Mound springs of the Great Artesian Basin in South Australia: a case study from Olympic Dam

G.M. Mudd

Abstract The mound springs of South Australia are a unique groundwater discharge feature of the Great Artesian Basin (GAB), a deep regional groundwater system that covers 22% of the Australian continent. They are the principal sources of surface water in the arid to semi-arid inland heart of Australia, and have great ecological, scientific, anthropological and economic significance. Excessive development of the Great Artesian Basin over the past century by European activity has seen an overall decline in the flows from the springs. Recent development of the water supply borefields for the Olympic Dam copper-uranium mine in the midst of one the most important spring groups has exacerbated this problem. A review of the history of the Olympic Dam borefields, an analysis of the impacts on the Mound Springs, and future recommendations for the return of environmental flows and protection of the springs is presented.

Key words Mound springs · Great Artesian Basin · Olympic Dam (Roxby Downs)

Introduction

The Olympic Dam polymetallic copper, uranium, gold and silver deposit in northern South Australia was discovered in 1975 by Western Mining Corporation (now WMC) and contains the largest known uranium ore body in the world (Roxby Downs is the name of the pastoral station and township, although the Olympic Dam mine is colloquially known as Roxby Downs). The deposit was developed as a joint venture between WMC (51%) and British Petroleum (BP) (49%), although WMC acquired full ownership of the mine in 1993 (Kinhill 1997). After the operation of pilot plant studies in the mid-1980s, a commercial mine began operation in 1988 and is currently nearing completion of a major expansion. It is presently ranked seventh as a world producer of uranium (UI 1998).

The Olympic Dam mine currently produces about 85,000 tonnes per annum (tpa) of refined copper, 1600 tpa of uranium oxide (U_3O_8), 13 tpa of silver and 850 kg per annum of gold (Kinhill 1997). The State and Commonwealth governments approved the development of the mine in 1983. In 1997, a formal proposal was made to expand production in two stages to 200,000 tpa of copper and associated products, and further to 350,000 tpa of copper and associated products (Kinhill 1997). However, only the expansion to levels of 200,000 tpa of copper, 4630 tpa of uranium oxide, 23 tpa of silver and 2 tpa of gold was approved by State and Commonwealth governments due to the lack of detail on the expansion to 350,000 tpa of copper level (Assessment Report 1997).

The ore reserves of the multi-mineral deposit are large by any standard, with 11.4 million tonnes (Mt) of copper, 340,000 tonnes of uranium (as U_3O_8), 2790 tonnes of silver and 400 tonnes of gold (Kinhill 1997). The ore reserves may be as high as 30 Mt copper, 1 Mt uranium (as U), 7000 tonnes of silver and 1200 tonnes of gold, as further exploration continues to delineate the actual extent of economic mineralisation (Campbell and others 1998). The expanded production rate and large reserves will allow production from the mine for at least the next 50–100 years.

The process and potable water supply for the Olympic Dam mine and Roxby Downs township is derived from two borefields located approximately 120–200 km to the north, near the southern margins of the Great Artesian Basin (GAB) near Lake Eyre South. Since the start of pilot plant operations and the commercial mine, the amount of water extracted has steadily increased, averaging about 2.3 million litres (ML) per day in 1986 and 15 ML/day during 1996 (ODC 1997). The borefields are located directly within or near the Lake Eyre supergroup of mound springs. The original 1982 Environmental Impact Statement (EIS; Kinhill 1982) and 1997 Expansion Project EIS (Kinhill 1997) predicted impacts on the springs as well as other users of GAB water in the region. However, the actual impacts have been markedly different.

