge which also accounts for its higher salinity.

Lake Bathurst is a terminal lake situated in the lowest part of the drainage basin. The hydrograph (Fig 22) shows it has contained water for almost 100% of the time except for a short 2-3 month dry period in early 1988; maximum lake depth recorded is 3.47 m (669.7 m ASL). However, the concentric arrangement of palaeoshorelines is an indicator that in the past the lake has been capable of holding water for long periods. In fact, a depth of about 12m is needed for a palaeo megalake to accomplish overflow to Mulwaree Creek across the sill on the western barrier of the lake (678.3 m ASL). Proportionately, this contrasts with the Lake George basin which has an area 6 times greater and requires a water depth of about 36 m to reach a possible palaeo overflow site at Gearys Gap (Coventry 1976). When Lake Bathurst reaches a depth of 10.7 m (677 m ASL) it will connect with the Morass to form one large lake (megalake). Documentation of water level records prior to 1981 is sparse. However, some direct observations of the lake supplemented by local anecdotal information is reported in Taylor 1907, 1970 and Jennings et al (1964):

1844	- Dry
1870 - 78	- Full*
1873 - 74	- Overflow across western barrier to Mulwaree Creek
1890	- Full
1906 - 07	- Low (0.3m depth)
1926	- Full
1940 - 45	- Low

1950	- Full
1956	- Full
1963	- Full
1976	- Full

* the term "full" is taken to be a lake approaching its maximum dimensions.

Fences constructed across the lake attest to it drying out long enough for subdivision of the lake bed for grazing. The historical information also indicates that major water level oscillations at Lake Bathurst correlate with similar trends observed at Lake George. A lag of several months in the response time of water levels to major rainfall periods (Fig 22) and a drying out phase associated with longer amplitude climate fluctuations suggest there is a buffering effect from groundwater input to the lake. The clarity (lack of turbidity) of the brackish-saline water is in part attributed to clay flocculation but extensive plant growth (Ruppia sp.) also hinders sediment movement. A strong musty smell associated with this decaying vegetation is released when lake muds are disturbed. A wind driven seiche has not been detected at Lake Bathurst probably because of a smaller lake area and complex lake bed bathymetry. In 1982, a hydrograph obtained during a low lake level condition showed small oscillations in water level were due to strong westerly winds producing a fetch banking up water on the eastern side of the lake (Fig 24). Based on the bathymetry, the volume of Lake Bathurst at increasing water levels is given at Table 2.

Water level (metres ASL)	Volume (megalitres)
666.5	350
667.0	2000
667.5	4500
668.0	7900
670.0	27900
672.0	54500
674.0	85000
676.0	119100

Table 2 Water level - volume relationship at Lake Bathurst (Information supplied by the Australian Survey Office 1983)

The naming of the Morass dates back to early European settlement when this area was observed as waterlogged, marshy ground. At this time (170 years ago) a more extensive tree cover across the lake basin would have restricted surface runoff and lowered the water table. Progressive land use change (mostly tree clearing) has now altered the original appearance of the Morass from a marsh to an open lake environment. The Morass has been less studied; the monitoring station at the northernmost of the two lakes (Fig 21) was only established in 1987. The hydrograph (Fig 23) shows water level oscillations are similar to Lake Bathurst. In contrast, greater water depths in the Morass reflect not only a quicker response time to rainfall events but the availability of more catchment runoff entering the eastern side of the lake. The Morass is an ephemeral "flow - through" lake; its position in a more elevated part of the basin means that surface/groundwater fluctuations are more marked and drying out periods occur over shorter periods of time cf. Lake Bathurst. This is also confirmed to some extent by a lack of palaeoshorelines around the lake. When the northern lake reaches a depth of 3.4 m it overflows through a broad outlet on its western margin.However during the study period a direct connection with Lake Bathurst was not observed; the overflow water appearing to infiltrate the sand/gravel barrier sediments. While overflow of the Morass into Lake Bathurst is an unusual event it would have occurred more often in the past but the old drainage channel has been blocked with loose rubble in an effort to increase the capacity of the Morass and lessen the area of waterlogged ground. The Morass last dried out in 1982 ; the drying out process starting with the southern Morass (lake bed elevation 674.5 m ASL) followed by the northern Morass (lake bed elevation 672.9 m ASL).

Groundwater

The surficial groundwater hydrology in the basin is essentially an interaction between aquifers in unconsolidated Cainozoic sediments and the lakes. Surficial sandy sediments are recharged by rainfall. During flood runoff some streambed infiltration may occur in the upper reaches of the catchment, but at other times groundwater will persist as baseflow in creeks eg. Chain O Ponds Creek. In the elevated parts of the catchment there is direct recharge to fractured bedrock aquifers. It is possible there maybe upward flow into the surficial aquifers from fractured rocks in lower areas of the basin but no supporting piezometric data is available (Fig 20).

The groundwater data collected since 1982 mostly relates to the Cainozoic sequence and was obtained from stratigraphic drillholes that were later equipped as groundwater observation bores. The few bores monitored in the basin show that groundwater movement takes place mostly through surficial sediments towards Lake Bathurst (Fig 21). The groundwater gradients shown in Figure 25 indicate a closed groundwater system , although a reversal of the gradient towards Mulwaree Creek may occur when Lake Bathurst approaches the top of the western barrier (Fig 25 A). Within the basin the water table data shows no interlake divide between the Morass and Lake Bathurst (Fig 25 C). The former is a "flow - through" lake with groundwater moving along a low gradient path on the eastern side and out from the western side where it establishes hydraulic connection with Lake Bathurst through sandy sediments in the central barrier. Finally, indicators that Lake Bathurst is an internal discharge area are expressed by converging groundwater flow paths, maintenance of water in the lake over long periods, salinities greater than the Morass and perched groundwater seepages around the lake. Groundwater hydrographs from C347 and C348 show a clear but lagged response to seasonal patterns of rainfall (Fig 26). The water level fluctuations are taken to be representative of groundwater conditions in the basin and this is confirmed by a shorter record from C348 sited on the central barrier west of the Morass.

Hydrochemistry

Chemical analyses of surface and groundwater in and around Lake Bathurst drainage basin is given in Table 3. The data base of 37 analyses mainly covers the period 1981-91. The sources of data (unless otherwise stated) are AGSO (formerly BMR) and ANU (P.de Deckker pers. comm.1994). The analyses are tabulated in chronological order with a numbering system specific to the drainage basin. Sample locations are shown at Fig 27.

Surface water

The field of major ions on the Piper trilinear diagram (Fig 28) shows surface waters are of the Na-HCO_3 -Cl type. With increasing salinity these waters trend towards the Na and Cl corners of the diagram reflecting the process of evaporative concentration. For lakewaters, salinity varies inversely with lake stage (Figs 22 and 23) and show compositional changes as lake levels fall (Table 3).

Under normal seasonal conditions, the Morass may be classified as a freshwater lake. Field salinities are normally < 1000 microsiemens/cm and increase above this value when water depths reach < 1.4 m (Fig 23). Field pH values commonly range within 7.0 - 9.5 and there is seasonal variation (Fig 23). In winter pH values decrease when water temperatures are low (~ 10^0 C) and water levels rise due to an excess of rainfall over evaporation; the reverse relationship is apparant during summer. At this stage it is unclear what factors disturb the CO_3 - HCO_3 - CO_3 equilibrium of the lake, but it is possible that changes in hydrogen ion concentration are affected by seasonal biota activity. The waters are of the Na-HCO_3 - Cl type and plot in the same field as analyses for Mulwaree Creek (Table 3 and Fig 28). The low Mg /Ca ratios of the lakewaters are similar to shallow groundwater analysed from bores in the central barrier (Fig 27 and table 3). This hydrochemical data suggests that the water budget for the Morass is dependant mainly on surface water input and groundwater output. Hydraulic connection with Lake Bathurst by flood overflow and groundwater output provides a regular flushing mechanism limiting the accumulation of salt in the lake.The Morass supports a freshwater lake ecology eg. the floodplain mollusc Velusunio ambiguus and the crayfish - "yabbie" (Cherax sp.)

The water chemistry for Lake Bathurst differs markedly from the Morass. In normal seasonal conditions it may be classified as a brackish lake becoming saline (> 10,000 microsiemens /cm) when depths are < 1m (Fig 22). In contrast to the Morass, salinity values are consistently 10 times greater and the waters show higher concentrations of Na-Cl-HCO_3 ions (see Figs 22, 23, and 28). Field pH values commonly range from 8.0-10.5; seasonal variation in pH (Fig 22) is less obvious (cf. the Morass) but values > 10 measured in 1992-93 and 1993-94 are unusual and may relate to excessive growth activity of the halophyte Ruppia. Changes also occur in the Mg/Ca ratio of the lakewaters (see table 3). The higher ratios tend to occur during low lake stage and are explained by precipitation of $CaCO_3$ probably as monohydrocalcite (P de Deckker pers. comm. 1994). According to Taylor (1975), the formation of monohydrocalcite ($CaCO_3.H_2O$) by precipitation from saline waters is favoured by Mg/Ca ratios (>10) and high pH (>8.0). The variable Mg/Ca ratio at Lake Bathurst may also relate to the biological activity of ostracods. Chivas et al. (1986) studying the Mg content of Mytilocypris valves demonstrated that it was dependant on the complex processes of growth stage and also temperature, salinity and Mg content of the host water. A brackish-saline water ecology is evidenced by the presence of Ruppia supporting the halobiont ostracod Mytilocypris henricae (Martens et al. 1985). Pink-red (carotenoid pigment) photosynthetic sulphur bacteria also colonise Ruppia near the lake surface; their growth cycle is in part favoured by the presence of sulphate in the lake waters (J.Bauld pers. comm. 1994). However the bacterial consumption of sulphate may also explain its gradual decline in concentration along the evolutionary path of the lakewater (see Fig 28). The local presence of Velusunio ambiguus is indicative of a precarious freshwater environment where Chain O Ponds Creek enters Lake Bathurst.

Groundwater

Chemical analyses are too few to provide a satisfactory interpretation of the hydrogeochemical environment in the basin. Groundwater analyses are almost entirely from surficial sediments (see table 3); most samples were obtained from stratigraphic drillholes tapping multiple aquifers. Little is known about the hydrochemistry of fractured bedrock. The cation diagram (Fig 28) shows the groundwater component plots close to the Morass which may reflect limited water-sediment interaction in a small catchment and the fact that the Morass is in part a groundwater window (see also Fig 25). In the anion diagram, the groundwater chemistry appears to be dominated by silicate mineral dissolution in the aquifers but is complicated by the flow patterns in surficial sediments (distribution of recharge areas, flow path lengths and aquifer geochemistry). The evolutionary path for groundwater is towards the Na-Cl apex where Lake Bathurst waters define the end member of the mixing system. The change in anion composition is largely governed by the chloride ion and is most probably related to soluble salts stored in weathered zones, surficial sediments and the continuous input from rainfall.

Groundwater in the basin is characterised by variable concentration of total dissolved solids ranging from 143-5270 mg/l TDS; generally slightly alkaline (pH range 6.5 - 8.0); fairly constant Mg/Ca ratios (0.7-2.4) and generally low nitrate values. The chemical data suggests that in most cases groundwater quality is within the acceptable limits for human consumption (1,200 mg/l TDS) and for stock (3,000 mg/l TDS). Most groundwater is hard, often exceeding the acceptable limit of 180 mg/l $CaCO_3$.

Table 3 Chemical analyses of suface water and groundwater[1]

SURFACE WATER

The Morass

No	Date	Lake stage (m)	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	CL	NO_3	Mg/Ca ratio (atoms)	pH	EC (μ/S)	TDS (mg/l)	Analysis Source	Remarks
M1	7/5/84	-	8.8	5.2	12.0	2.2	29.0	-	10.0	23.0	<1	0.95	6.3	155	76	AMDEL	Surface water extraction
M2	7/5/84	-	17.0	9.0	42.0	9.4	78.0	-	24.0	63.0	1.0	0.50	7.1	390	203	"	
M3	7/5/84	-	8.5	3.7	14.0	4.3	40.0	-	7.0	20.0	1.0	0.40	7.0	154	78	"	
M4	1/5/87	1.0	50.0	27.0	130.0	19.0	220.8	-	83.0	212.0	0.2	0.80	8.1	1200	632	"	Low lake leval
M5	5/6/91	2.5	10.9	7.9	36.3	5.5	36.2	-	9.1	60.6	2.6	1.20	7.3	340	170	BMR	
Mulwaree Creek																	
MC1	7/5/84	-	50.0	33.0	56.0	1.6	134.0	-	48.0	151.0	<1	1.10	7.2	790	407	AMDEL	
MC2	7/5/84	-	50.0	35.0	48.0	1.4	150.0	-	62.0	124.0	<1	1.10	7.6	760	395	"	

Footnote
1 Sample locations shown in Figure 27.
2 Numbering system M - Morass ; LB - Lake Bathurst ; MC - Mulwaree Creek ; G - Groundwater.
3 Aquifers SS - Surficial Sediments ; FR - Fractured Rock

Lake Bathurst

No	Date	Lake stage (m)	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	CL	NO_3	Mg/Ca ratio (atoms)	pH	EC (μ/S)	TDS (mg/l)	Analysis Source	Remarks
LB1[2]	14/11/60	-	16	30	200	18	165	-	17	313	-	3.1	9.3	1310	714	-	Jennings et al (1964)
LB2	30/1/69	-	18	90	990	15	700	-	10	1420	0.77	8.2	8.3	4575	2935	AMDEL	Burton (1972)
LB3	i6/1/81	-	12	70	1030	61	359	78	15	1540	-	9.6	-	-	-	ANU	
LB4	2/7/81	<2.5	29.2	84	1070	53	652	12	33	1560	-	4.7	8.3	5400	-	"	
LB5	27/8/81	2.5	33	84.1	875	43	584	37	36	1332	-	4.2	9.1	5300	-	"	
LB6	15/12/81	2.3	144	42	1270	73	685	11	30	1950	-	0.5	8.3	-	-	"	
LB7	19/1/82	2.2	154	36	1320	72	660	30	32	2030	-	0.4	8.8	-	-	"	
LB8	2/3/82	1.9	160	59	1570	89	705	89	37	2420	-	0.6	8.9	6500	-	"	
LB9	1/4/82	2.0	146	64	1440	75	730	42	35	2270	-	0.7	8.8	-	-	"	
LB 10	29/4/82	1.9	179	50	1256	64	780	40	38	1930	-	0.5	8.7	5650	-	"	
LB 11	24/5/82	1.9	185	57	1386	70	811	46	39	2145	-	0.5	8.8	-	-	"	
LB12	2/2/83	0.7	47.3	554	4440	42	2150	118	8	7150	-	19.2	8.7	-	-	"	Sample depositing $CaCO_3.H_2O$ on Ruppia.
LB 13	5/5/83	0.7	135	282	3310	159	1195	99	98	5350	-	3.4	-	-	-	"	
LB 14	12/5/83	0.7	131	292	3230	154	1228	108	86	5470	-	3.7	9.7	-	-	"	
LB 15	7/5/84	1.2	23	96	1015	55	528	5	34	1535	10	4.2	8.4	5450	3033	AMDEL	
LB 16	7/5/84	1.2	37	185	1890	99	853	-	65	2861	22	8.3	8.3	9750	5628	"	
LB 17	7/5/84	1.2	28	280	3100	160	1003	110	125	4816	<1	16.4	8.8	15300	9114	"	
LB 18	1/5/87	0.4	9	660	14300	410	655	722	370	22490	<0.1	120	9.7	58000	39288	"	

GROUNDWATER

No	Year	Ext. Type	Aquifer[3]	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl	NO_3	Ca/Mg ratio (atoms)	pH	EC (μ/S)	TDS (mg/l)	Analysis Source	Remarks
G1	7/5/84	Seepage	SS	7.2	3.5	16.0	3.3	29.0	_	4.0	17.0	<1	0.7	6.7	143	75	AMDEL	Cent. barr.
G2	7/5/84	Strat. bore	SS	18.0	19.0	70.0	4.2	85.0	_	1.0	154.0	<1	1.7	6.9	540	309	"	C348
G3	7/5/84	"	SS	107.0	<0.1	190.0	16.0	_	16.0	41.0	416.0	<1	_	10.9	1700	794	"	C347
G4	7/5/84	"	SS	36.0	50.0	193.0	2.1	35.0	_	2.0	483.0	<1	2.3	6.5	1650	785	"	C345
G5	28/3/89	"	SS	59.1	66.2	309.0	17.0	180.0	_	124.0	570.0	<0.1	1.8	7.9	2500	1282	BMR	C349
G6	28/3/89	"	SS	24.4	20.5	59.8	4.6	82.5	_	0.6	143.0	<0.1	1.4	7.5	688	246	"	C 348
G7	28/3/89	Bore (GH1)	SS	38.4	34.9	251.0	1.4	282.5	_	181.0	236.0	0.9	1.5	7.7	1690	908	"	Hawkes (1989)
G8	28/3/89	Bore (GH2)	SS	16.0	7.9	57.7	1.6	133.7	_	12.2	27.9	5.5	0.8	7.9	436	118	"	"
G9	28/3/89	Bore (GH3)	SS	49.2	22.8	53.5	6.2	162.5	_	13.3	84.5	0.4	0.7	7.8	664	280	"	"
G 10	4/4/91	Strat. bore	SS	94.5	52.1	180.0	4.2	270.0		26.9	312.0	19.8	0.9	7.6	1500	968	"	C376
G11	4/4/91	"	SS	138.0	113.0	821.0	14.5	(acid water)	_	321.0	1760.0	<1.0	1.3	4.7	5270	3450	"	C375
G12	5/6/91	Obs. bore	FR	137.0	201.0	168.0	3.0	256.2	_	64.6	770.0	17.4	2.4	7.4	2880	1460	"	_

WATER BALANCE

A water balance for the drainage basin was undertaken to estimate the amount of recharge from rainfall that is available for groundwater storage. The parameters involved in the water balance are rainfall and evaporation which are dependant on spatial boundaries in the basin and the timescale of the hydrographic monitoring (inclusive of the Morass) from March 1987 to July 1994. Important spatial boundaries are basin area (115km^2) and lake areas that fluctuate with lake level change.

The water balance equation can be simply expressed as:

$$\underset{\text{(Input)}}{P} = \underset{\text{(Output)}}{E_{AL} + E_{AC} \pm \Delta S}$$

where P = Rainfall
E_{AL} = Lakewater evaporation (open water)
E_{AC} = Catchment evaporation (vegetated)
ΔS = Change in groundwater storage

Re-arranging the above equation in terms of the unknown , groundwater storage ΔS , gives

$$\pm \Delta S = P - (E_{AL} + E_{AC})$$

All terms on the right hand side of the equation can be quantified by measurement or estimation and thus groundwater recharge can be determined (see table 4). The water balance procedure is based on the basin being a closed surface water system and that no water enters or leaves by means of water supply or sewage disposal schemes.

Rainfall

The monthly rainfall record at Gilmour (Met Stn 070036) provides the most reliable input for the water balance. Although this station is sited near Lake Bathurst village and just beyond the northern end of the basin (see Fig 27), it is considered to adequately reflect the rainfall pattern - the record is continuous from 1931. Rainfall is also collected on Bundong and Kywong properties (Hawkes 1989); these unofficial data sets indicate some variation in rainfall across the basin but otherwise correlate well in time with the record at Gilmour HS. The mean annual rainfall for the basin taken over the period 1931-93 is 700 mm. For the six years of the water balance study (1988-94) it was 804.5 mm; this higher mean reflecting wet years following the prolonged dry conditions during the 1980's.

Evaporation

Evaporation and transpiration constitute the major output of water from the hydrologic system of the basin. Evaporation includes water that is evaporated directly from lakes, soil, plant and rock surfaces. Transpiration refers to water drawn by plants from the soil, groundwater or swamps which evaporates through plant pores during periods when the plant surface is dry. For the basin, the potential (actual) evaporation is greater than the rainfall in summer but generally less in winter (Fig 29).The nearest meteorological stations to the basin measuring evaporation are at Woodlawn Mine 10km to the west on the Great Divide and at Goulburn (Met

Stn 070263) 35 km to the north.The record at Woodlawn Mine is incomplete with data missing for a period of 18mths (July 1988-Dec 89). The evaporation data at Goulburn was also discounted due to poor overall correlation with Woodlawn; a site change at Goulburn giving 30-35% lower monthly totals over the water balance period. It was therefore decided to use the International Class "A" pan data at Canberra Airport (Met Stn 070014) which is complete and correlates reasonably well with monthly totals for Woodlawn. The rate of open water evaporation from the Morass and Lake Bathurst was estimated using a pan coefficient (K_P) of 0.7 based on information outlined in AWRC (1970). Areal estimates of the two lakes for changing water depths are shown at Figs 30 and 31. The graphs were generated by E.Bleys (AGSO) from the detailed 1:10.000 lake bed bathymetry (ASO 1982). Bathymetric contours falling within the measured range of water depths were digitised on ARCINFO to calculate lake areas. The crop factor (K_C) of 1 (Doorenbos & Pruitt 1977) was used in the estimate of potential evapotranspiration (E_{pot}) based on a catchment that is ~ 90% grassed with stands of open eucalypt woodland. Areas of eucalypt forest along the basin margin near Percy Trig. and west of Timbertop HS are not considered to greatly affect groundwater recharge rates because of their small areal extent.

Water balance procedure

The following spreadsheet calculations were used for estimating groundwater recharge:

Eq. 1 - Volume of rainfall over drainage basin (P_V) = $P/1000 \times A_b$ m^3
where P = rainfall in mm
A_b = drainage basin area (115×10^6 m^2)

Eq. 2 - Lake evaporation (E_L) = $E_{Pan} \times K_P$ mm
where E_{Pan} = measured evaporation in mm
K_P = pan coefficient (0.7)

Eq. 3 - Potential evapotranspiration (E_{pot}) = $E_L \times K_C$ mm
where K_C = crop factor (1.0)

Eq. 4 - Sum lakes area (A_L) in m^2 from area - depth graphs (Figs 30 and 31)

Eq. 5 - Surrounding catchment area (A_C) = $A_B - A_L$ (m^2)

Eq. 6 - Volume of evaporation from lakes area (E_{AL}) = $E_L / 1000 \times A_L$ (m^3)

Eq. 7 - Volume of evaporation from catchment (E_{AC}) = $E_{pot} /1000 \times A_C$ (m^3)

Eq. 8 - Total volume of evaporation (E_V) = $E_{AL} + E_{AC}$ (m^3)

Eq. 9 - Change in storage ($\pm \Delta S$) = $P_V - E_V$ (m^3)

Change in storage

The quantity of water stored in the basin is estimated at Table 4 (Eq. 9) which it is assumed approximates to groundwater recharge.The negative values for ΔS at Eq.9 indicate months where E_V exceeds P_V and hence no liklihood of groundwater recharge. Generally recharge tends to take place in winter months when rainfall is high and evaporation low; some recharge may occur in summer if there are intense rainfall periods.Yearly recharge events are shown graphically at Fig 29.

The water balance procedure adopted for this study is simplistic and only covers a limited time frame of about 7 years during which there was adequate rainfall in the basin. The values for recharge may be an underestimate as there are a number of constraints:-

(a) the estimate of water available for recharge includes a soil moisture component. Groundwater recharge will only occur when soils are fully saturated ie. when soil moisture reaches 100%. Soil moisture replenishment rates depend on the surface and near surface permeability of the soil. The evaporation

Year	Month	P (mm)	P_V ($m^3 \times 10^3$)	E_{pan} (mm)	E_L (mm)	E_{pot} (mm)	Area Lake Bathurst ($m^2 \times 10^6$)	Area Morass ($m^2 \times 10^6$)	Total Lake Area A_L ($m^2 \times 10^6$)	Land Area A_C ($m^2 \times 10^6$)	E_{AL} ($m^3 \times 10^3$)	E_{AC} ($m^3 \times 10^3$)	Total Evaporation E_v ($m^3 \times 10^3$)	Change in Storage Δs ($m^3 \times 10^3$)
			Eq. 1		Eq. 2	Eq. 3			Eq. 4	Eq. 5	Eq. 6	Eq. 7	Eq. 8	Eq. 9
1987	Mar	56.4	6486	173.4	121.4	121.4	3.48	2.65	6.13	108.87	744.06	13214.64	13958.70	-7472.70
	Apr	30.2	3473	121.4	84.98	84.98	3.10	2.50	5.60	109.40	475.89	9296.81	9772.70	-6299.70
	May	40.0	4600	74.2	51.94	51.94	2.63	2.48	5.11	109.89	265.41	5707.69	5973.10	-1373.10
	Jun	36.0	4140	44.2	30.94	30.94	2.95	2.38	5.33	109.67	164.91	3393.19	3558.10	581.90
	Jul	60.4	6946	51.0	35.7	35.7	2.90	2.40	5.30	109.70	189.21	3916.29	4105.50	2840.50
	Aug	71.9	8268.5	68.4	47.88	47.88	3.25	2.43	5.68	109.32	271.96	5234.24	5506.20	2762.30
	Sep	26.1	3001.5	125.6	87.92	87.92	2.70	2.43	5.13	109.87	451.03	9659.77	10110.80	-7109.30
	Oct	66.2	7613	151.4	106	106	2.63	2.30	4.93	110.07	522.48	11665.22	12187.70	-4574.70
	Nov	121.6	13984	217.4	152.2	152.2	2.45	2.20	4.65	110.35	707.64	16793.06	17500.70	-3516.70
	Dec	80.2	9223	235.4	164.8	164.8	3.05	2.05	5.10	109.90	840.38	18109.32	18949.70	-9726.70
1988	Jan	35.4	4071	279.5	195.7	195.7	1.15	1.67	2.82	112.18	551.73	21948.02	22499.75	-18428.75
	Feb	56.4	6486	229.4	160.6	160.6	0.00	1.40	1.40	113.60	224.81	18241.89	18466.70	-11980.70
	Mar	43.0	4945	184.8	129.4	129.4	0.00	1.17	1.17	113.83	151.35	14725.05	14876.40	-9931.40
	Apr	141.4	16261	91.2	63.84	63.84	0.00	1.13	1.13	113.87	72.14	7269.46	7341.60	8919.40
	May	83.0	9545	63.2	44.24	44.24	4.23	1.72	5.95	109.05	263.23	4824.37	5087.60	4457.40
	Jun	35.4	4071	44.4	31.08	31.08	4.60	2.05	6.65	108.35	206.68	3367.52	3574.20	496.80
	Jul	92.6	10649	45.8	32.06	32.06	5.75	3.95	9.70	105.30	310.98	3375.92	3686.90	6962.10
	Aug	55.8	6417	81.2	56.84	56.84	5.70	4.03	9.73	105.27	553.05	5983.55	6536.60	-119.60
	Sep	67.6	7774	117.0	81.9	81.9	6.05	4.07	10.12	104.88	828.83	8589.67	9418.50	-1644.50
	Oct	29.0	3335	213.0	149.1	149.1	5.75	3.88	9.63	105.37	1435.83	15710.67	17146.50	-13811.50
	Nov	171.2	19688	188.2	131.7	131.7	5.40	3.70	9.10	105.90	1198.83	13951.27	15150.10	4537.90
	Dec	142.8	16422	193.4	135.4	135.4	5.60	3.80	9.40	105.60	1272.57	14296.13	15568.70	853.30
1989	Jan	51.6	5934	209.2	146.4	146.4	6.10	3.80	9.90	105.10	1449.76	15390.84	16840.60	-10906.60
	Feb	16.8	1932	196.6	137.6	137.6	5.70	3.50	9.20	105.80	1266.10	14560.20	15826.30	-13894.30
	Mar	43.0	4945	147.2	103	103	5.30	3.28	8.58	106.42	884.08	10965.52	11849.60	-6904.60
	Apr	141.4	16261	74.4	52.08	52.08	8.55	5.12	13.67	101.33	711.93	5277.27	5989.20	10271.80
	May	83.0	9545	46.0	32.2	32.2	9.40	5.28	14.68	100.32	472.70	3230.30	3703.00	5842.00
	Jun	35.4	4071	37.0	25.9	25.9	9.43	5.28	14.71	100.29	380.99	2597.51	2978.50	1092.50
	Jul	92.6	10649	43.2	30.24	30.24	10.00	5.35	15.35	99.65	464.18	3013.42	3477.60	7171.40
	Aug	55.8	6417	65.2	45.64	45.64	10.20	5.37	15.57	99.43	710.61	4537.99	5248.60	1168.40
	Sep	67.6	7774	104.6	73.22	73.22	10.40	5.38	15.78	99.22	1155.41	7264.89	8420.30	-646.30
	Oct	29.0	3335	180.6	126.4	126.4	10.20	5.33	15.53	99.47	1963.30	12575.00	14538.30	-11203.30
	Nov	171.2	19688	157.8	110.5	110.5	10.00	5.30	15.30	99.70	1690.04	11012.86	12702.90	6985.10
	Dec	142.8	16422	236.2	165.3	165.3	10.05	5.30	15.35	99.65	2537.97	16476.13	19014.10	-2592.10
1990	Jan	33.8	3887	230.8	161.6	161.6	9.45	5.27	14.72	100.28	2378.16	16201.24	18579.40	-14692.40
	Feb	115.0	13225	160.2	112.1	112.1	9.00	5.25	14.25	100.75	1598.00	11298.10	12896.10	328.90
	Mar	18.8	2162	169.4	118.6	118.6	9.00	5.25	14.25	100.75	1689.77	11946.94	13636.70	-11474.70
	Apr	146.8	16882	93.6	65.52	65.52	8.65	5.20	13.85	101.15	907.45	6627.35	7534.80	9347.20
	May	123.6	14214	71.4	49.98	49.98	9.00	5.25	14.25	100.75	712.22	5035.49	5747.70	8466.30
	Jun*	19.2	2208	40.8	28.56	28.56	9.50	5.30	14.80	100.20	422.69	2861.71	3284.40	-1076.40
	Jul	55.8	6417	54.0	37.8	37.8	9.75	5.30	15.05	99.95	568.89	3778.11	4347.00	2070.00
	Aug	127.6	14674	77.2	54.04	54.04	11.35	5.40	16.75	98.25	905.17	5309.43	6214.60	8459.40
	Sep	43.8	5037	95.2	66.64	66.64	11.80	5.35	17.15	97.85	1142.88	6520.72	7663.60	-2626.60
	Oct	53.2	6118	115.6	80.92	80.92	11.95	5.37	17.32	97.68	1401.53	7904.27	9305.80	-3187.80
	Nov	5.4	621	233.8	163.7	163.7	11.90	5.33	17.23	97.77	2819.86	16001.04	18820.90	-18199.90
	Dec	7.7	885.5	322.6	225.8	225.8	11.50	5.29	16.79	98.21	3791.52	22177.78	25969.30	-25083.80
1991	Jan	65.4	7521	295.4	206.8	206.8	11.00	5.23	16.23	98.77	3356.04	20423.66	23779.70	-16258.70
	Feb	36.6	4209	241.2	168.8	168.8	10.87	5.14	16.01	98.99	2703.13	16713.47	19416.60	-15207.60
	Mar	12.2	1403	214.2	149.9	149.9	10.40	5.10	15.50	99.50	2324.07	14919.03	17243.10	-15840.10
	Apr	25.0	2875	126.4	88.48	88.48	10.15	5.05	15.20	99.80	1344.90	8830.30	10175.20	-7300.20
	May	28.8	3312	67.2	47.04	47.04	10.00	5.02	15.02	99.98	706.54	4703.06	5409.60	-2097.60
	Jun	162.4	18676	56.2	39.34	39.34	9.90	5.02	14.92	100.08	586.95	3937.15	4524.10	14151.90
	Jul	83.0	9545	54.2	37.94	37.94	10.50	5.22	15.72	99.28	596.42	3766.68	4363.10	5181.90
	Aug	75.1	8636.5	94.0	65.8	65.8	11.25	5.37	16.62	98.38	1093.60	6473.40	7567.00	1069.50
	Sep	40.8	4692	112.4	78.68	78.68	11.30	5.34	16.64	98.36	1309.24	7738.96	9048.20	-4356.20
	Oct	21.8	2507	170.8	119.6	119.6	11.20	5.34	16.54	98.46	1977.52	11771.88	13749.40	-11242.40
	Nov	33.8	3887	215.8	151.1	151.1	11.05	5.30	16.35	98.65	2469.83	14902.07	17371.90	-13484.90
	Dec	97.6	11224	218.0	152.6	152.6	10.75	5.27	16.02	98.98	2444.65	15104.35	17549.00	-6325.00
1992	Jan	124.4	14306	227.2	159	159	10.60	5.27	15.87	99.13	2523.96	15765.64	18289.60	-3983.60
	Feb	84.4	9706	152.2	106.5	106.5	10.50	5.25	15.75	99.25	1678.01	10574.10	12252.10	-2546.10
	Mar	67.0	7705	141.4	98.98	98.98	10.50	5.25	15.75	99.25	1558.94	9823.77	11382.70	-3677.70
	Apr	19.4	2231	97.4	68.18	68.18	10.50	5.25	15.75	99.25	1073.84	6766.86	7840.70	-5609.70
	May	33.0	3795	53.0	37.1	37.1	10.45	5.20	15.65	99.35	580.62	3685.88	4266.50	-471.50
	Jun	39.2	4508	40.8	28.56	28.56	10.40	5.17	15.57	99.43	444.68	2839.72	3284.40	1223.60
	Jul	15.6	1794	58.0	40.6	40.6	10.40	5.18	15.58	99.42	632.55	4036.45	4669.00	-2875.00
	Aug	76.8	8832	68.8	48.16	48.16	10.20	5.16	15.36	99.64	739.74	4798.66	5538.40	3293.60
	Sep	68.6	7889	95.4	66.78	66.78	10.30	5.15	15.45	99.55	1031.75	6647.95	7679.70	209.30
	Oct	46.5	5347.5	107.2	75.04	75.04	10.20	5.15	15.35	99.65	1151.86	7477.74	8629.60	-3282.10
	Nov	80.1	9211.5	132.0	92.4	92.4	10.15	5.25	15.40	99.60	1422.96	9203.04	10626.00	-1414.50
	Dec	69.0	7935	143.0	100.1	100.1	10.10	5.14	15.24	99.76	1525.52	9985.98	11511.50	-3576.50
1993	Jan	119.4	13731	193.4	135.4	135.4	10.05	5.13	15.18	99.82	2055.07	13513.63	15568.70	-1837.70
	Feb	20.2	2323	158.4	110.9	110.9	9.80	5.10	14.90	100.10	1652.11	11099.09	12751.20	-10428.20
	Mar	93.6	10764	131.2	91.84	91.84	9.45	5.05	14.50	100.50	1331.68	9229.92	10561.60	202.40
	Apr	9.0	1035	97.6	68.32	68.32	9.35	5.05	14.40	100.60	983.81	6872.99	7856.80	-6821.80
	May	33.0	3795	58.8	41.16	41.16	8.90	5.02	13.92	101.08	572.95	4160.45	4733.40	-938.40
	Jun	27.0	3105	43.6	30.52	30.52	8.85	5.00	13.85	101.15	422.70	3087.10	3509.80	-404.80
	Jul	128.0	14720	42.4	29.68	29.68	8.80	5.00	13.80	101.20	409.58	3003.62	3413.20	11306.80
	Aug	21.0	2415	70.6	49.42	49.42	7.40	5.03	12.43	102.57	614.29	5069.01	5683.30	-3268.30
	Sep	83.4	9591	93.0	65.1	65.1	9.00	5.02	14.02	100.98	912.70	6573.80	7486.50	2104.50
	Oct	113.4	13041	143.0	100.1	100.1	9.40	5.05	14.45	100.55	1446.45	10065.06	11511.50	1529.50
	Nov	83.4	9591	173.4	121.4	121.4	9.00	5.05	14.05	100.95	1705.39	12253.31	13958.70	-4367.70
	Dec	33.2	3818	203.0	142.1	142.1	8.95	5.00	13.95	101.05	1982.30	14359.21	16341.50	-12523.50
1994	Jan	10.6	1219	299.4	209.6	209.6	8.23	4.82	13.05	101.95	2735.02	21366.68	24101.70	-22882.70
	Feb	104.4	12006	185.2	129.6	129.6	7.62	4.70	12.32	102.68	1597.16	13311.44	14908.60	-2902.60
	Mar	84.0	9660	139.4	97.58	97.58	7.42	4.60	12.02	102.98	1172.91	10048.79	11221.70	-1561.70
	Apr	115.0	13225	110.0	77	77	6.90	4.50	11.40	103.60	877.80	7977.20	8855.00	4370.00
	May	16.6	1909	89.6	62.72	62.72	7.50	4.55	12.05	102.95	755.78	6457.02	7212.80	-5303.80
	Jun	46.0	5290	46.8	32.76	32.76	7.30	4.50	11.80	103.20	386.57	3380.83	3767.40	1522.60

Table 4 Water Balance (1987-1994)

component in the water balance equation also determines the availability and amount moisture. A more informed distribution of vegetation types would allow better estimates of interception and crop coefficient. Field measurement of the spatial distribution of soil moisture zone thickness and replenishment rates are needed to accurately calculate the volume of recharge to the water table.

(b) the growth of sedge and reeds - types identified as Juncus , Eliocharis, and Charex sp. (E. Canning, pers comm.1994) in lower lying areas of the basin suggest that perched groundwater locally accumulates and may temporarily inhibit recharge to a deeper water table. Sandy sediments adjacent to the lakes initially have high infiltration rates but downward movement of soil moisture is inhibited by clay layers which promote lateral movement of water and discharge as perched seepages (Fig 32). This is particularly evident where thin strandline sands overlie clay around Lake Bathurst. Elsewhere the patchy growth of this vegetation over granite to the south of Lake Bathurst and sometimes on ferricrete are also indicative of moist habitats and temporary build-up of soil moisture which will eventually move into weathered bedrock to form the regional water table.

(c) the water balance is calculated under the assumption that no water leaves the basin through groundwater outflow. Given that groundwater gradients in the uppermost (perched) aquifers are directed towards Lake Bathurst this assumption is probably valid. However little is known about the configuration of the regional water table in the basin. If as seems likely there is slow leakage of groundwater from surficial aquifers to a deeper regional water table then groundwater outflow may occur through fractured rock aquifers towards Mulwaree Creek. For longer term water balances incorporating periods of high lake levels, then groundwater outflow might be achieved across the western barrier to Mulwaree Creek and perhaps by diversion of shallow groundwater into the headwaters of Mulwareee Creek from the extreme southwest area of the basin.

RESOURCES

Metalliferous resources such as gold and base metals are unknown although a little bauxite is associated with Tertiary basalt. The main non-metalliferous deposits are stratified sand and gravel of Quaternary to Recent age. Surface water is an important ecological resource and there is scope for groundwater development from sandy aquifers in Cainozoic sediments.

Bauxite

Small bauxitic outcrops (aluminous duricrust) are restricted to basalts mapped in the extreme northeast of the basin (Fig 5). Alumina (Al_2O_3) from bauxite sampled in the nearby Windellama district show values commonly ranging from 15-50% (Ruxton & Taylor 1982 and Taylor & Ruxton 1987). Little information exists on the economic potential of the bauxite in the Lake Bathurst drainage basin but it is unlikely there is a significant resource as the outcrops are too small and localised.

Sand and Gravel

Extensive deposits of sand and gravel occur around the lakes (Fig 5). Along the northern margin of Lake Bathurst at MR 450/202, a large pit currently operates in strandline sand and gravel banked up against an ancient cliff line etched into granitic bedrock. Other abandoned sand pits are also shown at Fig 32. In general these deposits though areally widespread have variable thickness; operations maybe restricted by high water tables.In many cases sand mining has led to the deterioration and disappearance of native vegetation and the subtle landforms associated with these deposits. Fortunately, Shire Council legislation requires that pit owners/operators undertake restoration by replanting grass and native tree species. Such reclamation work has been completed in a disused sand pit at the southern end of Lake Bathurst adjacent to Chain O Ponds creek (approx MR 457/148). While in the past sand exploitation has been in support of local needs, there is a continuing demand for construction materials in the region and pressure will exist to exploit sand and gravel resources in the basin. In this context MacRea (1993) recommends that the extent of construction sand deposits in the Lake Bathurst drainage basin needs further assessment. However this report advises that continued development of these resources will create environmental pressures on the valuable ecological habitats in the basin.

Road Base

Material for surfacing gravel roads is taken from deeply weathered Palaeozoic metasediments exposed in a small quarry at Leahys Lane (MR 499/134). Weathered granite and ferricrete have also been exploited locally by landowners for the repair of farm tracks.

Water

A mean annual rainfall of about 700 mm/annum is enough to sustain the direct use of rainwater as the commonest type of domestic water supply in the basin. Some use is made of surface water runoff. Numerous earth dams have been constructed to trap flood runoff for stock water use along creeks traversing impermeable bedrock and surficial ferricrete in elevated parts of the catchment. The Morass is an important source of freshwater. Direct use of this source is constrained by turbidity but a shallow well sunk into the sandy bed of the northern Morass can supplement supplies on Bundong property in drought. As far as is known Lake Bathurst has never been used for water supply purposes. It is too saline for human use and is only suitable for stock (sheep) when water depths exceed 2.0 m and salinity levels are generally < 4,000 microsiemens/cm.

The distribution of water bores is shown on Fig 32. A water bore survey indicates little groundwater development in the basin. Some groundwater is used to supplement rainwater storage and in other cases it is used for stock watering. In the few instances where groundwater is extracted it has been from fractured bedrock aquifers; most notably on Bundong property. There has been little attempt to develop good quality groundwater resources in the shallow unconfined and semi confined sandy aquifers in Quaternary sands and gravels surrounding Lake Bathurst and the Morass. In particular the Early Quaternary silt/sand sequence (Qs) logged in bores C348 and C376 appears permeable and warrants further investigation as an aquifer.

Scenic Values

Lake Bathurst and the Morass create a strong visual focus within the basin landscape. The lakes cannot be viewed from the main road linking Tarago and Goulburn but some vantage points are available on a secondary road traversing the basin from Tarago via the Morass and Bundong station ending at Lake Bathurst village (Barrow 1981). Unfortunately, there is restricted access to the lakes and historic sites unless permission is obtained from property owners. Nevertheless, a strong visual impression is obtained in the contrast between ecology and landscape as evidenced by the abundant birdlife on the lakes and the often exposed (sometimes bleak) appearance of the surrounding bald (cleared) hills and ridges.

LAND MANAGEMENT ISSUES

Across the Southern Tablelands of NSW, land degradation issues are closely associated with changes in land use patterns and in the longer term disturbance of the hydrological balance (Charman & Junor 1989). The main identifiable forms of land degradation are dryland salinity and erosion gullying ; their location and distribution in the basin is shown at Figure 32.

Dryland Salinity

Salt affected areas in the basin result from changes in land cover and practice dating from European settlement. Excessive clearing of native vegetation on hillslopes allows for greater penetration of rainfall recharge to the groundwater system causing a rise in the water table. The resulting hydrological imbalance increases the mobility of salts in the regolith and saline seepage may emerge at the surface usually in lower topographic areas of the basin (Fig 33). The visible effects of the process is the death of vegetation (grass) including trees, the production of bare sterile areas and salt efflorescence. This may be followed by an increase in runoff rates and an aggravation of erosion gullying in the landscape. In dry periods evaporation concentrates salt at these sites by promoting capillary rise of soil moisture. The process is further exacerbated by concentrated stock grazing.

In the Lake Bathurst drainage basin dryland salinity is recognised by bare patches of ground often several hectares in extent (Plates 11 and 12). The occurrence and distribution of affected ground seems to be related to the following:

- a rainfall belt ranging from 600-700 mm/annum.
- topographic elevations ranging from 680-700 m ASL.
- an association with cleared areas on fractured Palaeozoic metasediments.
- frequent outbreaks at the change of slope close to or along the surficial-bedrock boundary
- the influence on groundwater movement of the pre-Cainozoic landscape topography, thickness of deep weathering and geometry of impermeable layers in surficial sediments.
- evidence of a consistent fracture pattern acting as a preferred conduit for groundwater movement. Outbreaks of dryland salinity are aligned close to thenortheast trending long axis of the basin suggesting that regional structure may partly determine groundwater movement, salt migration and accumulation.
- sites where the water table is intercepted by drainage depressions.

In a closed basin with subdued relief salt accumulation is enhanced by poor drainage, slow groundwater movement and lack of a groundwater outlet. However the exposed physiographic position of the basin about 80 km from the coast and high in the landscape near the Main Divide ensures that long term climatic change (wind and rainfall patterns) will impact on the local hydrology and be a primary factor regulating the input and output of salt to the basin.

Erosion Gullying

In general, this form of land degradation is not a serious problem as topographic gradients are relatively small. Some gullying locally occurs on steeper cleared bedrock slopes where increased runoff has entrenched into the veneer of landscape colluvium (Fig 32). The worst case of soil erosion occurs south of the Tarago-Windellama road at MR 480/143. Here, on gently sloping alluvium, sheet erosion generated from overland flow has removed a substantial portion of the soil cover to form an extensive pattern of dendritic gullying.

Other Management Issues

Other anthropogenic activities impacting on the landscape include refuse disposal, drains, slope instability and recent land clearing. An unsightly rubbish tip spread over several hectares has been irresponsibly sited close to the southern end of Lake Bathurst. Leachate generated at the tip is a potential pollution hazard to groundwater in the underlying strandline sands which maybe in hydraulic connection with the lake. A network of drainage channels in the alluvial area east of the Morass may have alleviated swampy conditions but in turn has artificially increased runoff to the southern Morass. Slope instability is evident along the west facing margin of the Morass (Fig 18). Minor landslips (up to 1m) appear to result from land clearing and subsequent failure of the grassed steeply sloped lunette margin. Clearing is currently taking place in forested land in the extreme north of the basin (approx. MR 523/255). Here, tree removal has already resulted in swampy ground and increased runoff; this area is a potential site for dryland salinity.

Remedial Measures

To conserve the land and water resources and maintain productivity several easy and low cost control measures can be programmed to arrest dryland salinity and erosion gullying:

- re-afforestation of highland recharge areas with native trees.
- sow salt tolerant plant species in affected areas.
- encourage regeneration of native plants by fencing degraded areas to exclude stock.
- undertake conventional soil conservation earthworks such as diversion banks.

Some attempt at land conservation and reclamation has been tried in the headwaters of Chain O Ponds creek (approx. MR 435/110) where diversion banks have been installed to direct runoff from affected areas of erosion gullying and dryland salinity. In another case, refuse (mostly wood and metal hardware) has been dumped at the head of an erosion gully at MR 442/155 (Plate 13). Such practice is untenable not only on aesthetic grounds but over time leachate-rich runoff will reach Lake Bathurst. In this case infilling and recontouring the gully or earth dam construction is a more appropriate control measure.

DIRECTIONS FOR FURTHER STUDY

Cainozoic sediments and geomorphology

Further drilling (possibly trenching) and thermoluminescence dating is needed to attempt a better definition of the Cainozoic sequence in the basin. In particular, this can be achieved by further study of the subsurface geometry and environments of the Early Quaternary sedimentary sequence (Qs) logged in drillholes C349 and C376. A sedimentological model is needed to explain the co-development of the Quaternary lake barrier and lunette sequences. The basin may provide an important site for studying climatic and environmental changes in the Holocene and perhaps in more recent terms the impact of post European settlement. The proposed model for the geomorphological evolution of the basin lacks a supporting chronology particularly with reference to drainage modifications in the headwaters of Mulwaree creek. A study of the distribution and age of the calcareous nodules may help in understanding the impact of climate change on landscape processes.

Hydrology
The adoption of a refined water balance procedure paying special attention to estimates of evaporation and soil moisture that will more accurately quantify groundwater recharge. In terms of groundwater resources the Quaternary sequence (Qs) has potential as a surficial aquifer if its subsurface extent, thickness and water yielding properties can be evaluated.

Ecology
A study of the wetland areas of the basin to highlight the close but contrasting ecosystems of the Morass (a freshwater environment) and Lake Bathurst (a brackish-saline environment). Such an investigation would have further significance as a means of documenting the biological importance of these lakes as a refuge habitat for birds.