Received: 9 November 1998 · Accepted: 23 February 1999

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Darwin
NORTHERN TERRITORY
Townsville
FLINDERS
SPRINGVALE
BARCALDINE
Rockhampton
MULLIGAN RIVER
QUEENSLAND
SPRINGSURE
DALHOUSIE
LAKE EYRE
LAKE EYRE NORTH
EURO
Brisbane
LAKE EYRE SOUTH
LAKE FROME
SOUTH AUSTRALIA
BOURKE
OLYMPIC DAM
LAKE TORRENS
LAKE FROME
Roxby Downs
LAKE GAIRDNER
BOGAN RIVER
Broken Hill
NEW SOUTH WALES
Sydney
Adelaide
Groundwater flow direction
Great Artesian Basin boundary
Recharge area
Great Artesian Basin spring
Spring supergroup
Canberra
VICTORIA
Melbourne
N
0
500 km

Fig. 1
Location of the Olympic Dam Project and extent of the Great Artesian Basin, flowpaths and spring groups (Kinhill 1997)

The northern regions of South Australia are arid to semiarid, with evapotranspiration generally exceeding rainfall by an order of magnitude or more (Allan 1990; Badman and others 1996). The surface landscape has seen dramatic change over the past 500 million years, varying from shallow seas with active volcanoes, glaciers and ice caps, rich humid and tropical forests, to the dry arid landscape now present (Krieg and others 1990). Each climate has left distinctive marks on the landscape.
The availability and careful management of water supplies is thus critical to the overall project and its related environmental impacts.

The Great Artesian Basin

Overview of hydrogeology

The Great Artesian Basin is one of the world's largest and oldest groundwater systems, underlying 22% of the Australian continent or 1711,000 km^2, shown in Figure 1 (Hillier 1996). It consists of several contiguous sedimentary basins with confined aquifers of Triassic, Jurassic and Cretaceous continental quartzose sandstones, underlain by an impervious pre-Jurassic base (Habermehl 1996a). The aquifers are confined by the Rewan Group at the bottom and the Winton Formation at the top (Habermehl 1980). The maximum total thickness of about 3000 m occurs in the Mesozoic sedimentary sequence in the central GAB (Habermehl 1996a). The Basin forms a large synclinal structure, uplifted and exposed along its eastern margin, leaving the overall Basin tilted southwest (Keane 1997).
Recharge to the GAB occurs primarily along the uplifted eastern margins and also on the western margins where the aquifers are exposed or overlain by sandy sediments (Habermehl 1980). Environmental isotope and other hydrochemical studies of groundwater from across the Basin confirm the assumptions of continuous recharge from geological to modern times, and that the water is of meteoric origin (Airey and others 1983; Bentley and others 1986; Torgersen and others 1991; Habermehl 1996a). The age of the groundwater, determined from extensive carbon-14 and chlorine-36 studies and correlated with hydraulic modelling studies, ranges from several thousands of years near recharge areas to nearly two million years around the southwest of the GAB near Lake Eyre (Habermehl 1996a).
Natural discharge from the GAB occurs via two principal processes – vertical leakage towards the regional water table (at about 60–80 m depth) and concentrated outflow from springs around the margins (Habermehl 1996b). Since the onset of European development of the GAB for the pastoral industry late in the nineteenth century, and more recently the mining and resource extraction industries, discharge via free or controlled artesian bores and pumped abstraction from non-artesian bores has now become the primary discharge mechanism (Keane 1997).
The hydrochemistry of the majority of GAB water is dominated by sodium-bicarbonate-chloride waters, although waters around the western margin are of a sodium-sulphate-chloride type (Habermehl 1980). The total dissolved solids (TDS) of groundwater generally decreases as the depth of the aquifer being tapped increases, with the Lower Cretaceous-Jurassic aquifer containing good quality water with a TDS from 500 to 1000 mg/L. The water in the shallower Cretaceous aquifers have higher salinities up to a TDS of 10,000 mg/L (Habermehl 1980).
The surface temperature of groundwater from waterbores tapping the Lower Cretaceous-Jurassic sequence ranges from 30 to 100 °C, while the temperature of water from artesian springs are generally between 20 and 45 °C (Habermehl 1996a). The heat flow in the GAB is attributed to heat produced in the Earth's crust by uranium and thorium, and by recent volcanic activity (Torgersen and others 1992).