Lichenometry
A pilot project entailing the identification and measurement of lichen to establish a growth curve for the local area. This information with detailed surveying of granitic outcrops on the bed of Lake Bathurst can be used to determine the rate of colonisation of lichen on bare rock surfaces. Thereafter, a methodology might be attempted to measure the rate of subaerial exposure resulting from a decline in lake levels over the last few centuries.

Land Management
There is a growing need at the local level for property owners to share collective responsibility for land management issues in the basin. A possible pathway with government assistance is the formulation of a local land care group or equivalent body that with professional advice will program conservation schemes to manage the wetland environment and land degradation problems.Any Crown lands within the drainage basin could also be managed by forming a Reserve Trust as suggested in CALM (1994).

ACKNOWLEDGEMENTS

Messrs D.Morgan-Giles, J.Reynolds and D.Sim are especially thanked for granting property access to undertake hydrological monitoring, drilling and geological mapping. The technical staff at AGSO assisted in hydrological data collection. R. Cooper (AGSO) advised on word processing and E. Bleys (AGSO) undertook the digitising of the lake areas and compiled the spreadsheet in EXCEL for the water balance data. The assistance given by D.Vowles (ANU), R. Nicoll, J.Kamprad and A.Watson (AGSO) for undertaking preliminary SEM, XRD and sedimentological analyses of core samples from drillhole C376 is much appreciated. Dr P.de Deckker (ANU) for helpful discussions and providing water chemistry data. Prof.J.Elix (ANU) for identification of lichen samples. Ms E.Canning (Nat.Bot.Gdns) for identification of wetland plants from Lake Bathurst. The manuscript was reviewed by C.Pain, J.Kellett and G. Hunt ; their suggestions and amendments etc are greatly acknowledged. The maps and line drawings were drafted by G.Michalowski (Cartographic Services Unit, AGSO).

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PLATES

Plate 1. Biotite-rich hornfels veined with coarse grained adamellite ("Lake Bathurst Granite") and cut by aplite. Northern foreshore area of Lake Bathurst (MR473/209).

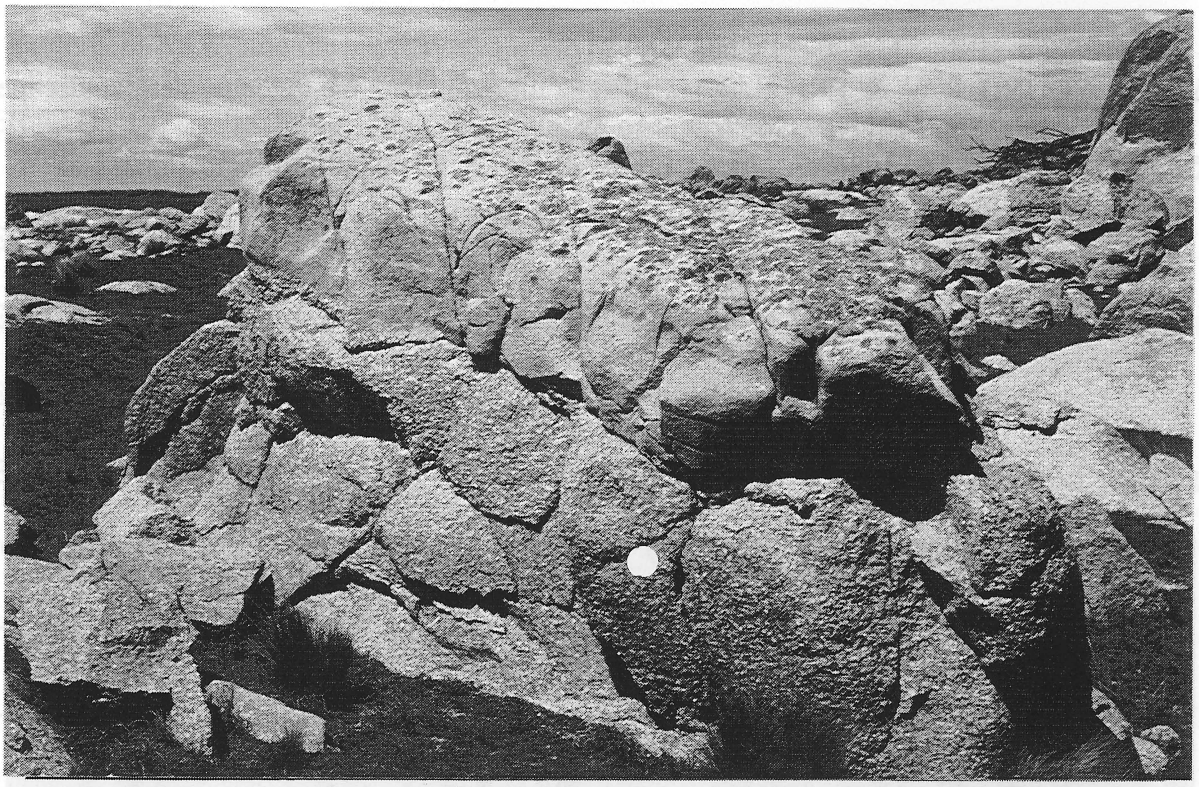

Plate2. Coarse grained adamellite in sharp contact with fine grained leucogranite ("Lake Bathurst Granite"). Note lichen growth on upper surface of the outcrop. Northern foreshore area of Lake Bathurst (MR 452/200)

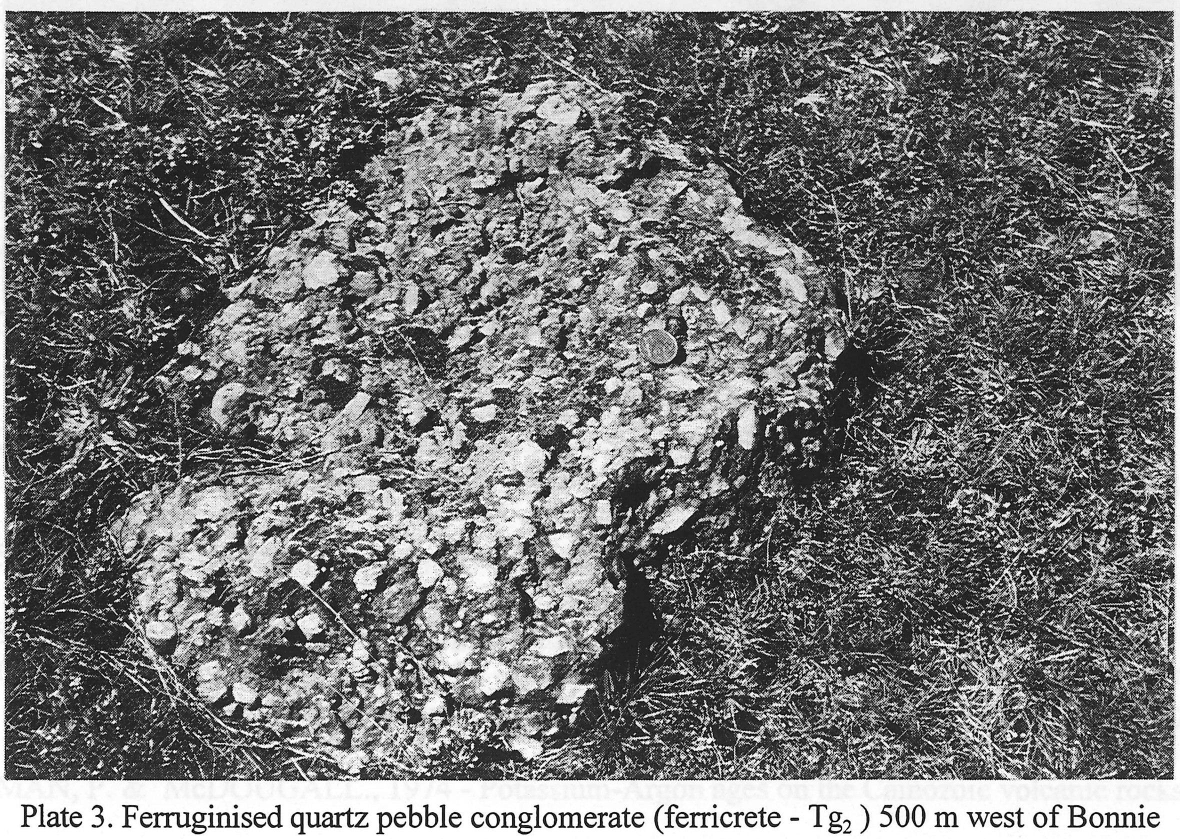

Plate 3. Ferruginised quartz pebble conglomerate (ferricrete - Tg_2) 500 m west of Bonnie Doon Station (MR 505/183).

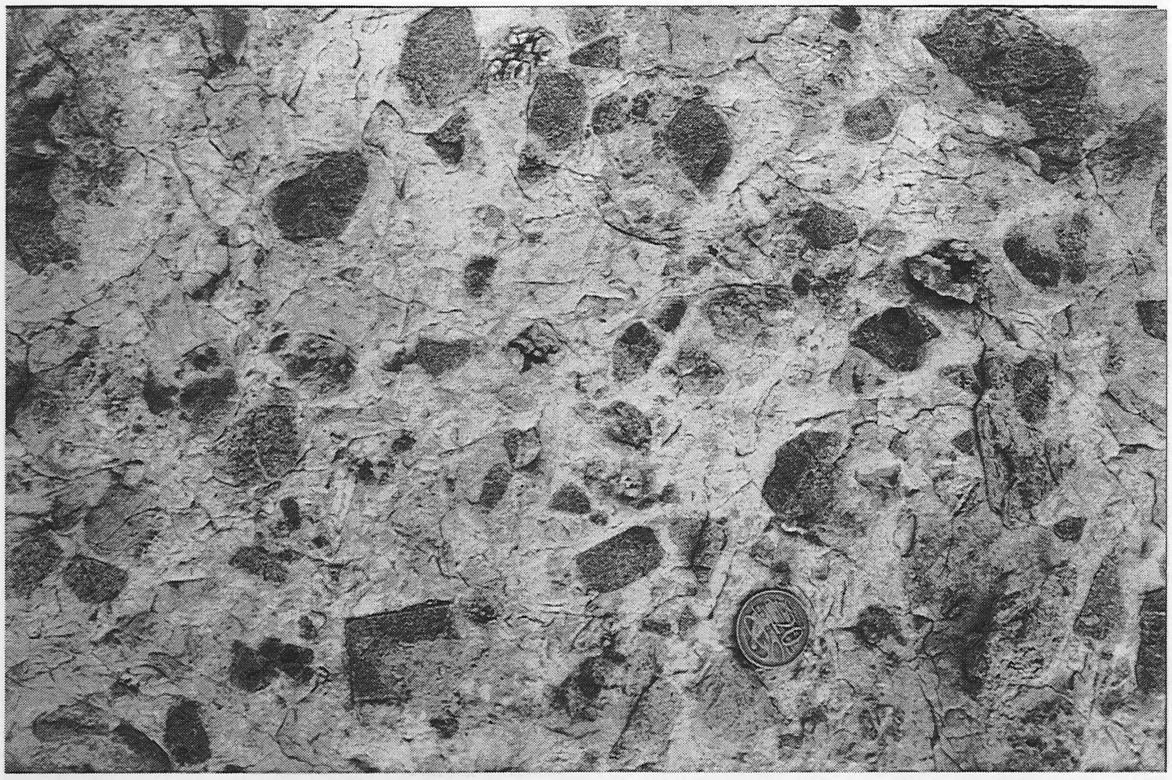

Plate 4. Silicified colluvium (silcrete-Tg_1). Note dominance of subangular lithic clasts of quartzite derived from surrounding Palaeozoic bedrock. Southern shore of Lake Bathurst (MR 448/164).

Plate 5. Pisolitic bauxite (Tbx) formed as a residual weathering cap to basalt. Low wooded ridge 1 km south of Hedley Park Station (MR 530/215).

Plate 6. Calcareous nodules exposed in the upper reaches of an erosion gully, south of the Tarago-Windellama road (MR480/143).

Plate 7. View of the western barrier at Lake Bathurst (MR425/184). Note the trimmed inner margin formed by past high lake levels and gradual slope of the outer west-facing margin.

Plate 8. Decayed Ruppia megacarpa (a perennial halophyte). Lake level recession has exposed the plant which has died off to form a brownish-white mat. Eastern foreshore area of Lake Bathurst.

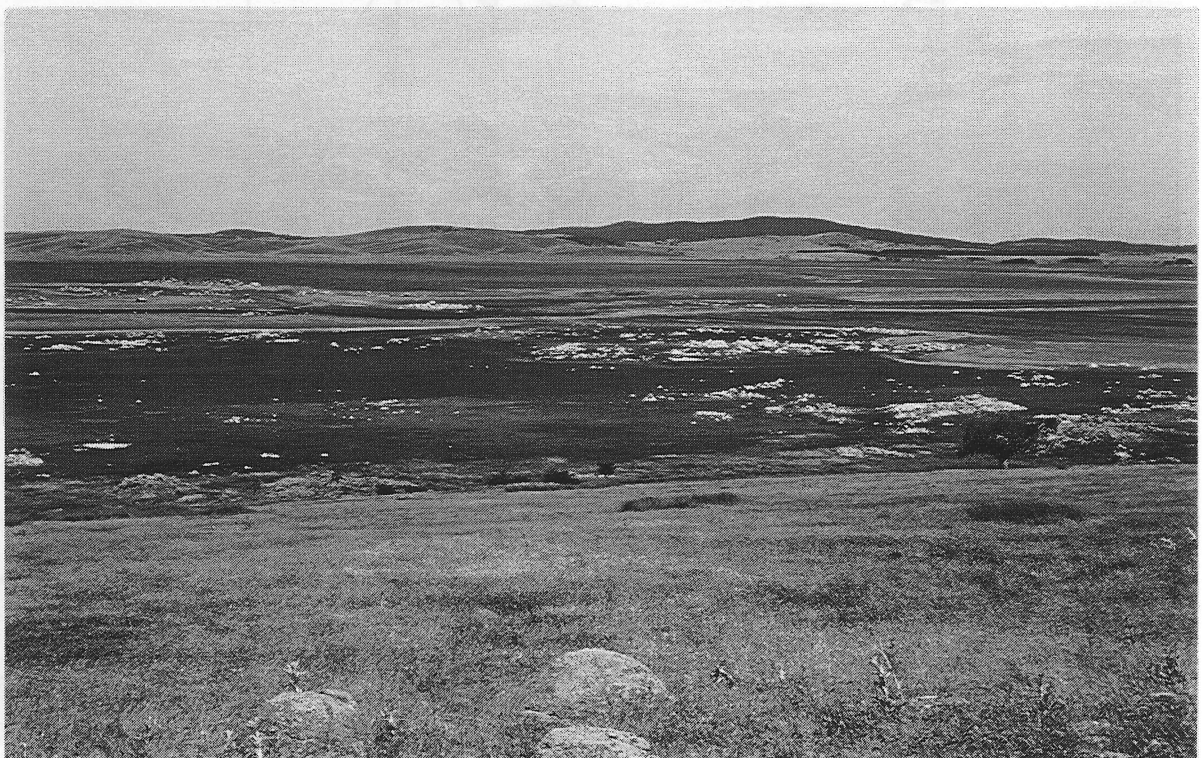

Plate 9. General view of the western side of Lake Bathurst showing granitic outcrops exposed on the dry lake bed.

p. 43 has been omitted in the hardcopy of record 1995/23

Plate 12. An advanced stage of dryland salinity (MR 493/223). Note the accelerated gully erosoin problems across the bare areas of soil.

Plate 13. An erosion gully leading into Lake Bathurst (MR 442/155). Refuse has been dumped to arrest headward movement of the gully.

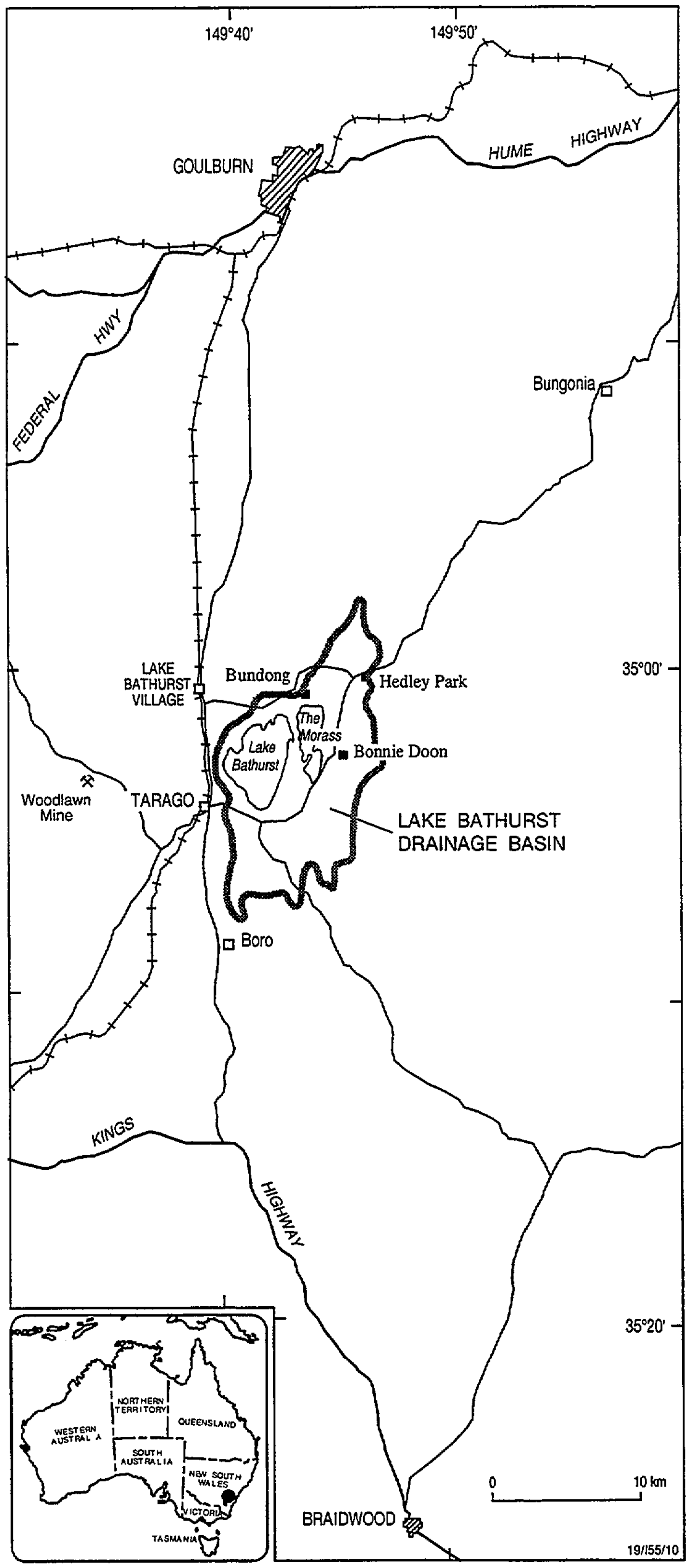

Fig. 1. Locality map

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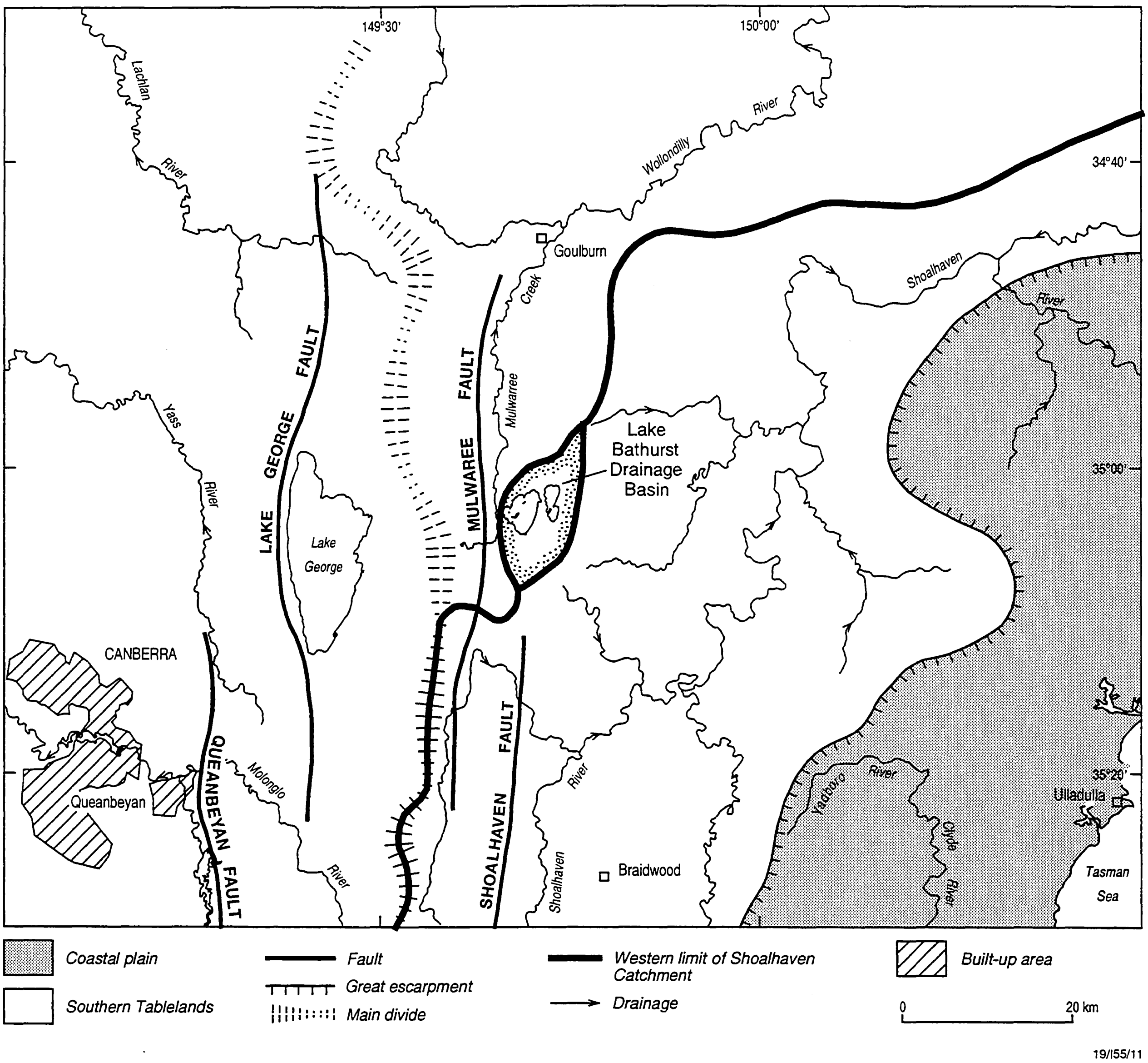