Groundwater management issues

The first bore to tap the GAB was in 1878, drilled near Burke, NSW (Habermehl 1980). Initially, bores were drilled near springs as these were known sources of artesian water, but the extensive areal nature of the GAB quickly became established and further deep bores were drilled in the central parts of the GAB (Habermehl 1980).
The combined flow rate from all bores across the GAB peaked early this century in 1918 at over 3000 ML/day, compared to current bore discharge of about 1500 ML/day (Habermehl, pers. comm. 1998). Many of the early bores now exhibit significantly reduced flows due to the release of water from elastic storage and are now approaching steady-state flows (Habermehl 1996a).
Estimates of the overall water balance for the GAB reflect both the difficulty of calculations on such a large scale and the scarcity of reliable regional data (Keane 1997). Based upon the available piezometric evidence, it is thought that the GAB has reached a new equilibrium condition, where recharge approximates total discharge (Habermehl 1980, 1996a, 1996b, 1998).
In estimating the water balances for the GAB and the South Australian portion given in Tables 1 and 2, a common assumption is that recharge approximates discharge (e.g. Berry and Armstrong 1995; Kinhill 1997; Habermehl 1998). The various components of discharge are now reasonably well quantified, except for vertical leakage. Although no quantitative field studies of recharge are yet available, the recharge areas are known to be at full piezometric pressure, suggesting abundant, continuous recharge (Habermehl 1998). When the above information is combined with some analytical techniques, assumed hydrogeologic properties and observed artesian pressures, it is possible to derive an estimate of total inflow. Thus the total outflow is assumed to be equivalent to this, and the vertical leakage is simply estimated as the difference. Es-

Table 1
Water balance estimates of the GAB (ML/day; adapted from Keane 1997); ND no data

Year	Recharge	Bores	Vertical leakage	Springs	Total discharge
1980	3024	1500	1394	130	3024
1982	3100	1500	1400	200	3100
1997	2630–2930	1200–1500	1300	130	2630–2930
1998[a]	ND	1200–1500	1100 ?	130	2815–3115

[a] Habermehl, pers. comm. (November 1998)

Table 2
Water balance estimates of the South Australian portion of the GAB (ML/day; adapted from Keane 1997); ND no data

Year	Inflow	Pastoral	Springs	Oil and Gas	Vertical leakage	ODO	Total discharge
1982	ND	210	80	ND	250	ND	540
1997	450	130	66	22	217	15	450
1997	425	132	66	22	190	15	425
1995	350–400	ND	ND	35	ND	ND	350–400
1995[a]	76	36	2	ND	24	14	76

[a] Water balance for the computer model of the borefields (see later section)

timates of vertical leakage have been attempted using approximate vertical hydraulic conductivities (e.g. Habermehl 1980; Kinhill 1982), however, these can only be considered as estimates and not an accurate assessment of vertical leakage. Hillier (1996) cautioned that the perceived steady-state condition may be a balance between outflow and transmission of water through the GAB aquifers rather than recharge.
The total number of bores is still increasing, currently at about 4700 bores, although an increasing proportion of these are no longer free-flowing and require pumping, see Figure 2 (Hillier 1996; Habermehl 1996a). Historically, the vast majority of the extracted water has been wasted, estimated at 80% and up to 95% in some cases, due to uncontrolled bore flows and inefficient open earth drain distribution systems (Hillier 1996; Habermehl 1996b).
The former Mines and Energy Department of South Australia commenced a bore rehabilitation and water conservation program in 1977, and presently only 10–12 of the present 170 bores in South Australia require further works (Sibenaler 1996). The estimated water saving of this program is about 90 ML/day (Sibenaler 1996).