Fig. 2. Regional physiography

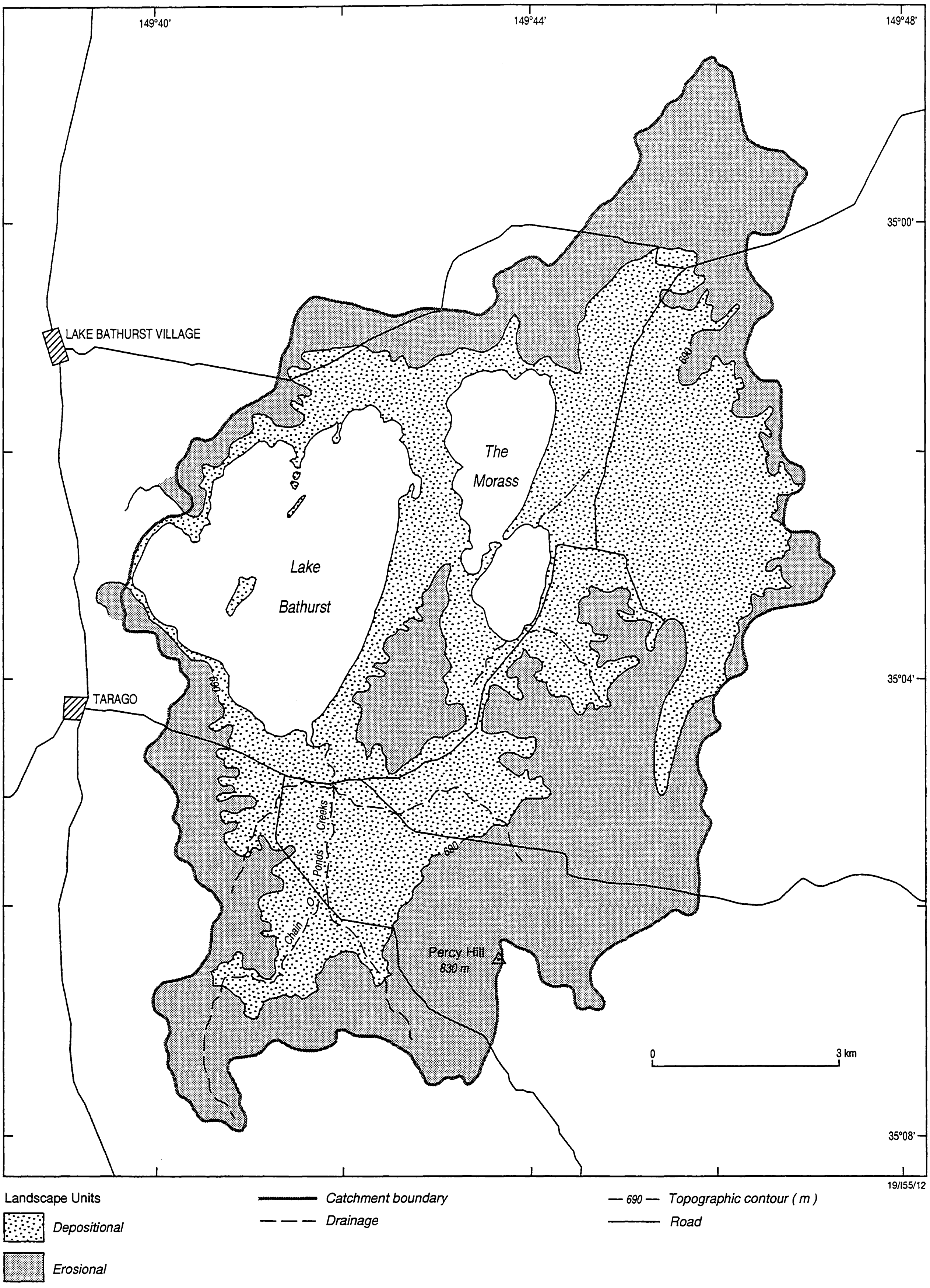


Fig. 3. Basin physiography and landscape units

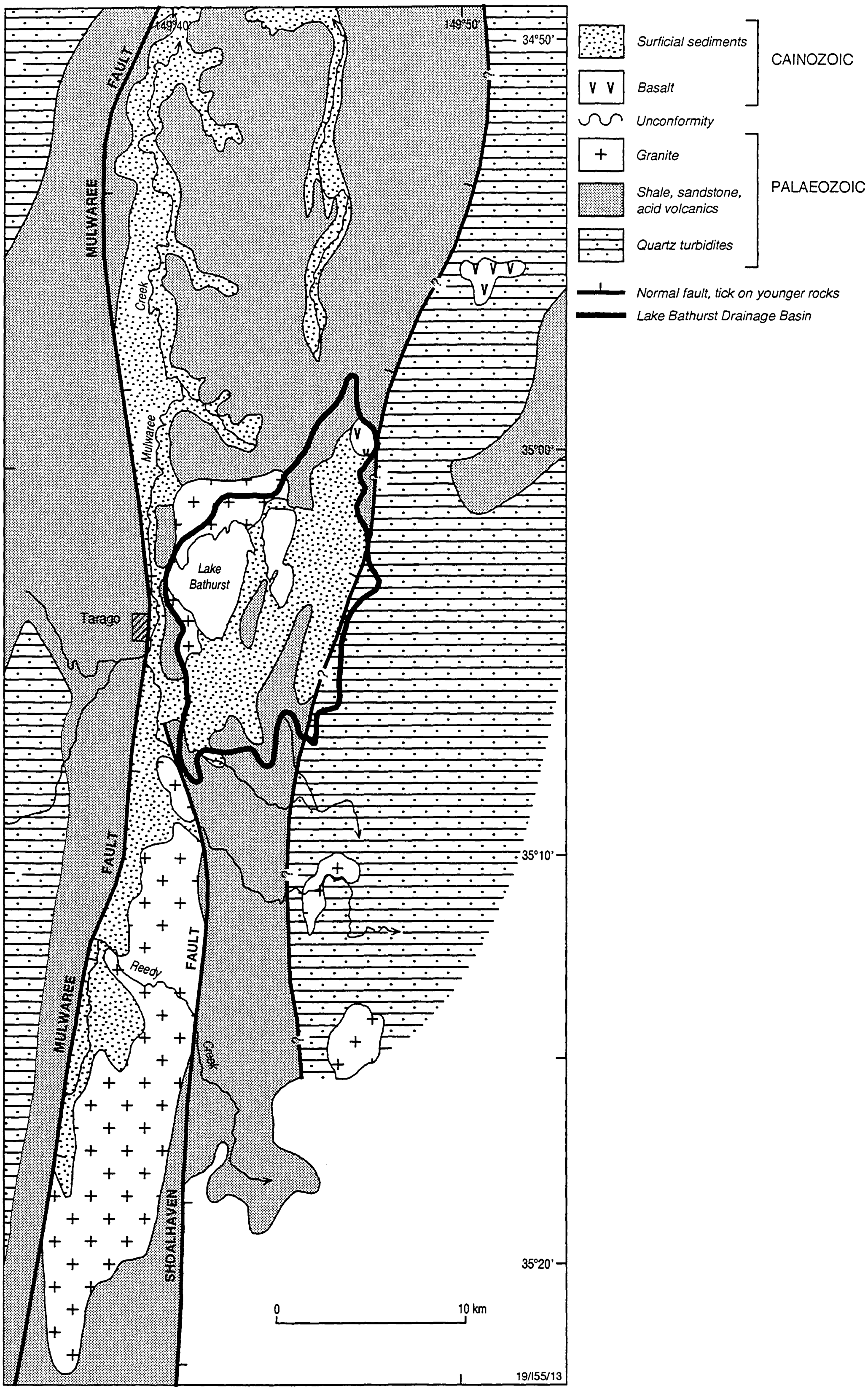


Fig. 4. Regional geology

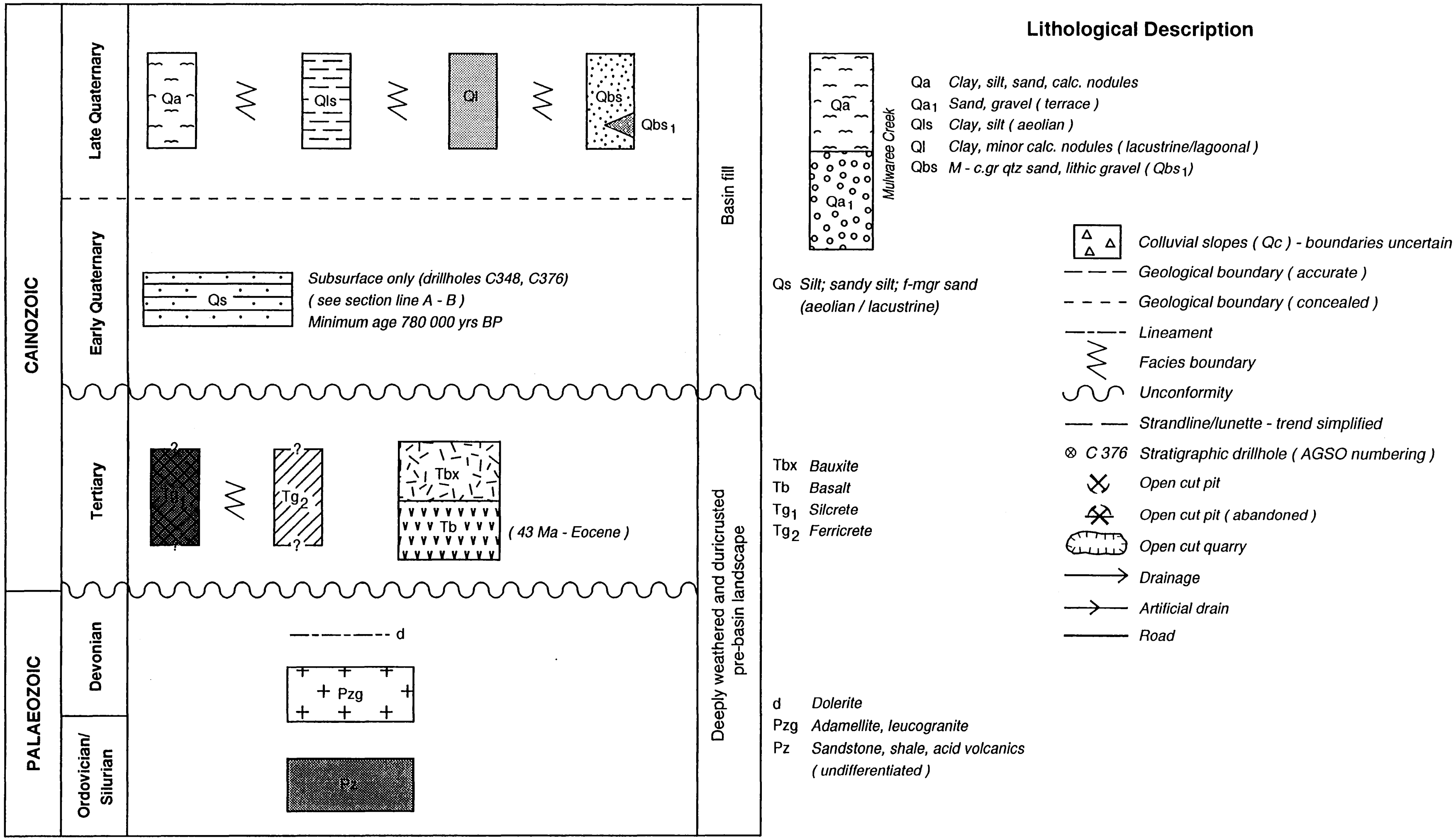
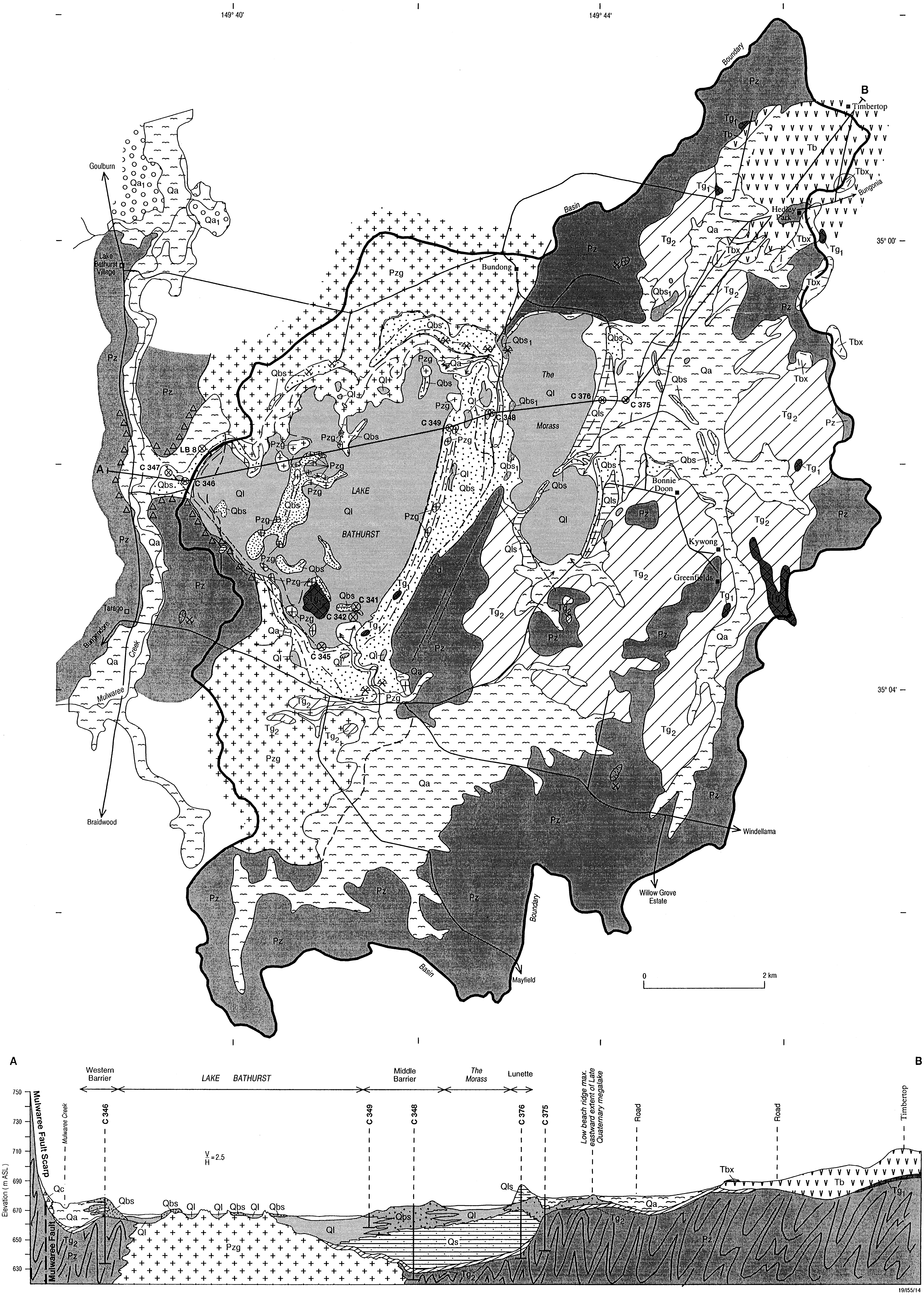


Fig. 5. Lake Bathurst drainage basin

Surficial and bedrock geology



149° 40'
149° 44'
35° 00'
35° 04'
Goulburn
Lake Bathurst Village
Tarago
Bungendore
Mulwaree Creek
Braidwood
Bundong
Basin
Boundary
Timbertop
Bungonia
Hedley Park
LAKE BATHURST
The Morass
Bonnie Doon
Kywong
Greenfields
Windellama
Willow Grove Estate
Mayfield
LB 8
C 347
C 346
C 349
C 348
C 376
C 375
C 341
C 342
C 345
Pz
Pzg
Qa
Qa1
Qbs
Qbs1
Ql
Qls
Tg1
Tg2
Tb
Tbx
0
2 km
A
B
Western Barrier
LAKE BATHURST
Middle Barrier
The Morass
Lunette
Mulwaree Fault Scarp
Mulwaree Creek
Mulwaree Fault
Low beach ridge max. eastward extent of Late Quaternary megalake
Road
Timbertop
Elevation (m ASL)
750
730
710
690
670
650
630
V/H = 2.5
Qc
Qs
19/I55/14

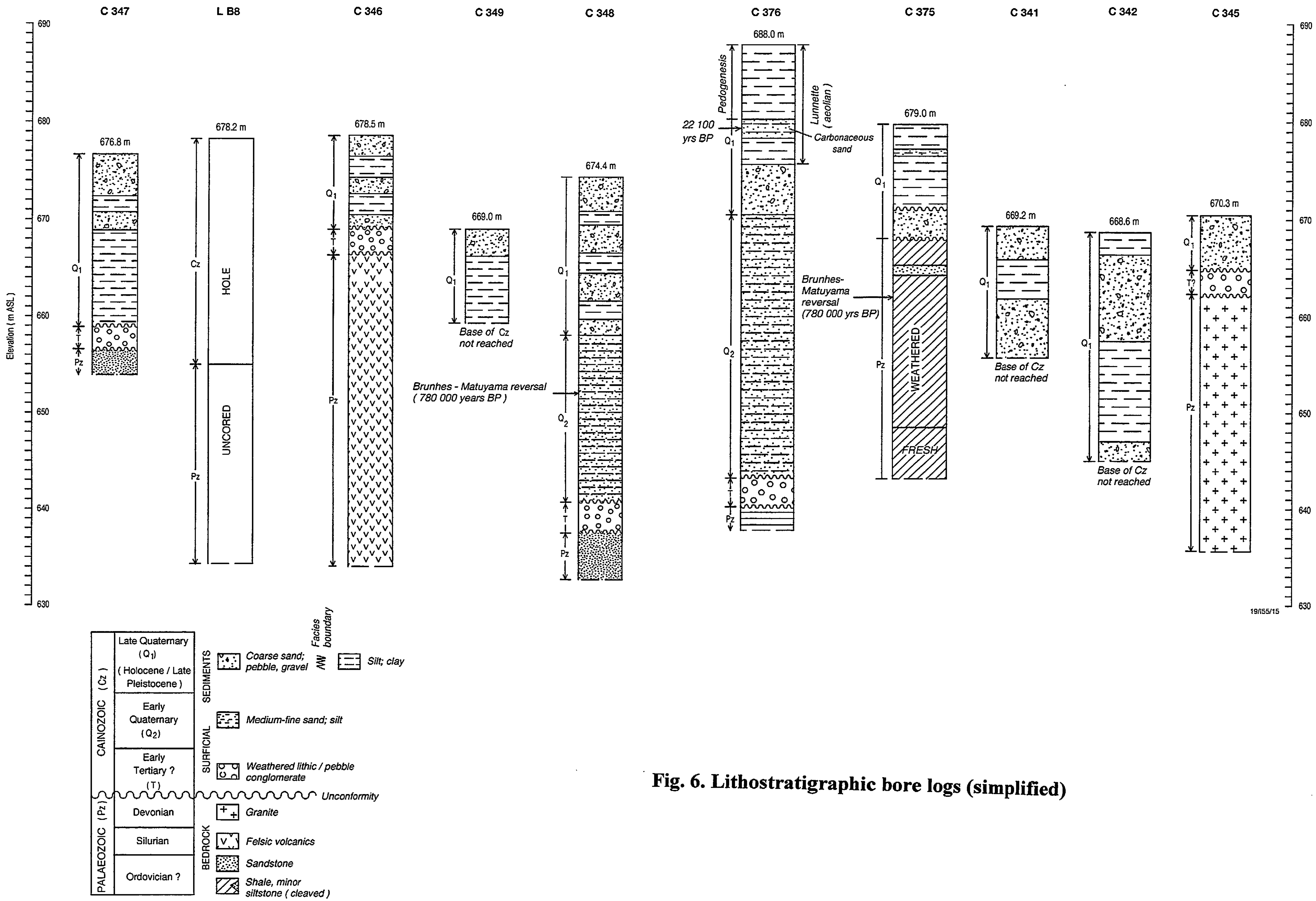


Fig. 6. Lithostratigraphic bore logs (simplified)

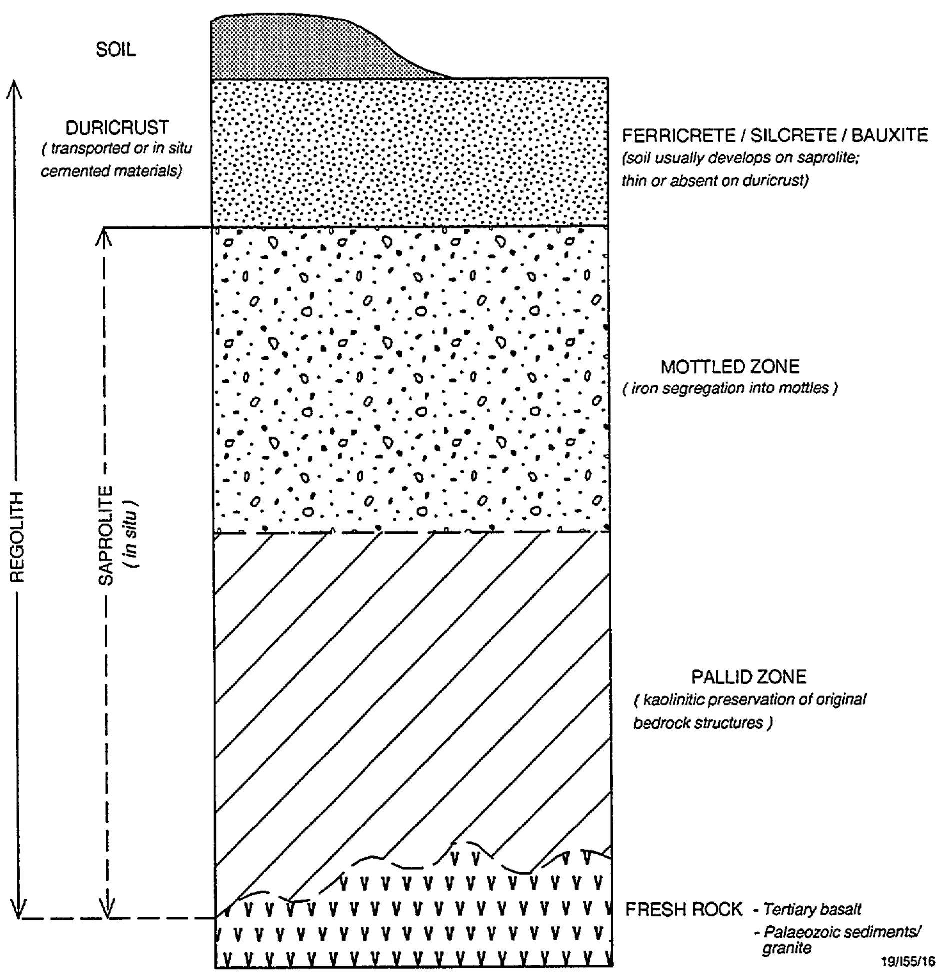


Fig. 7. Schematic deep weathering profile

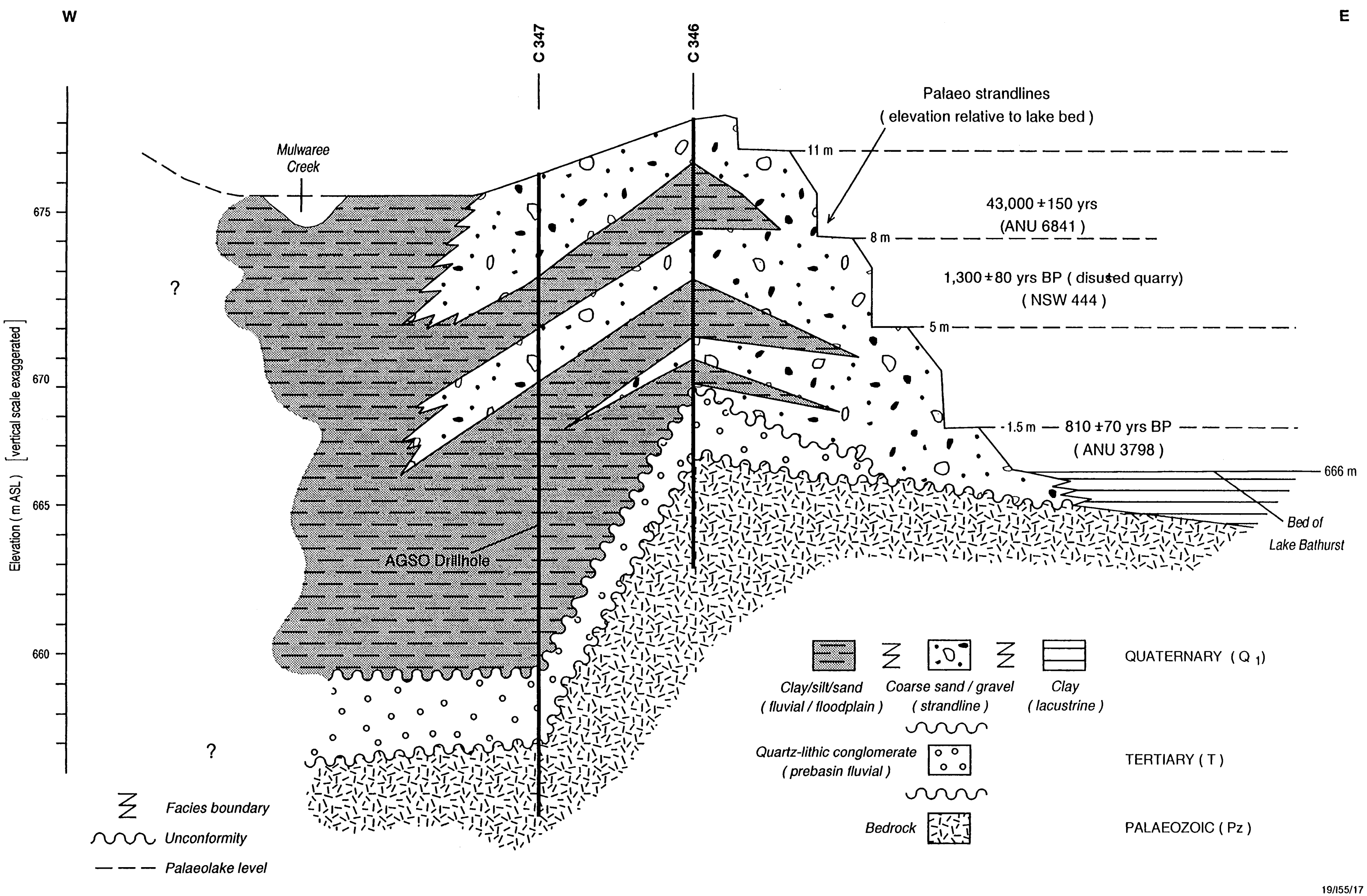


Fig. 8. Lithofacies distribution across the western barrier
(diagrammatic representation)