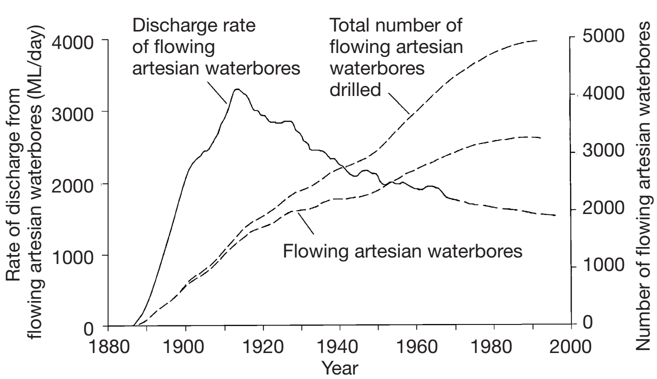


Fig. 2
GAB bore discharge and bores drilled summary (Habermehl pers. comm. 1998)

The Great Artesian Basin Bore Rehabilitation Program was introduced as an interstate working group in 1987 and water conservation measures are now being implemented across the entire GAB (Hillier 1996; Sampson 1996). This work includes rehabilitating bore headworks (such as corroded caps and valves), the use of polythene distribution piping, and float valve controlled tanks and trough systems (Habermehl 1996a). In areas of rehabilitated bores the artesian pressure is beginning to increase, due to improved efficiency reducing demand and lowering flow rates (Habermehl 1996b; Hillier 1996).

Mound Springs in the GAB

A unique feature of the GAB is the large numbers of artesian springs it supports. There are considered to be 11 main groups totalling about 600 individual springs, with the Lake Eyre supergroup around the south-western margin containing the largest concentration of active and unique springs (Habermehl 1982). The location of springs is controlled by geology, such as faults or erosion of confining beds (Boyd 1990; Keane 1997). The flow rates from individual springs are highly variable, with values ranging from 0.1 to 14 ML/day, with the majority being less than 0.5 ML/day (Habermehl 1982, 1996a).
The persistence of spring flows over recent geologic time has seen the accumulation and carbonate cementation of sand, silt and clay, building a characteristic mound. Hence, these particular springs, found only in the Lake Eyre supergroup, are referred to as “mound springs”. A typical mound consists of a central pool of water, an outer rim of reeds and vegetation, an outflow channel, and