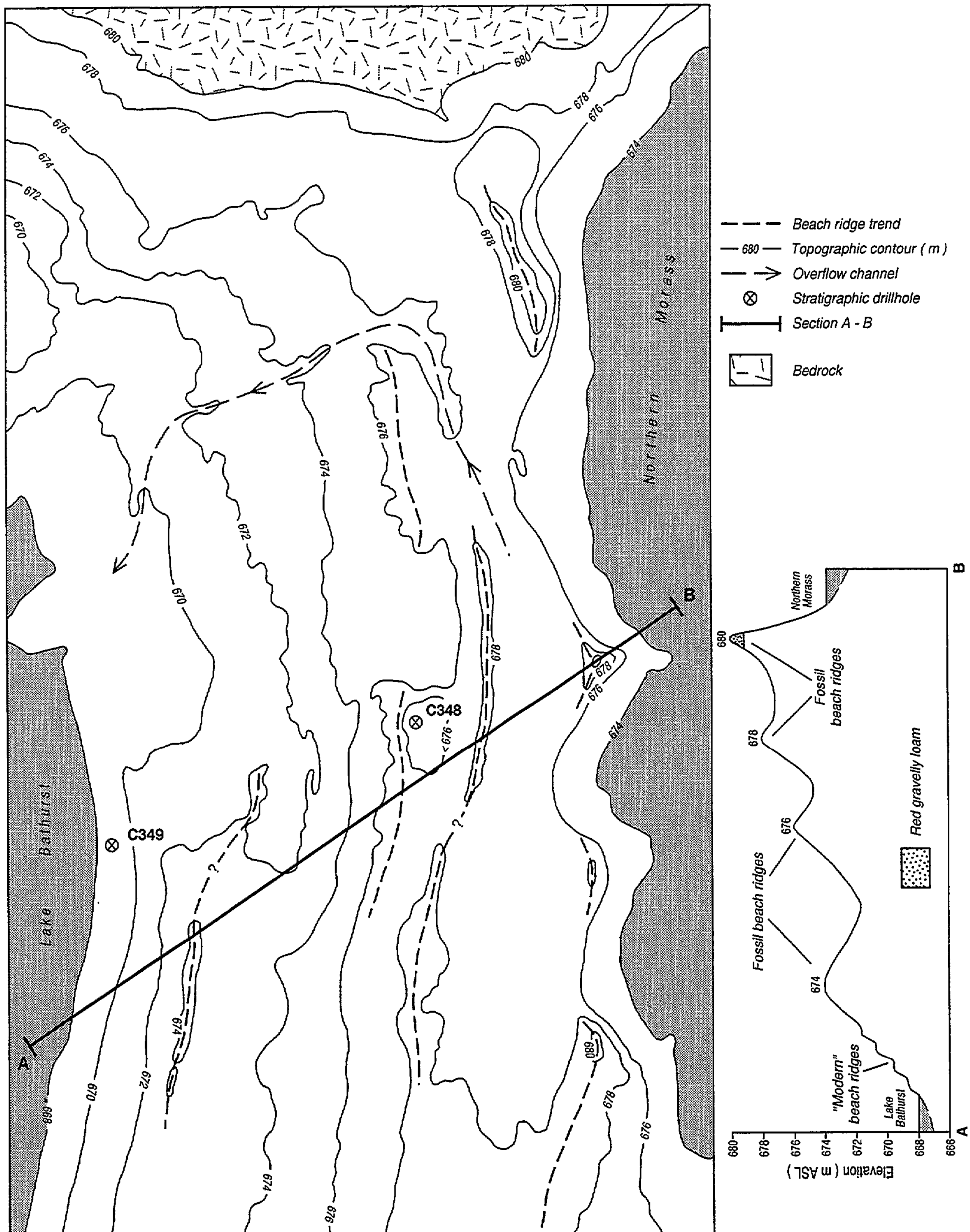


Fig. 9. Topography across the barrier between Lake Bathurst and the Morass

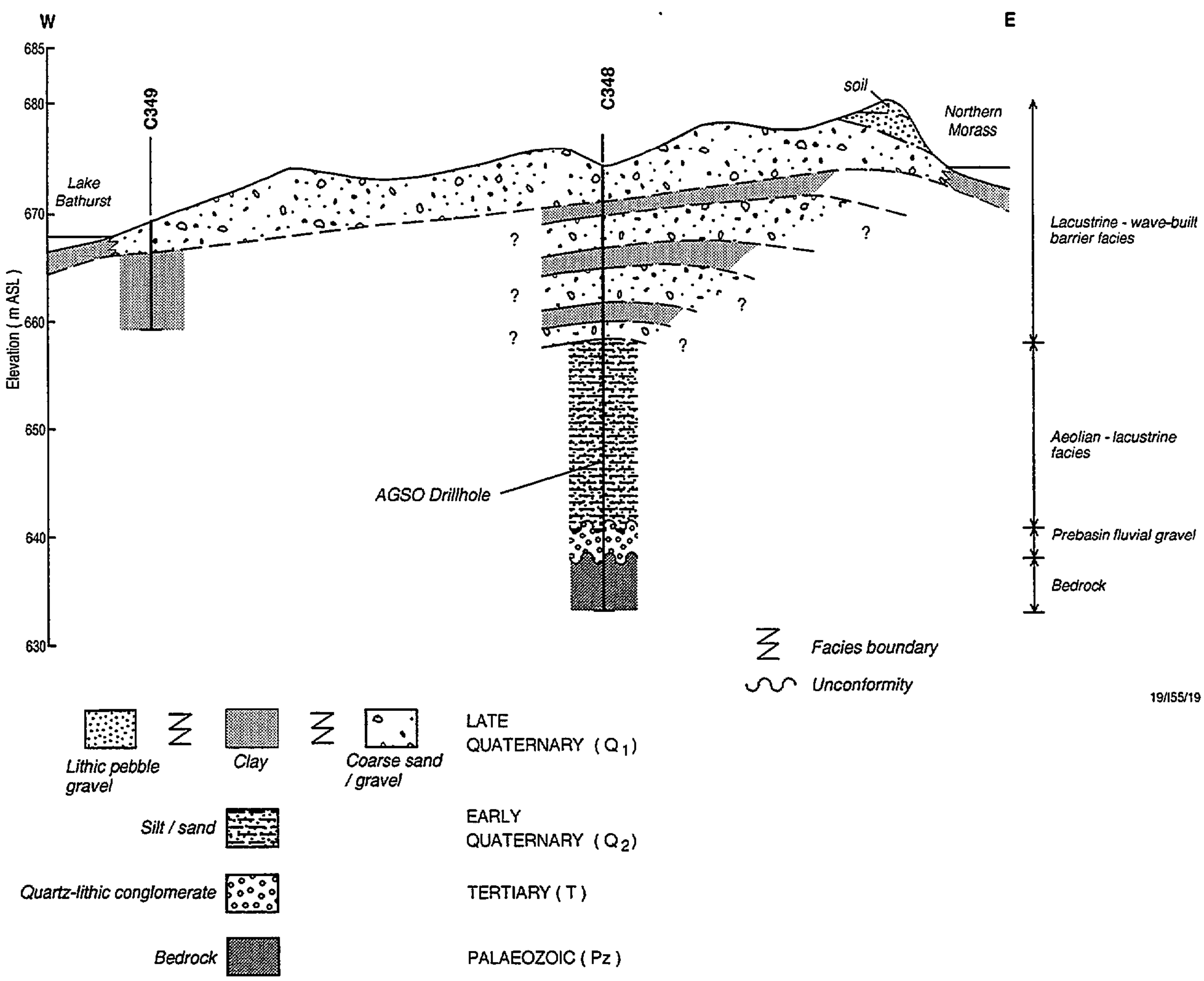


Fig. 10. Lithofacies distribution across the barrier separating Lake Bathurst and the Morass (diagrammatic representation)

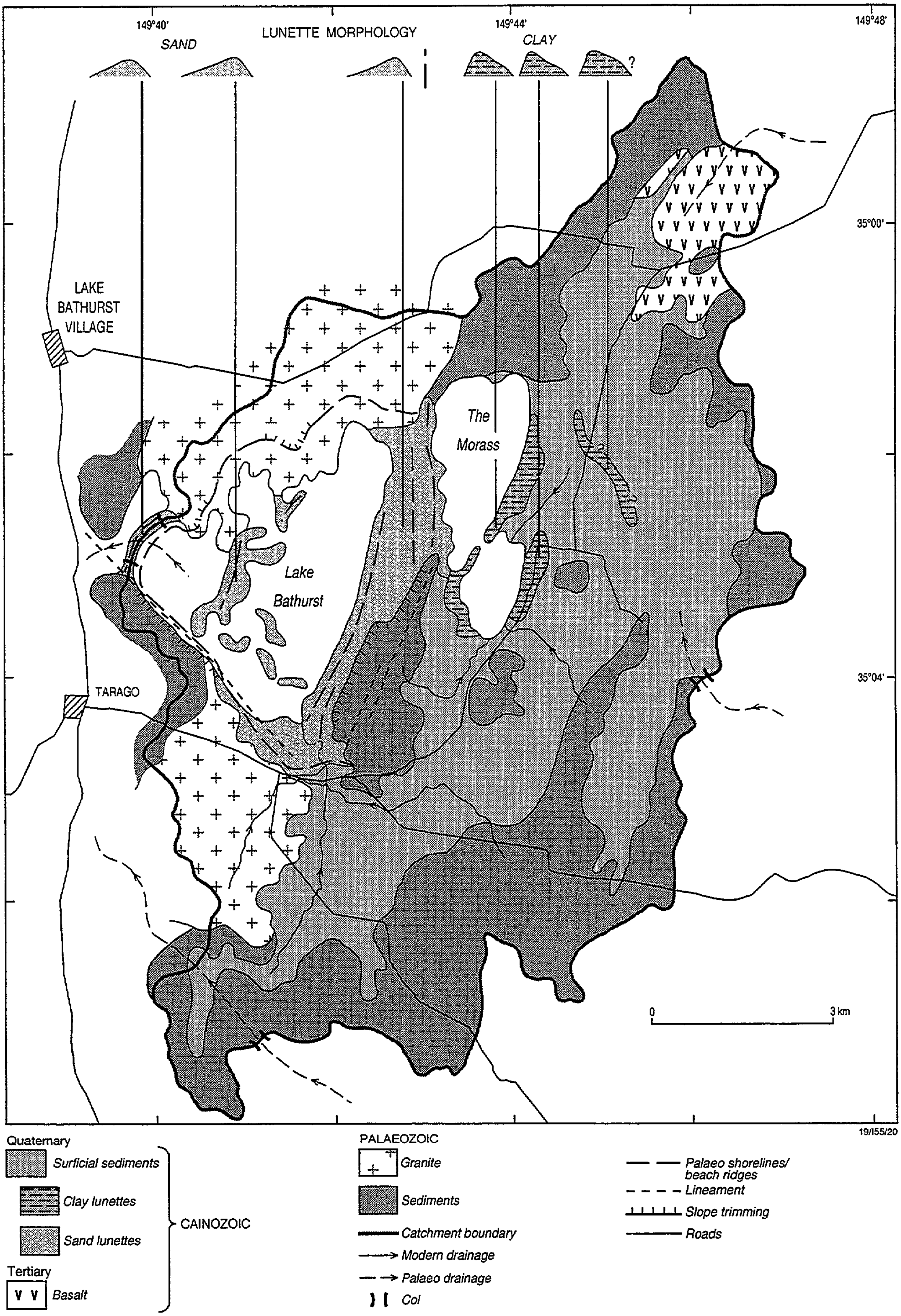


Fig. 11. Geomorphology

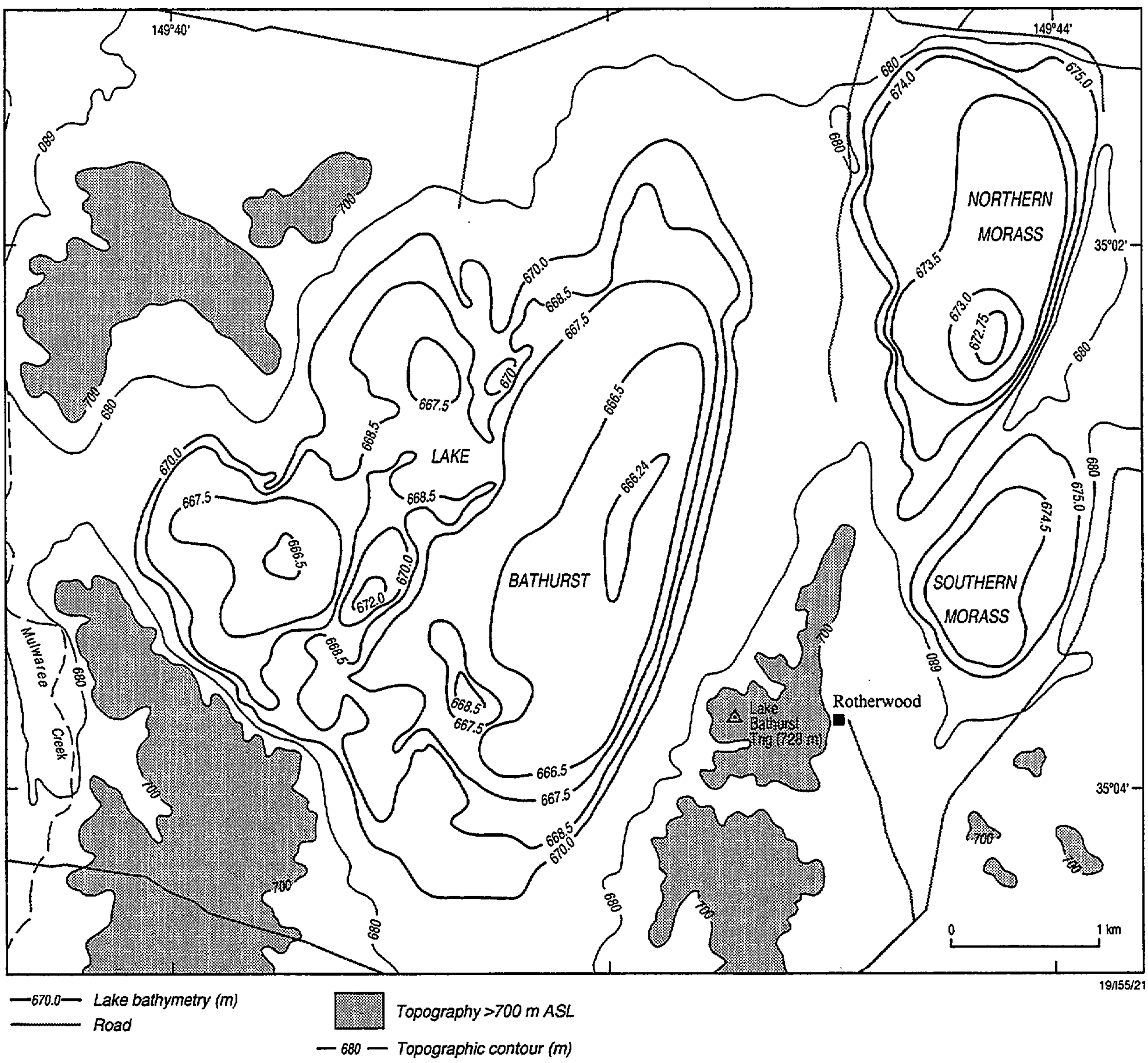


Fig. 12. Simplified bathymetry for Lake Bathurst and the Morass

(Lake bathymetry modified from 1:10,000 scale bathymetric contours prepared by the Australian Survey Office (ASO) in 1992)

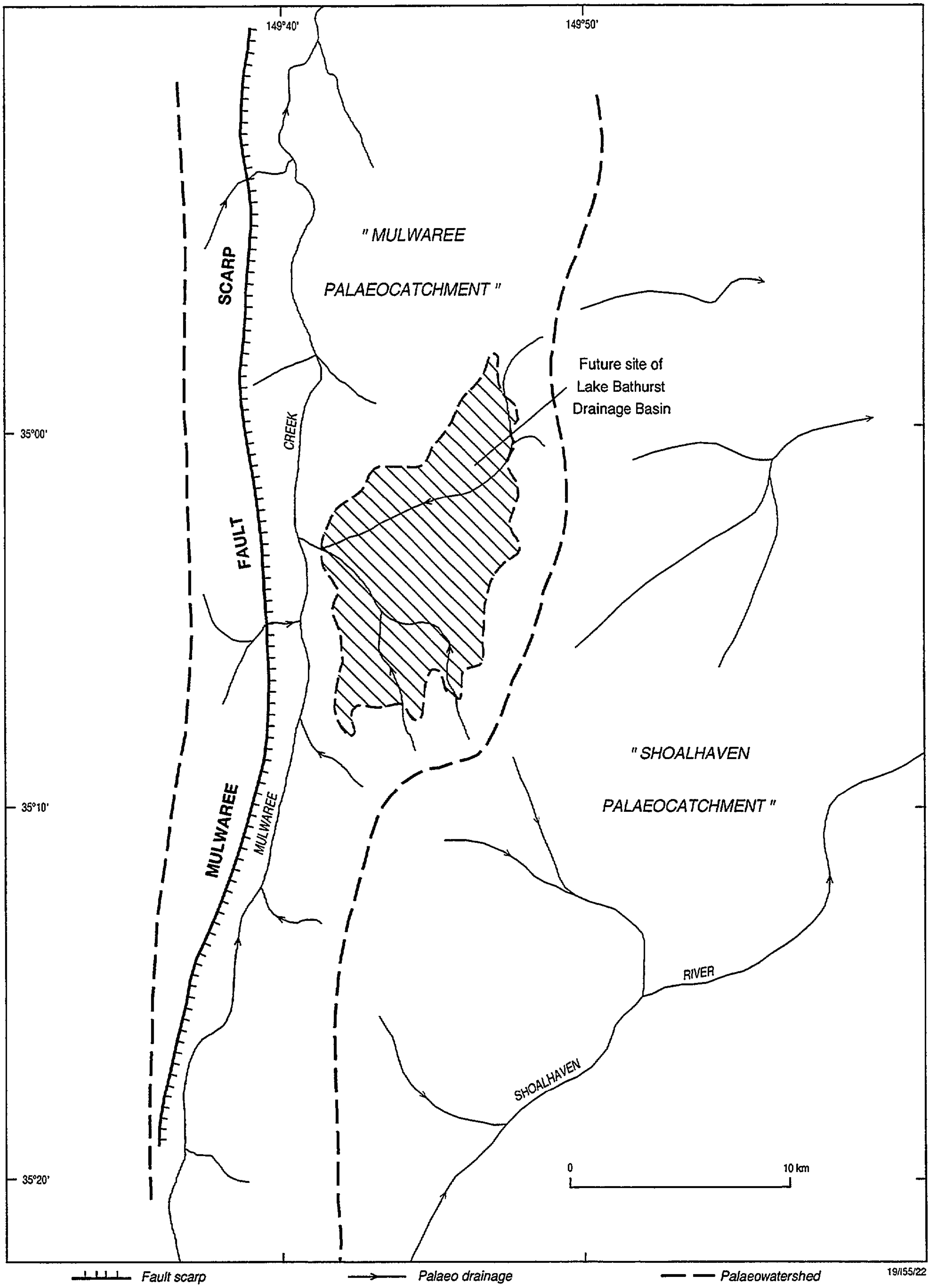


Fig. 13. Palaeodrainage scheme prior to the formation of Lake Bathurst drainage basin