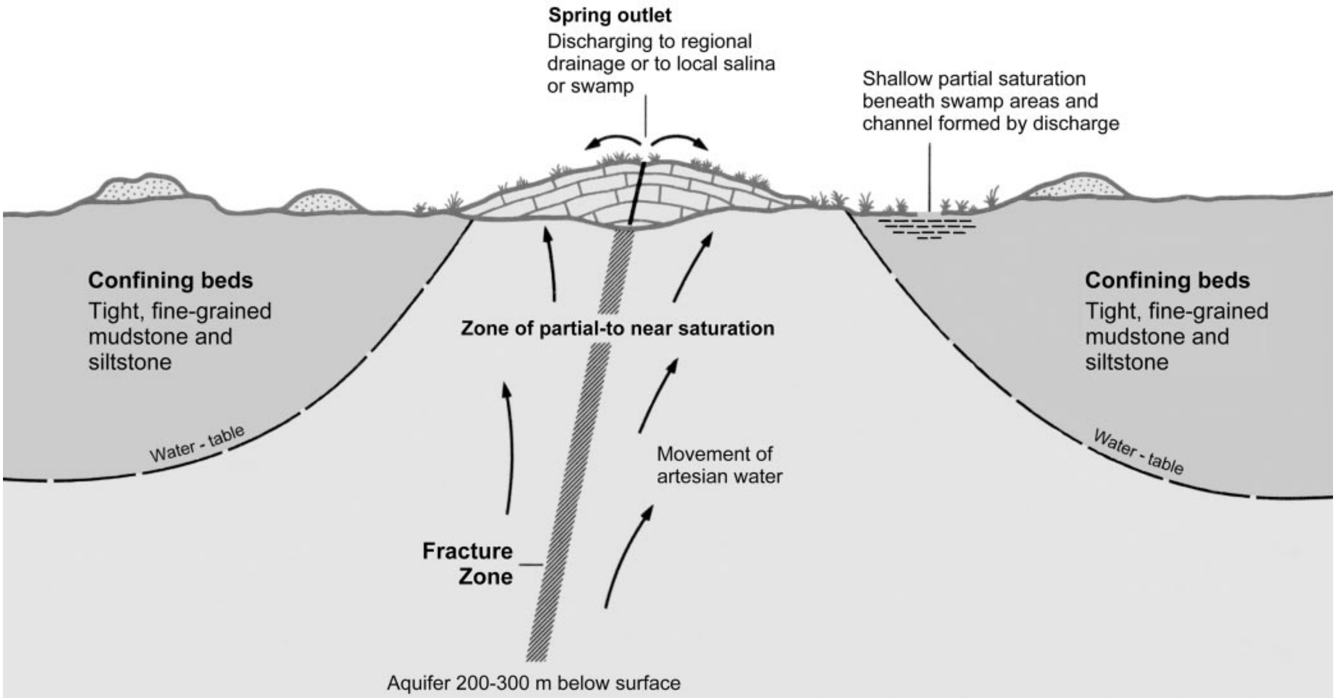


Fig. 3
Cross section of a typical Mound Spring (Kinhill 1982)

successive layers of carbonate shown in Figures 3 and 4. The mounds may be up to 8 m in height and up to 30 m in diameter (although the extinct Hamilton Hill Spring is about 40 m above ground level, suggesting that artesian pressures have been higher in the GAB over recent geologic time; Habermehl 1980, 1982). See Figures 3 and 4.
A wetland and sometimes a small creek are formed by the outflow from a spring. The flowrate from a spring has been shown to be directly proportional to the area of wetland vegetation a spring supports given in Figure 5 (Williams and Holmes 1978; Fatchen and Fatchen 1993). This "environmental flow" is critical in the ability of a spring to support its surrounding wetland.
There are numerous factors known to influence the observed flow rate from a spring. These include diurnal and other variations in atmospheric pressure (barometric effects), evaporation rates, vegetation communities on the mound springs, and pastoral impacts (Kinhill 1997).
There may also be variability due to differences in hydraulic conductivities at different springs, such as frac-

Fig. 4
The Bubbler Spring (*foreground*) and Hamilton Hill (*background*; Keane 1997)

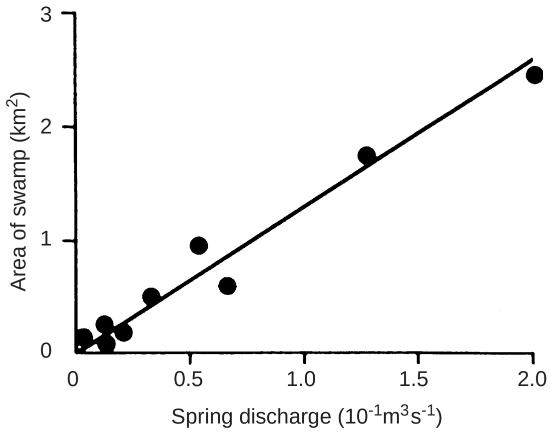


Fig. 5
Spring flow rate versus wetland area (Williams and Holmes 1978)

ture-dominated flow, upwards flow through coarse sands or lower permeability silty sands. In practice, these factors are hard to account for quantitatively and are typically ignored in compiling variations and long-term changes in spring flow rates.

Aboriginal heritage

The springs were a vital resource for the Aboriginal inhabitants of the region for many thousands of years and remain so to this day (Habermehl 1996b; Hercus and Sutton 1985; Keane 1997; Noble and others 1998). This is evidenced by the abundance of stone chips, grinding stones, other traditional tools in the vicinity of the springs, and by the rich mythological and oral history of the springs in Aboriginal culture (DHAE 1983; Hercus and Sutton 1985; Boyd 1990). The springs in the Lake Eyre region are recognised as being under the traditional custodianship of the Arabanna people (Hercus and Sutton 1985; Keane 1997).
All individual springs and complexes are known to hold significance for Aboriginal people, and it is impossible in modern times to predict, with any confidence, that an individual mound spring does not have any significance due to similarities with other springs in an area (Noble and others 1998). Hercus and Sutton (1985) emphasise that "the springs are considered so important that the large-scale deterioration of any group of springs would cause great distress to at least some Aboriginal people, whether their associations with the sites are direct or indirect."

Ecological importance of the mound springs

The mound springs are the only permanent source of water in the arid interior of South Australia and a delicate yet intricate ecological balance has been established (Keane 1997). Due to their prolonged isolation the mound springs contain many endemic and rare species that have undergone genetic differentiation and speciation (Kinhill 1997; Noble and others 1998). The springs are important as drought refuge areas for much wildlife and as wetlands for migratory birds, recognised as being of at least national importance (DHAE 1983; ANCA 1996).
The rare and endemic species include plants, fish, hydrobiids, isopods, amphipods and ostracods, many of which occupy specialised areas within a spring such as the open pool, outer rim or the rocky outflow channel (Keane 1997; Kinhill 1983; Ponder and Jenkins 1983). Despite the linear correlation of flow rate with wetland area, a minor reduction of flow of the order of 20% can impact animal populations by up to 70%, although current monitoring only counts total population and not individual species dynamics (Ponder and Zeidler 1997). Many species are only found within a particular mound spring or spring complex (Kinhill 1983; Habermehl 1996b). The mound springs provide unique opportunities for prehistoric, evolutionary, ecological and biogeographical studies (Keane 1997).

European heritage

The mound springs quickly established themselves as a principal water resource for the arid interior of Australia during the early years of European exploration and settlement. The springs were invaluable in the early exploration trails of Edward John Eyre in 1839 and followed by Benjamin Herschel Babbage, Peter Egerton Warburton and by John McDouall Stuart in 1862 (Kinhill 1984). These journeys paved the way for pastoralists such as Philip Levi, Francis Dunbar Warren, John Howard Angas, Thomas Elder and Sidney Kidman, eager to exploit the land (Kinhill 1984). The mound springs were seen as crucial in the success of pastoral ventures (Kinhill 1984). The building of the overland telegraph in the late nineteenth century was one of the greatest engineering and logistical feats of nineteenth century Australia, with the route closely following that of Stuart's 1862 journey through spring country (Kinhill 1984). The transcontinental railway, constructed from the late nineteenth to the early twentieth centuries from Adelaide to Alice Springs, subsequently followed the overland telegraph route through the springs (Kinhill 1984). Thus, the region of the springs also contains much of the rich and diverse struggles and themes of early Australia.