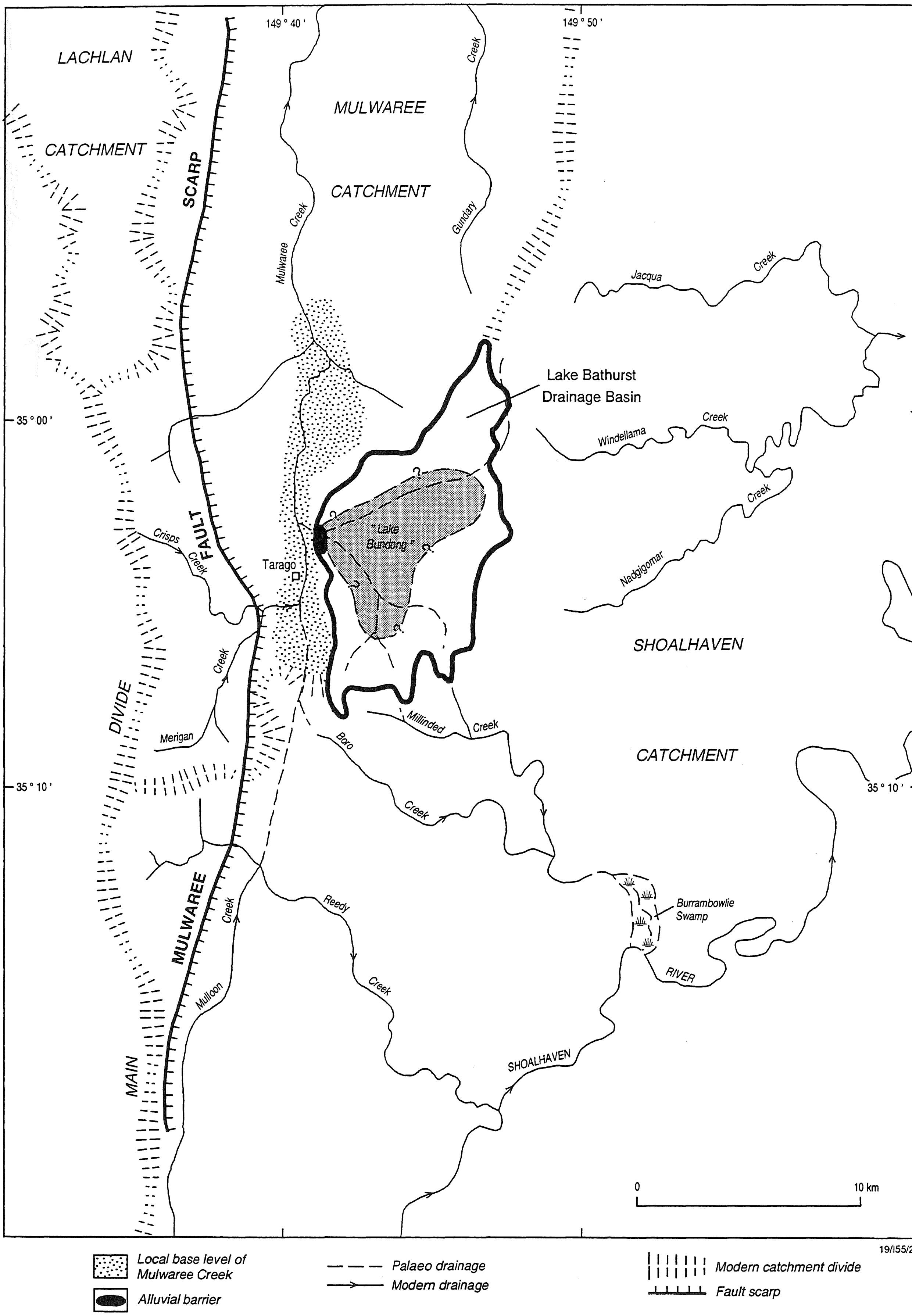
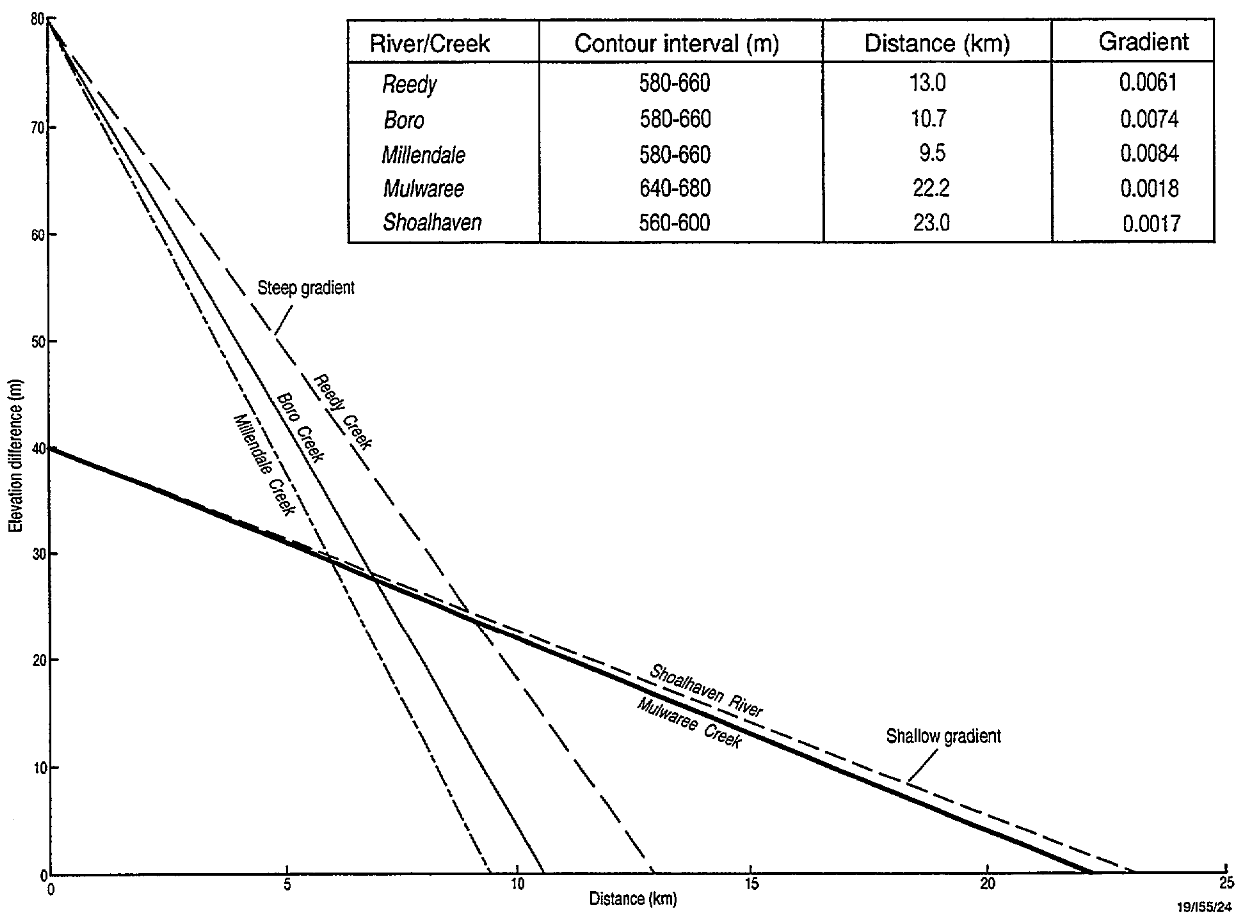


Fig. 14. Drainage diversions leading to the formation of Lake Bathurst and modern drainage network



River/Creek	Contour interval (m)	Distance (km)	Gradient
Reedy	580-660	13.0	0.0061
Boro	580-660	10.7	0.0074
Millendale	580-660	9.5	0.0084
Mulwaree	640-680	22.2	0.0018
Shoalhaven	560-600	23.0	0.0017

Fig. 15. Comparison of stream profiles

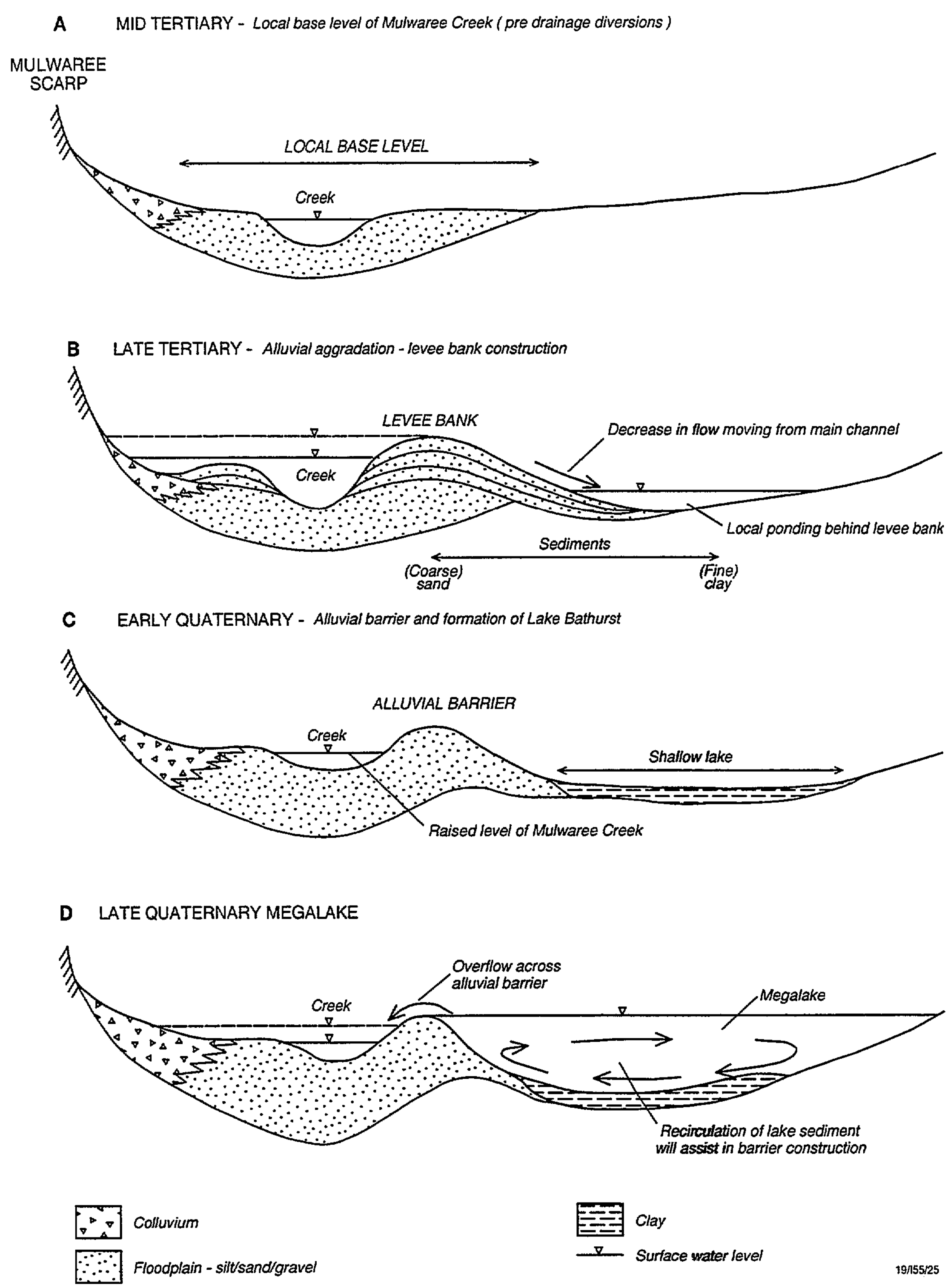


Fig. 16. Alluvial aggradation of Mulwaree creek and formation of Lake Bathurst drainage basin (schematic sections)

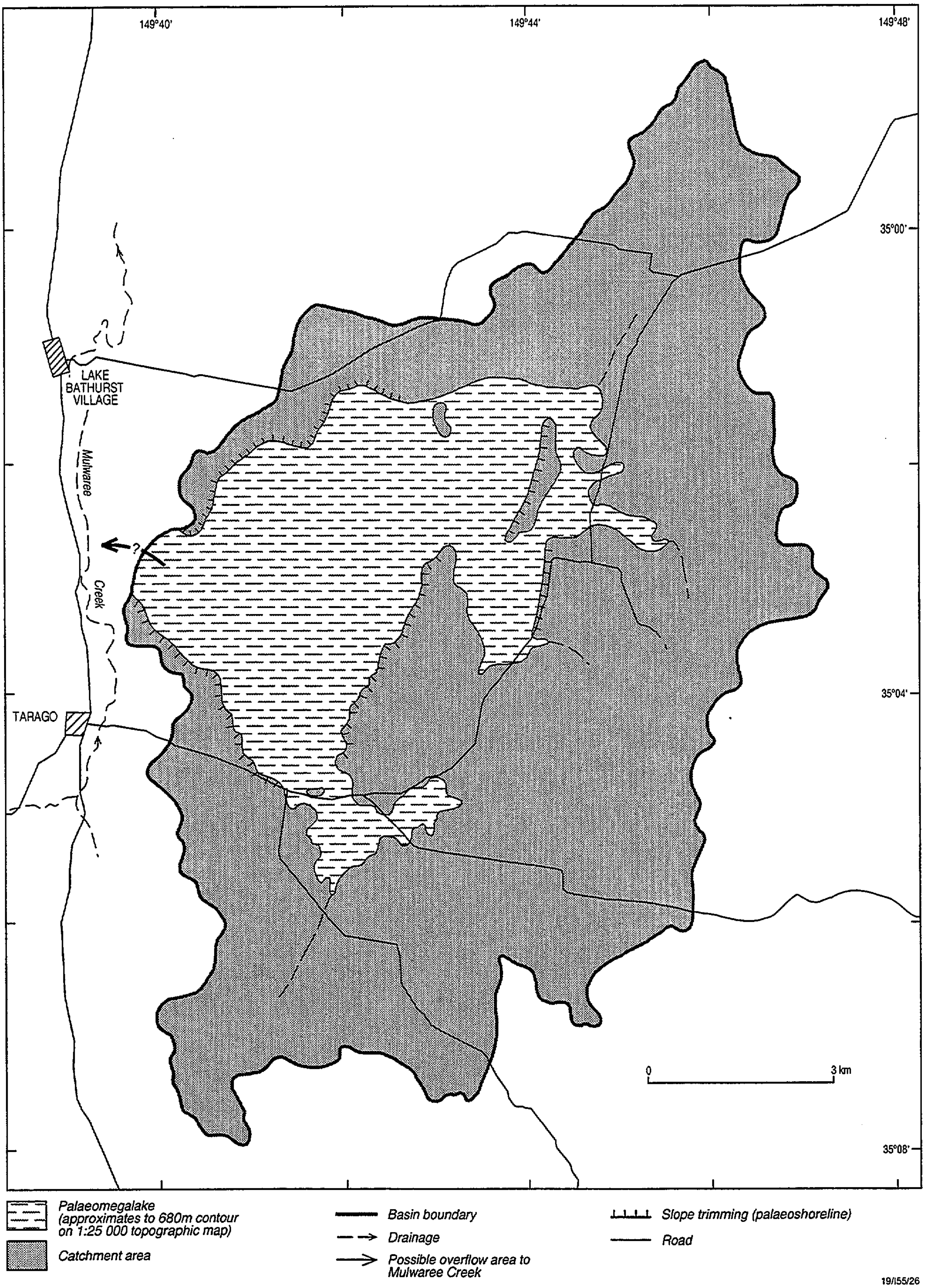


Fig. 17. Maximum extent of a Late Quaternary megalake in the Lake Bathurst drainage basin

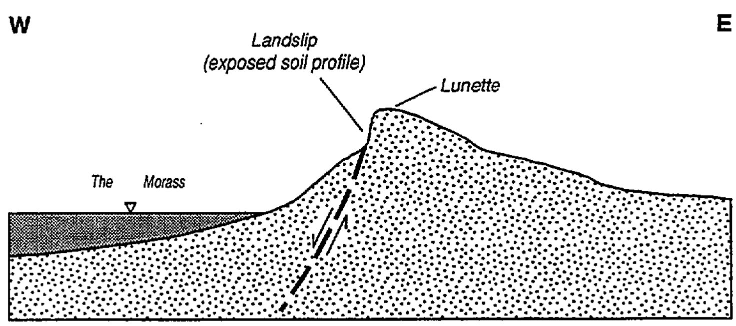


Fig. 18. Slope instability at the inner margins of lunettes at the Morass
(diagrammatic section)

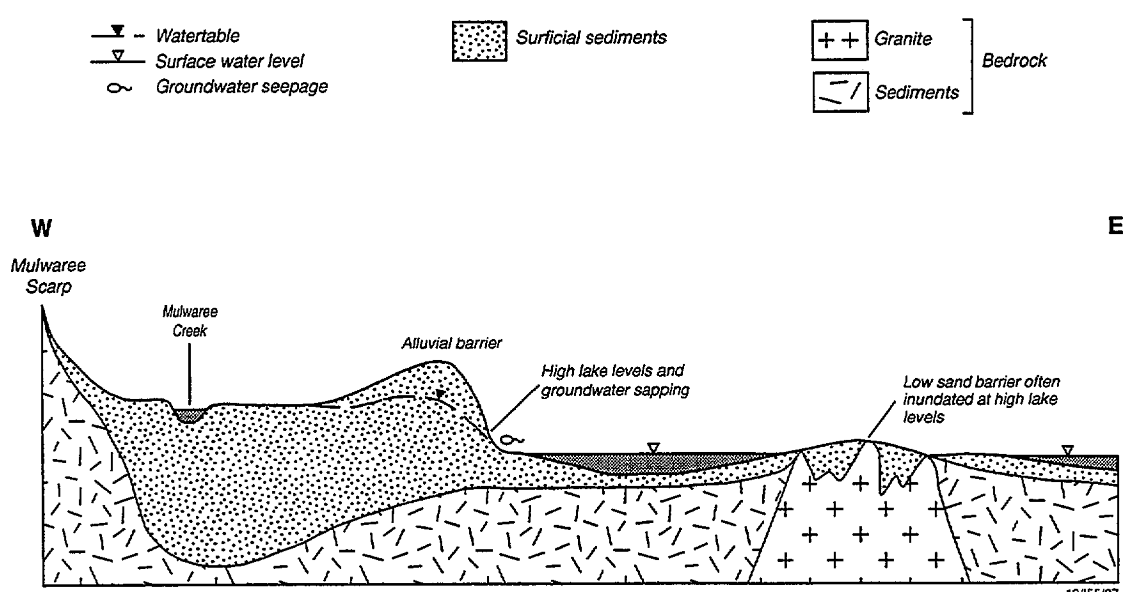


Fig. 19. Slope trimming at inner margin of the western barrier at Lake Bathurst
(diagrammatic section)

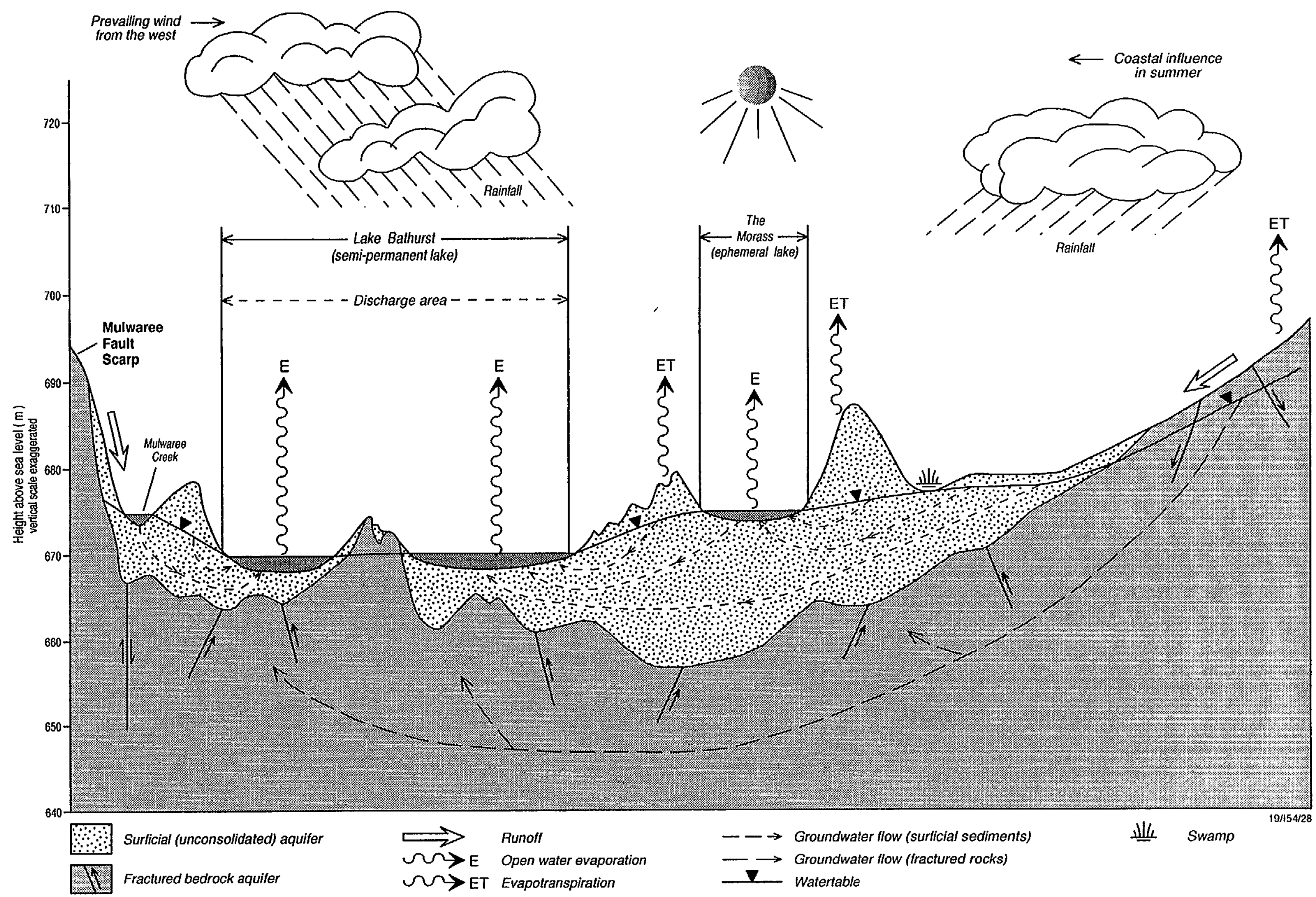


Fig. 20. Hydrological cycle (diagrammatic representation)

Fig. 21. Hydrogeology

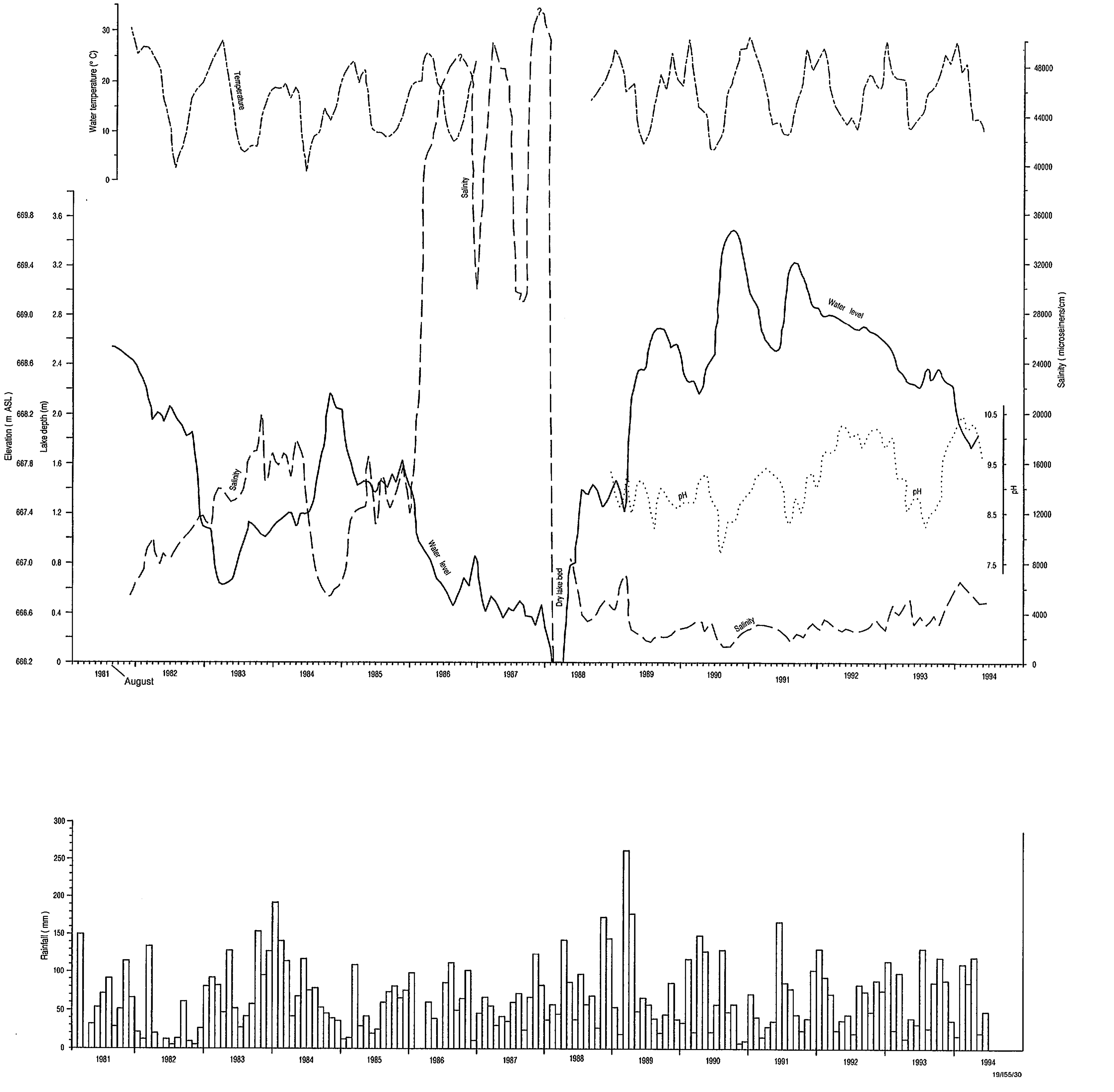


Fig. 22. Lake Bathurst hydrograph (1981 - 1994)

R9502306

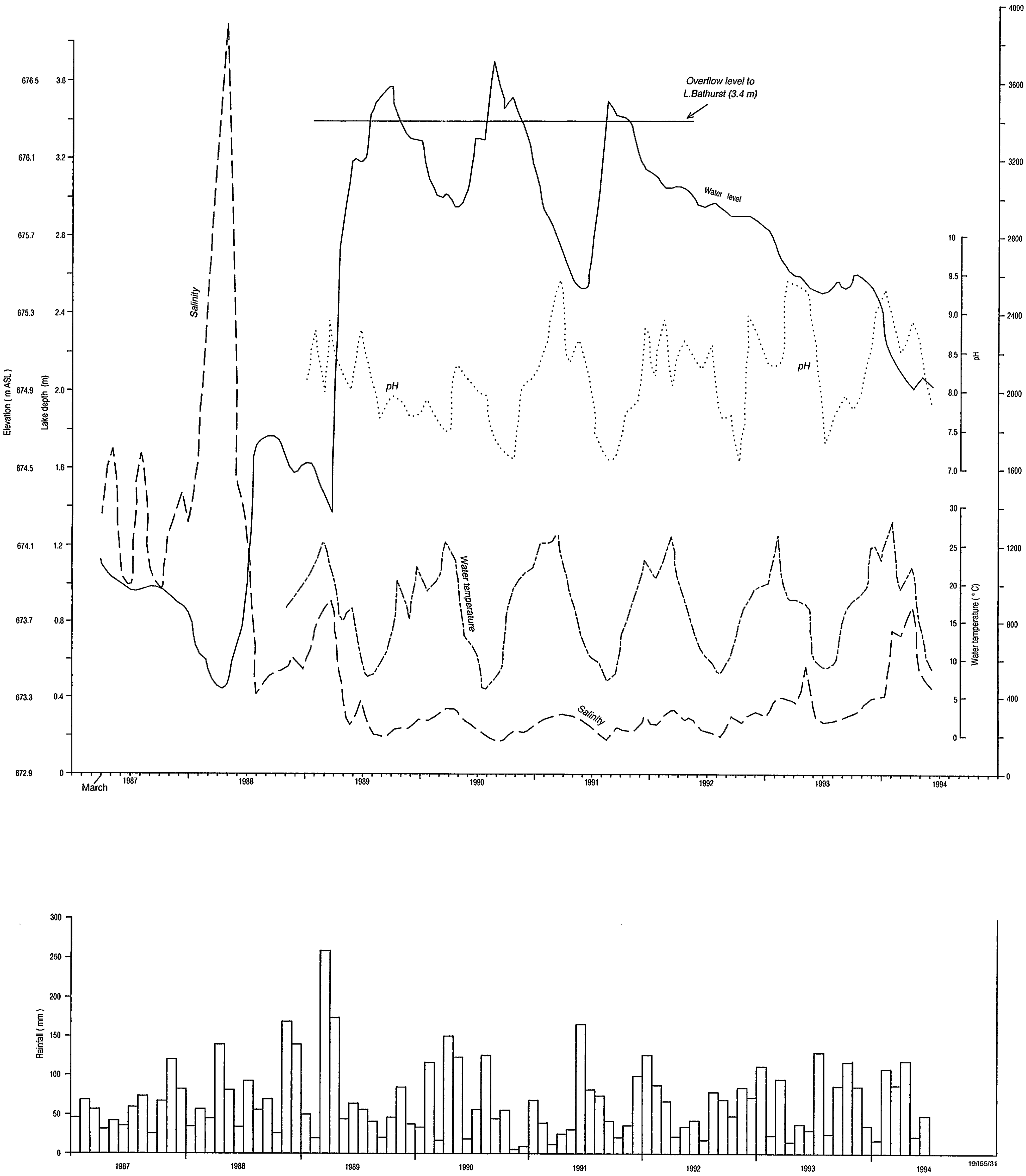
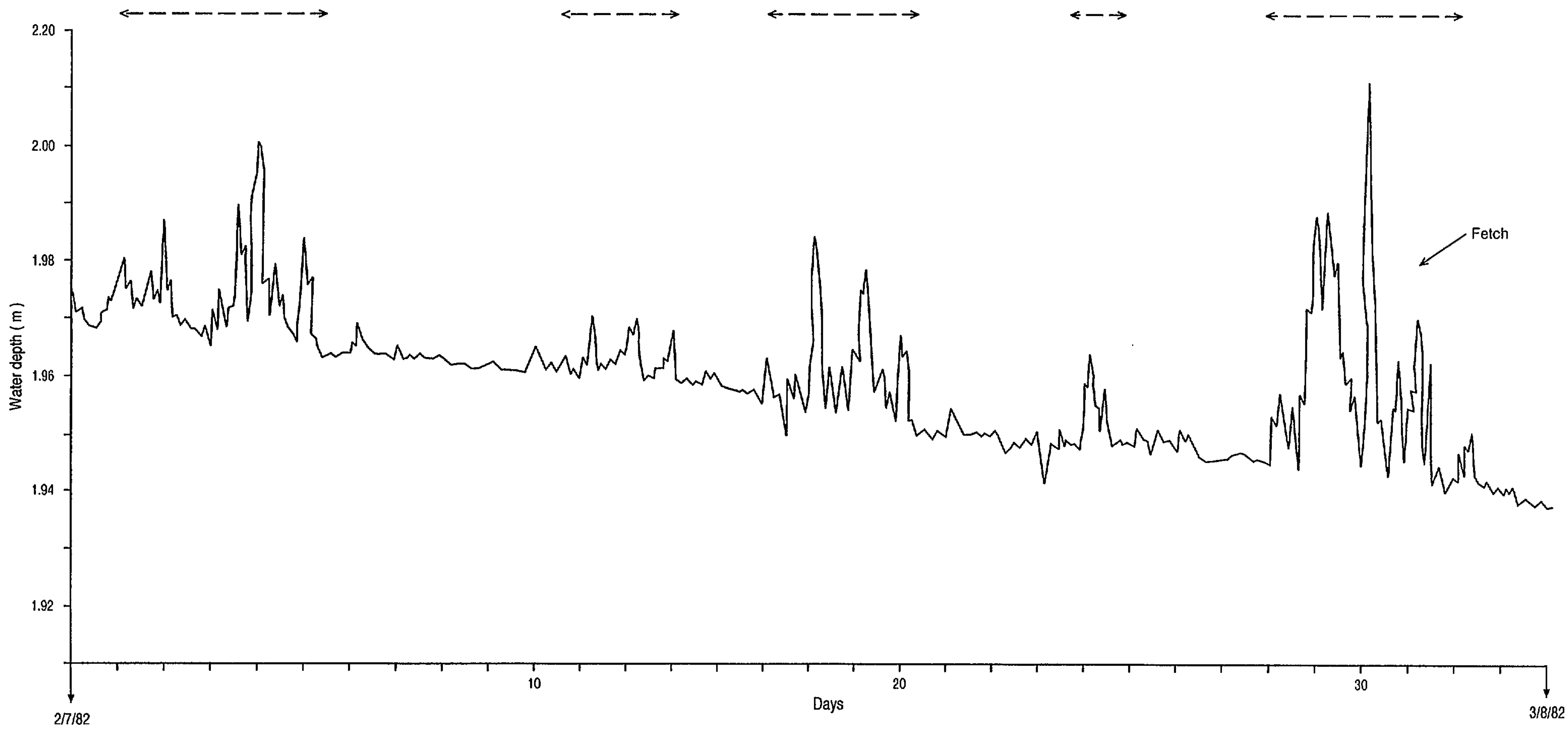


Fig. 23. The Morass hydrograph (1987 - 1994)



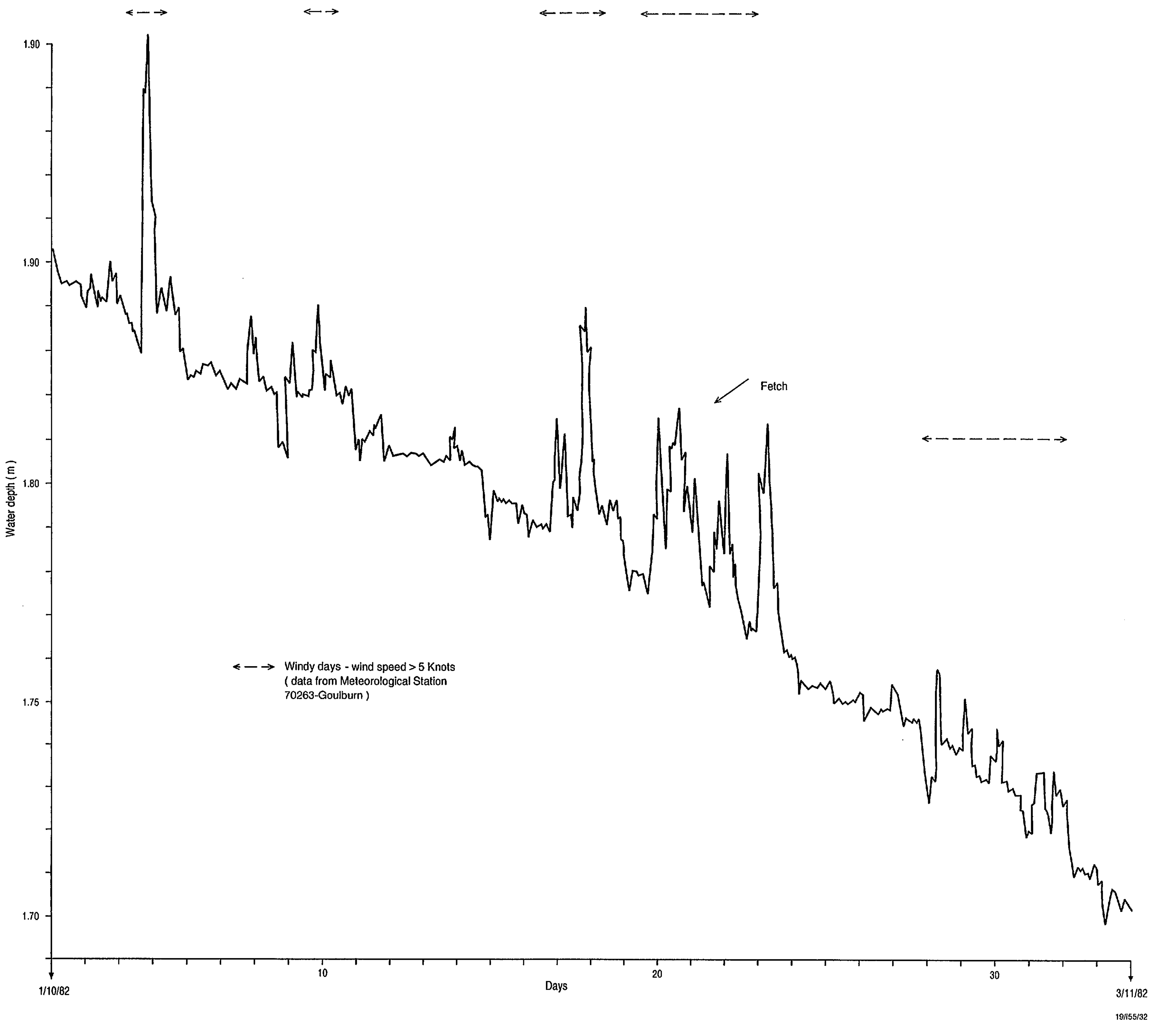


Fig. 24. Hydrographs showing wind driven fetch at Lake Bathurst

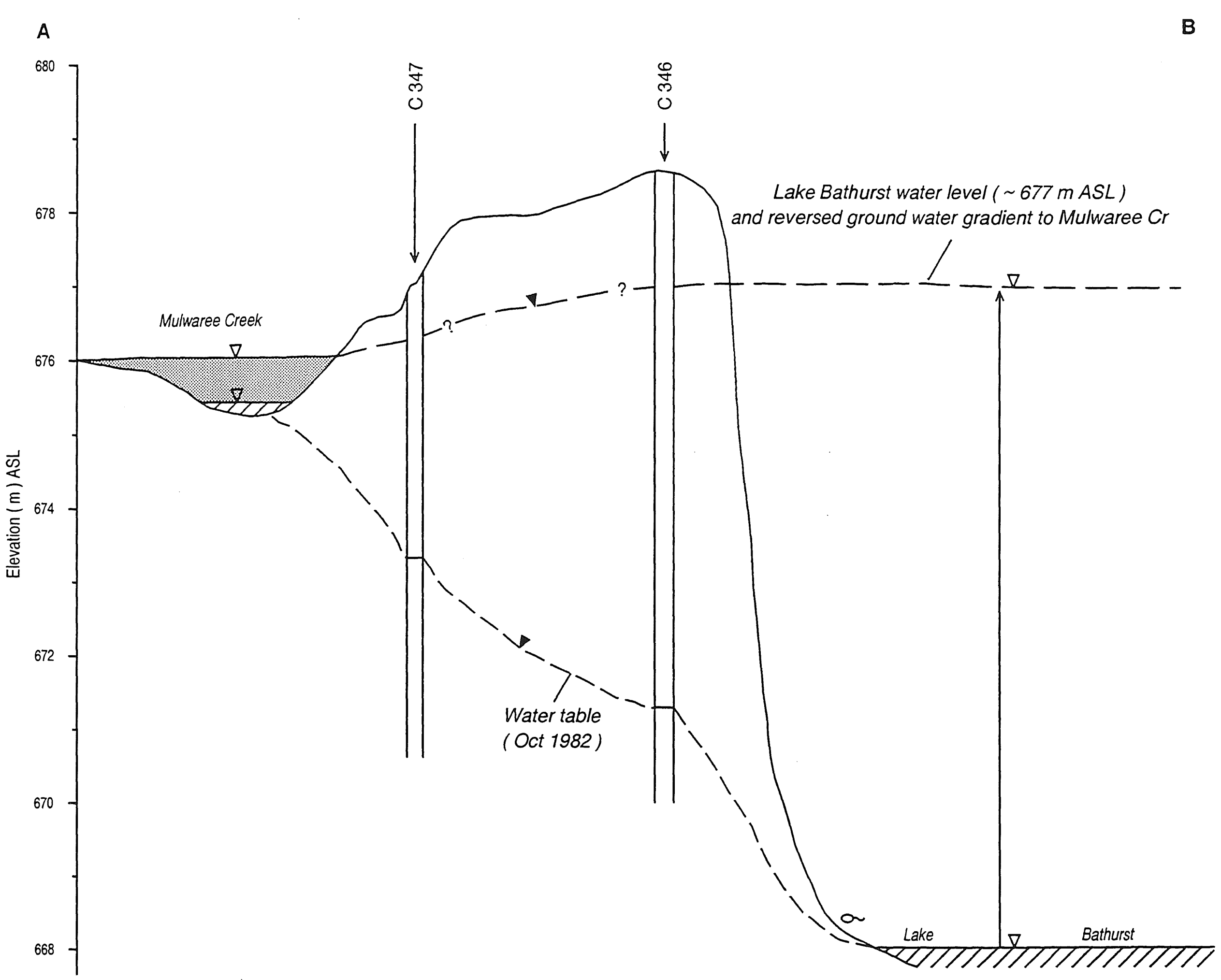


Fig. 25(a). Section A-B (Western barrier)

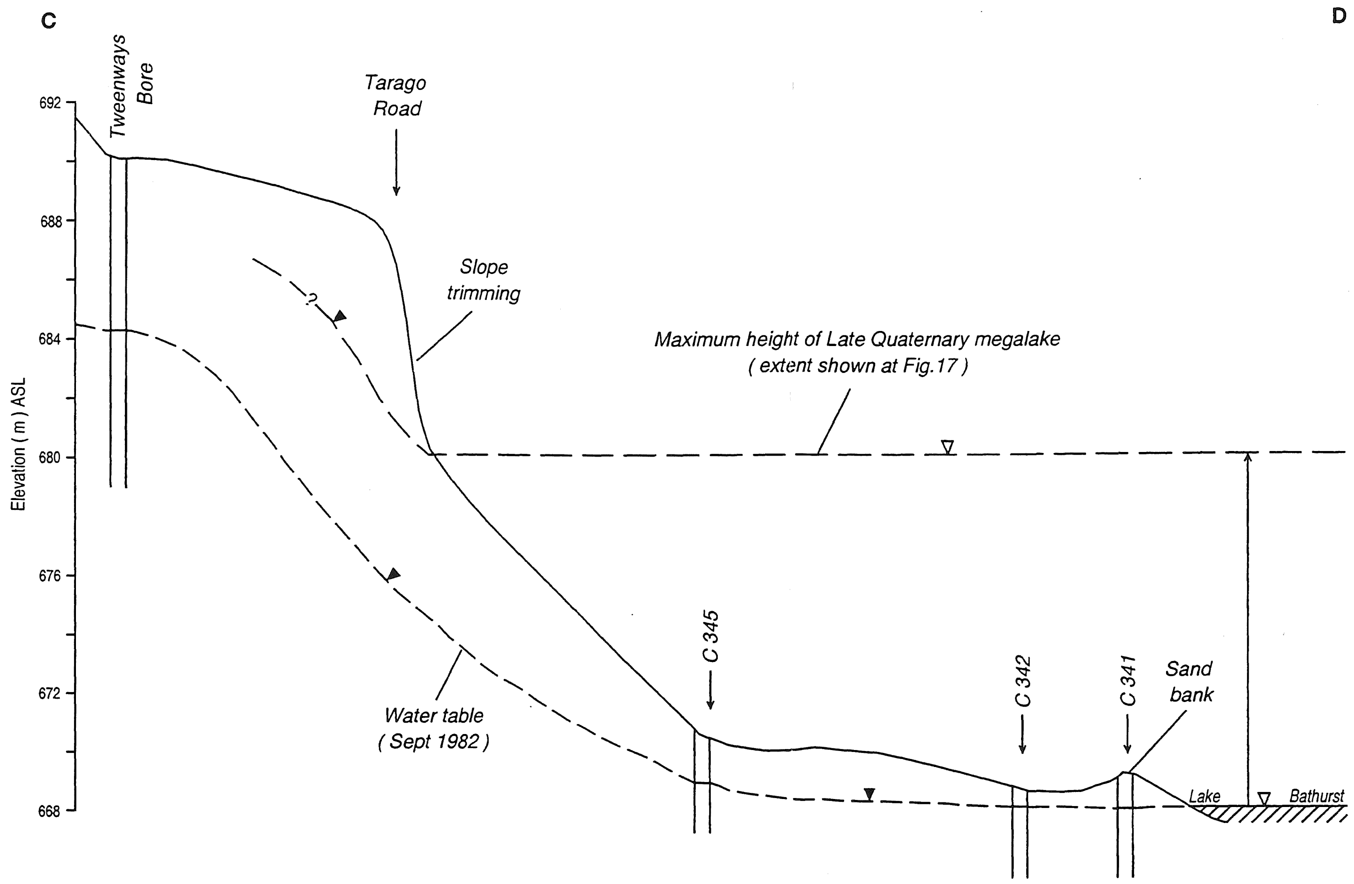


Fig. 25(b). Section C-D (Southern margin of Lake Bathurst)

Fig. 25. Water table gradients and groundwater - lake interactions

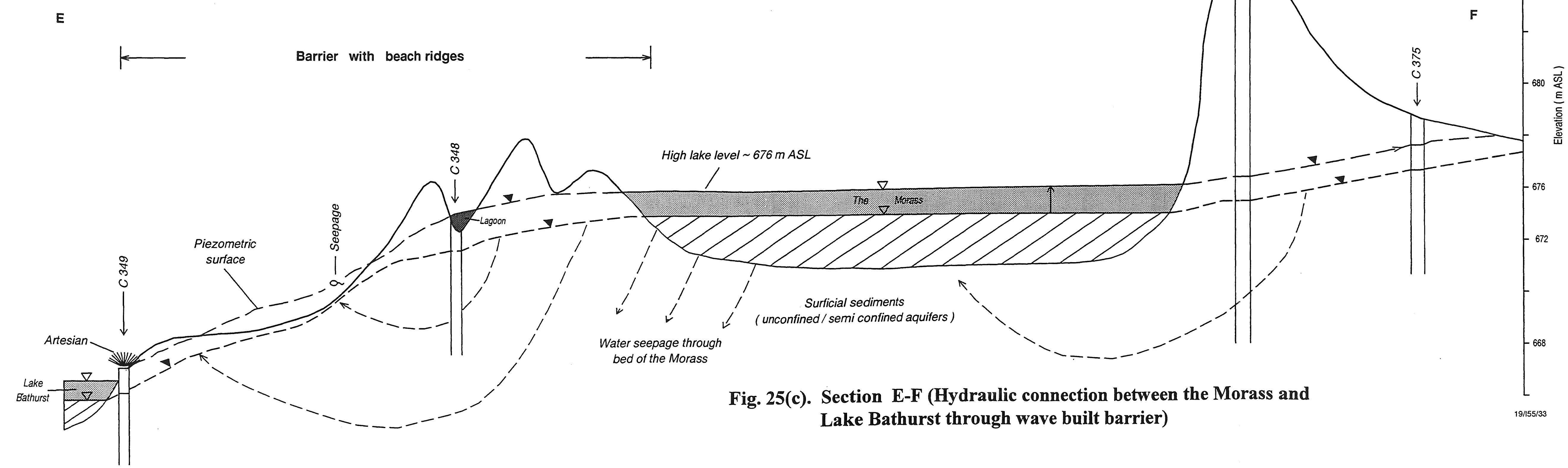


Fig. 25(c). Section E-F (Hydraulic connection between the Morass and Lake Bathurst through wave built barrier)

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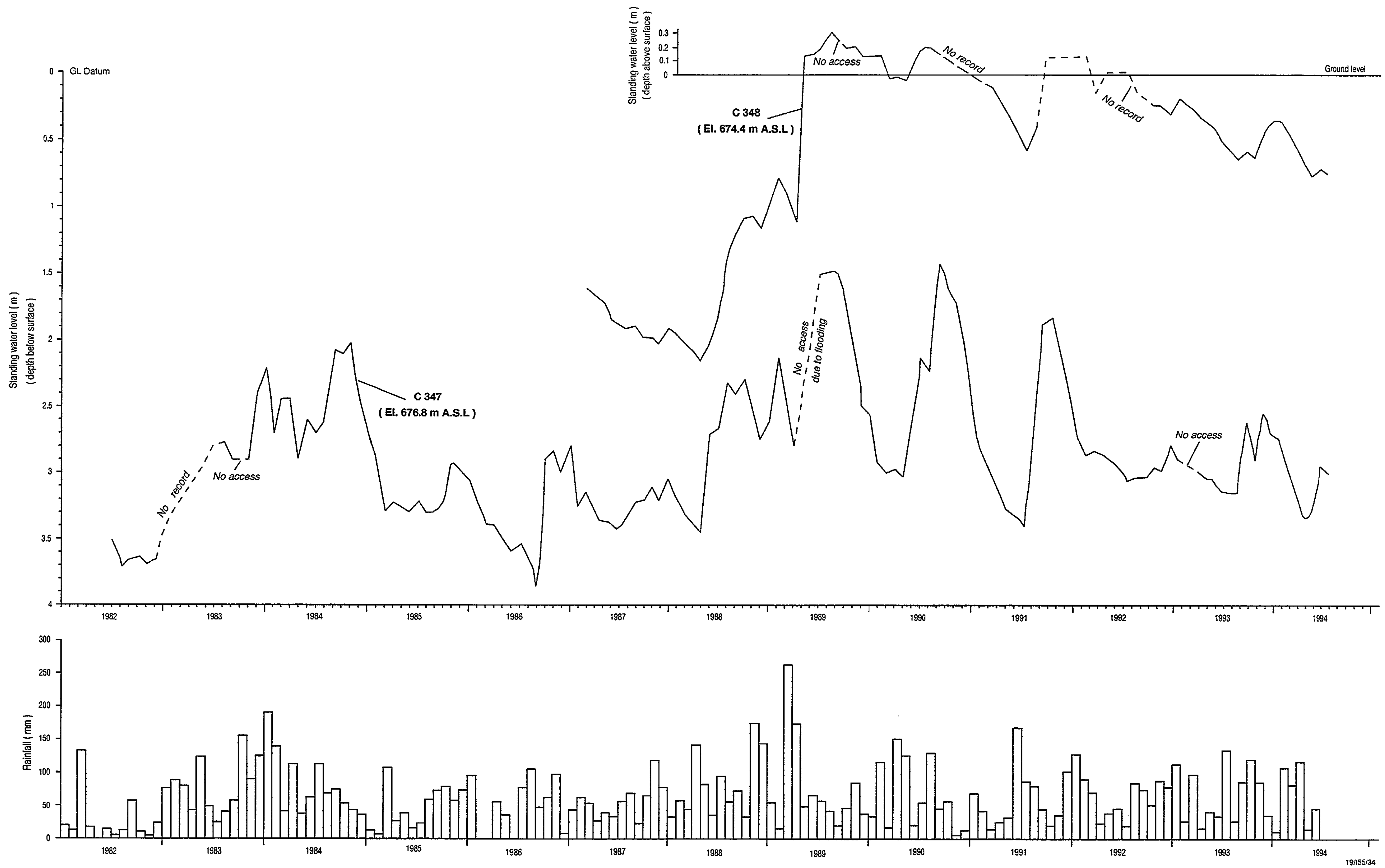

Fig. 26. Groundwater hydrographs for C347 and C348 (1982 - 1994)

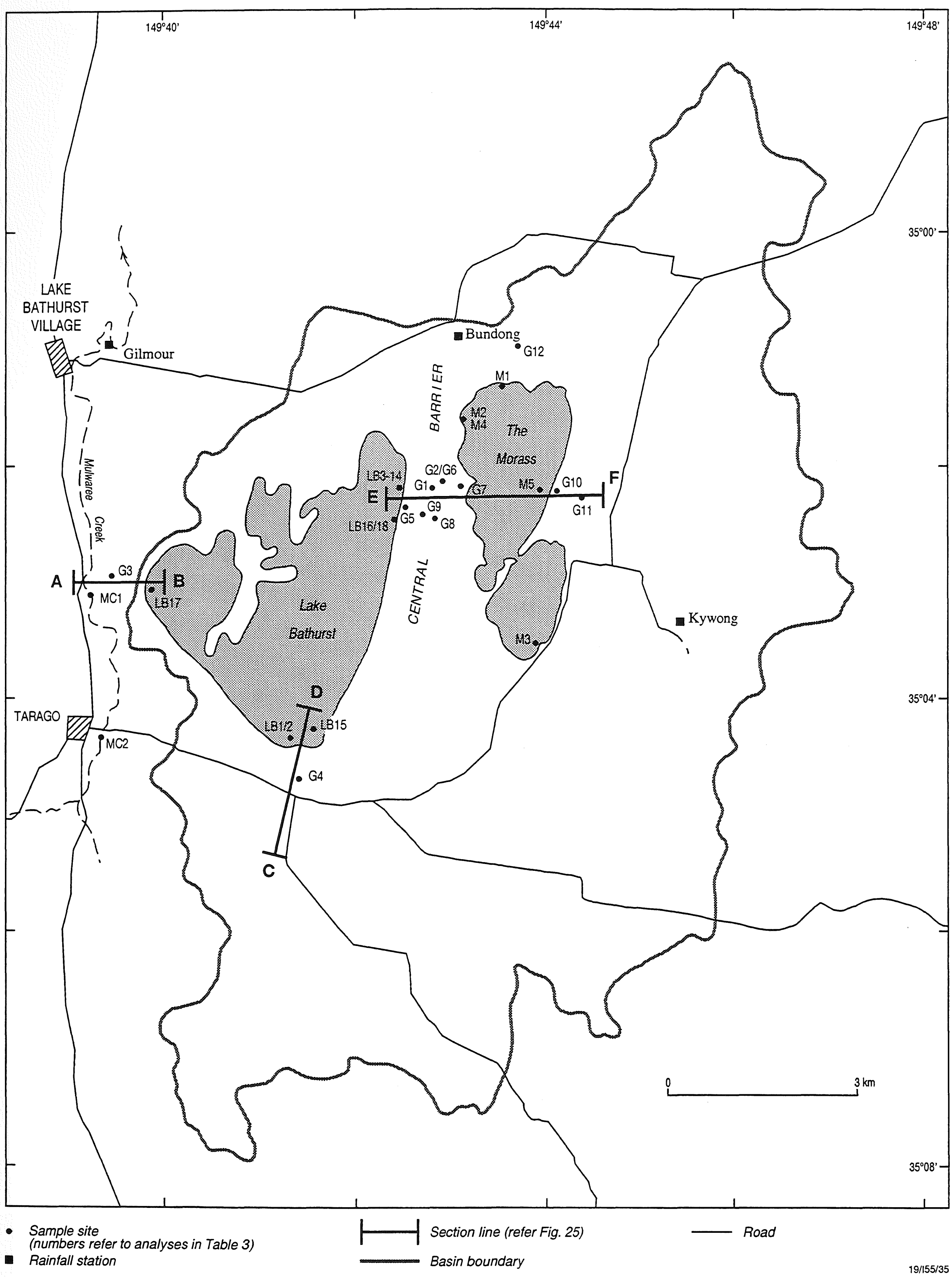

Fig. 27. Water chemistry sampling sites

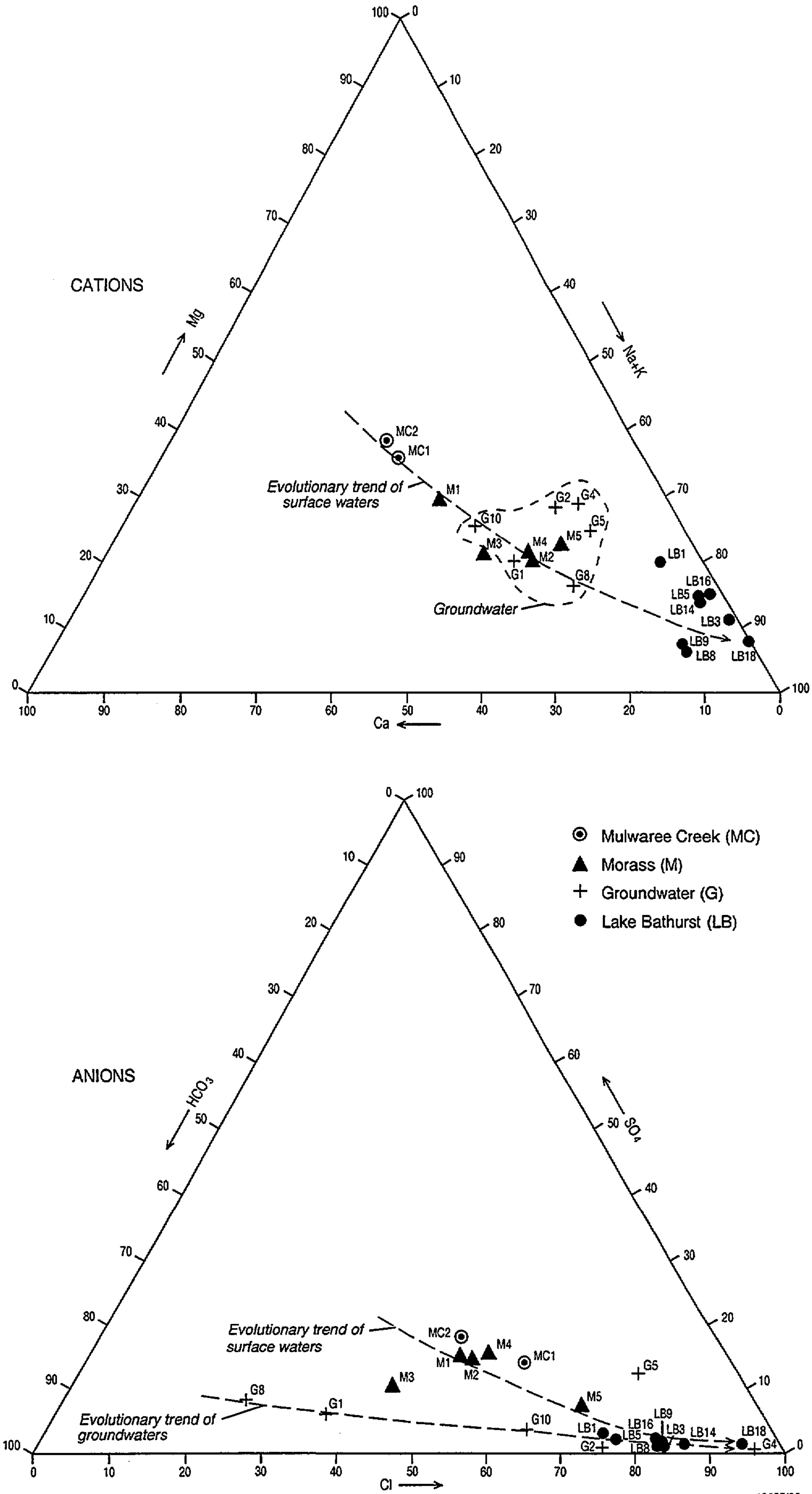

Fig. 28. Ternary cation and anion plots for selected waters in the Lake Bathurst drainage basin

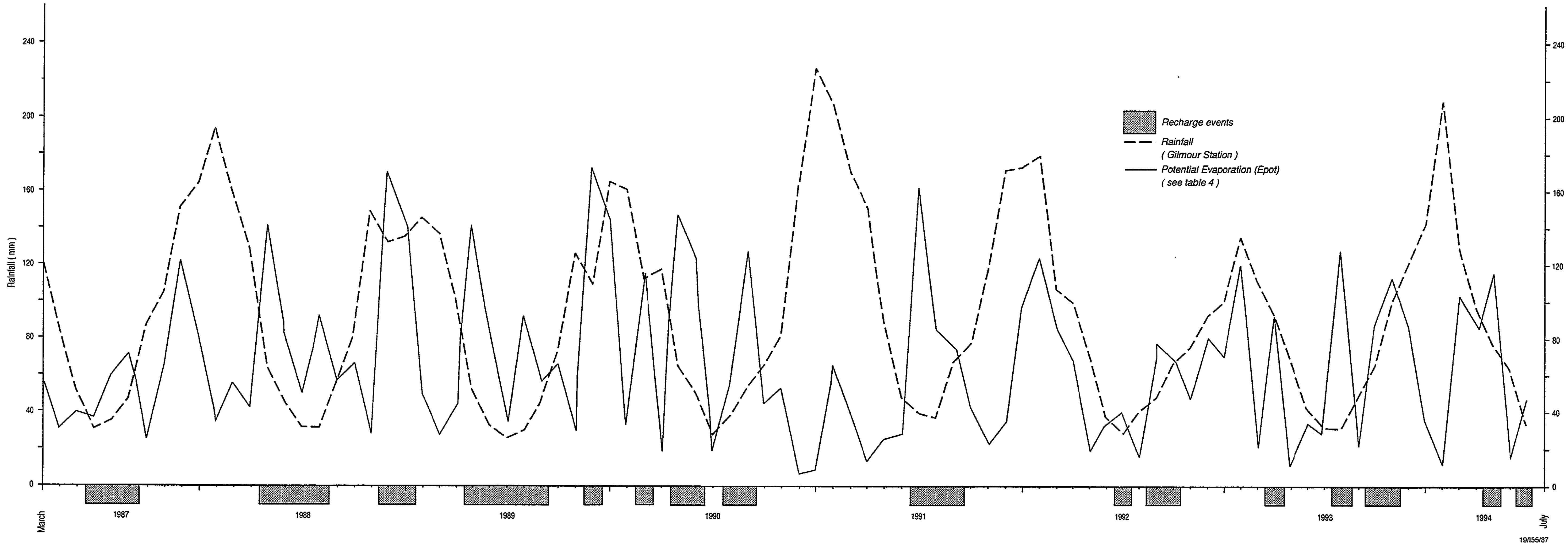

Fig. 29. Groundwater recharge availability

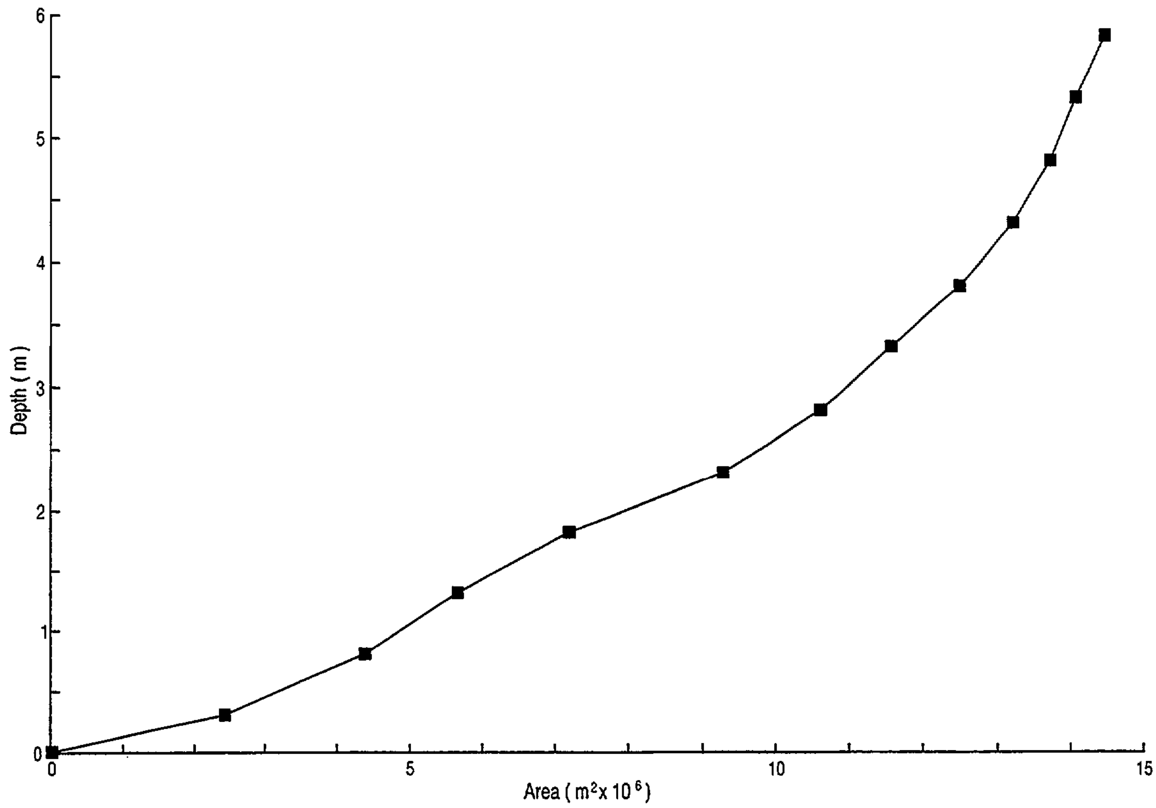

Fig. 30. Lake Bathurst - Area vs. water depth graph

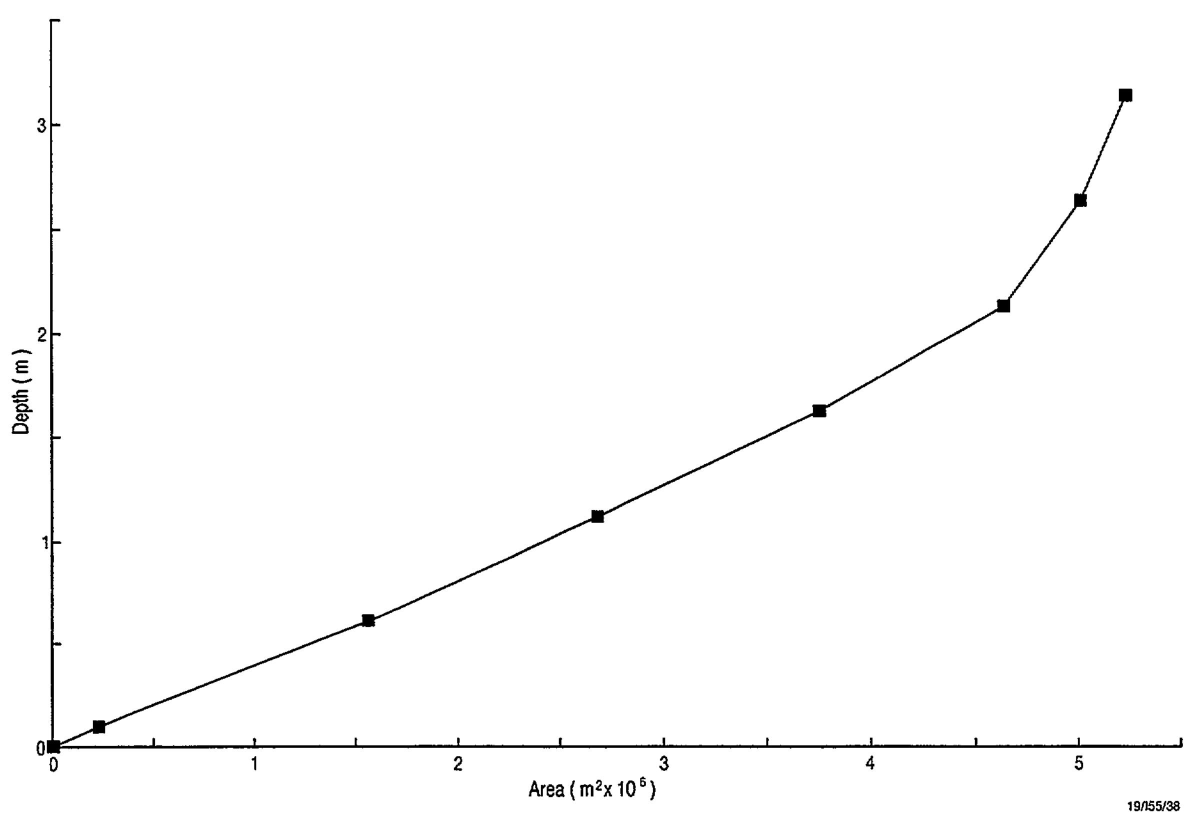

Fig. 31. The Morass - Area vs. water depth graph

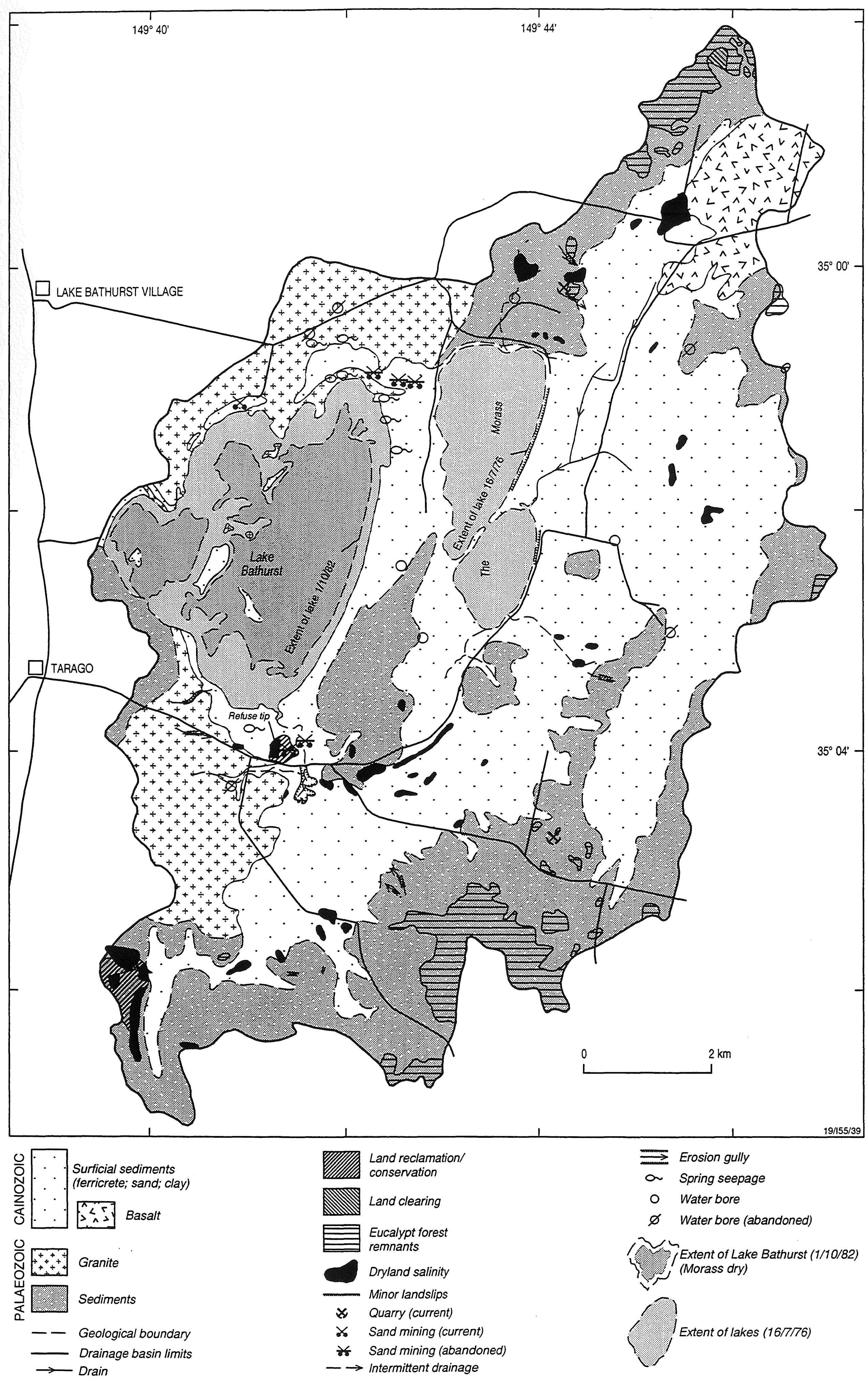

Fig. 32. Hydrological and anthropogenic landscape features

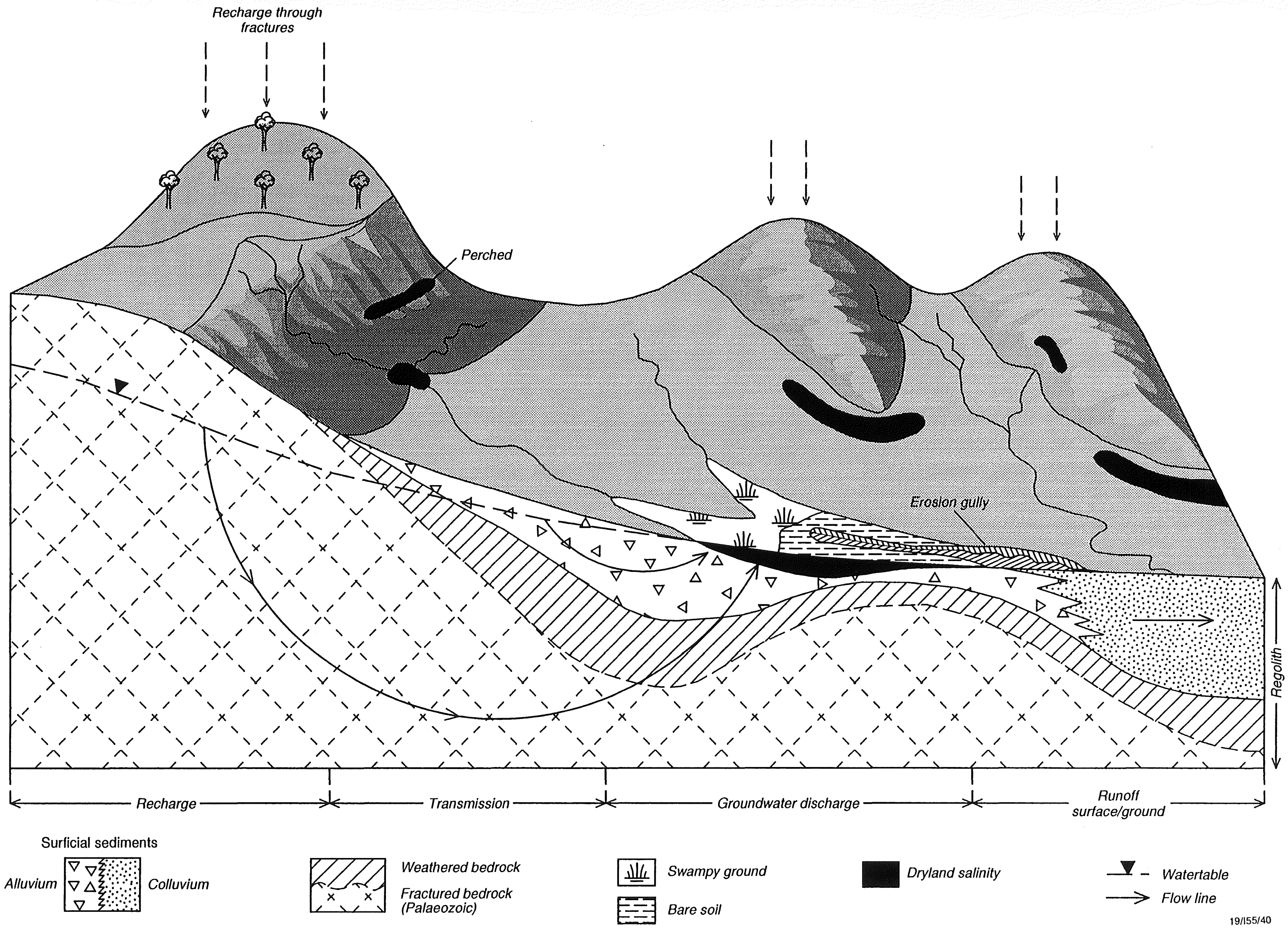

Fig. 33. Dryland salinity