The Olympic Dam water supply borefields

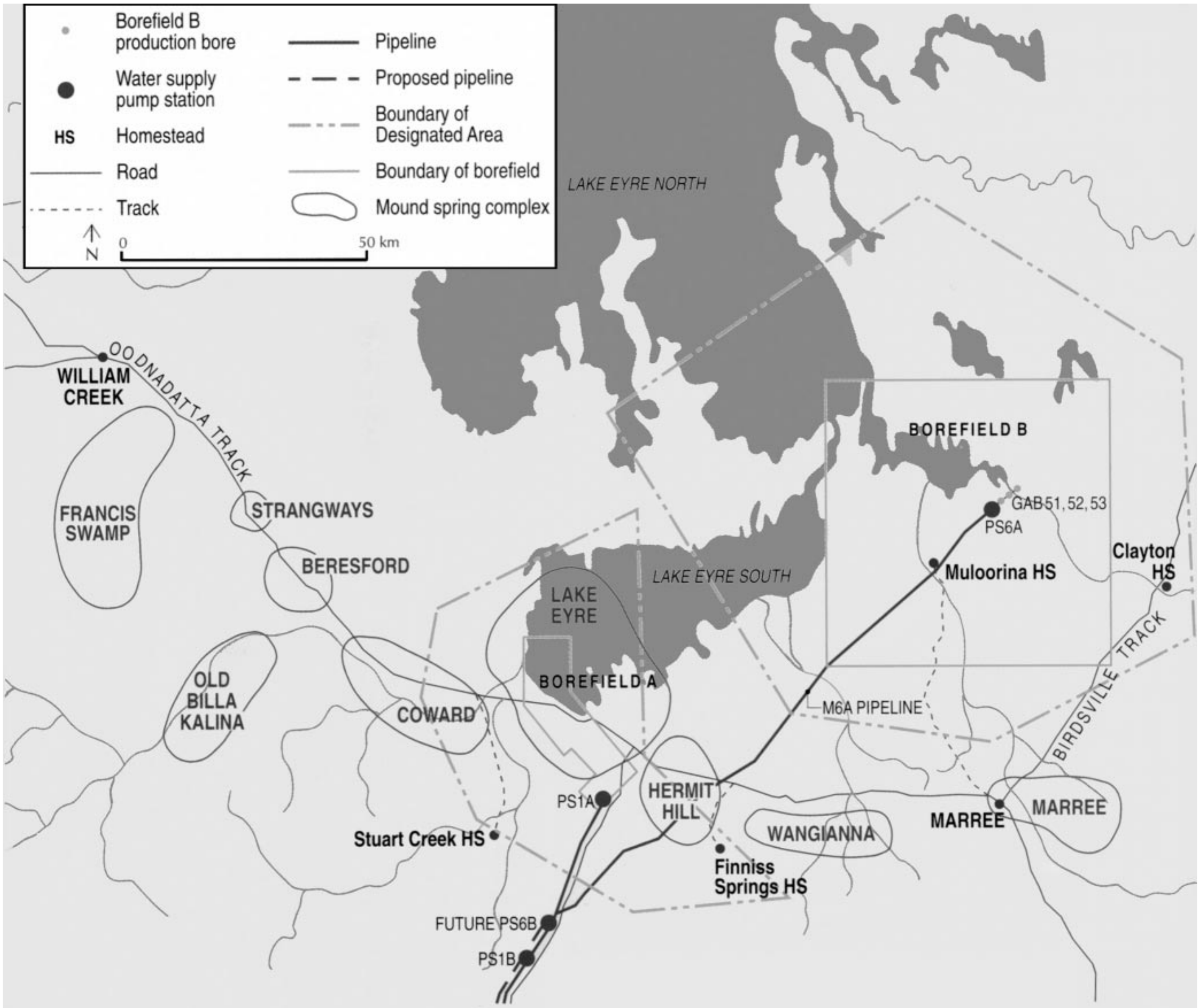
Overview of borefields development

The initial investigations for a water supply for the Olympic Dam Project in the late 1970s concentrated on an area deep into the GAB northeast of Marree. The Clayton Nr. 2 bore was drilled in 1980 by the Commonwealth Bureau of Mineral Resources and Geology as an investigation bore of the hydrogeologic properties of the GAB for a large borefield in this region (Habermehl 1998). The proposal given in the Draft Environmental Impact Statement in 1982 (Kinhill 1982), however, presented two borefields A and B, located closest to the mine, in the midst of the Lake Eyre group of mound springs as indicated in Figure 6. Borefield A was on the southern margin of the GAB, close to the Bopeechee, Venables, Hermit Hill, Sulphuric and numerous spring groups, while Borefield B was to be 50 km further into the GAB closer to Lake Eyre South. The proposed extraction rates of 6 and 27 ML/day from Borefields A and B were via 5 bores and 7–10 bores respectively, pumped via pipeline to Olympic Dam (Kinhill 1982). In response to public submissions on the Draft EIS expressing concern over long-term impacts on the GAB, it was suggested that the total water extracted of 33 ML/day was only 0.003% of the total water stored within the GAB in South Australia, although no reference was made by Kinhill concerning reductions in artesian pressure across the same region due to the Olympic Dam borefields (Kinhill 1983).

There are two important hydrogeologic principles behind placing the borefields in this region. Firstly, to harvest vertical leakage that is otherwise discharged to shallow, saline water tables and lost to surface evaporation (Kinhill 1982, 1997). Secondly, Borefield A was within a geologic sub-basin thought to be hydraulically separated from the mound springs by the Norwest Fault Zone, shown in Figure 7 (Berry and Armstrong 1995, 1996), although this approach is not explicit in Olympic Dam project literature (e.g Kinhill 1982, 1997).

The first bore from the southern region of Borefield A commenced extraction in August 1983 at approximately 1.3 ML/day, increasing in January 1987 to about 2.5 ML/day (ODO 1992). It is explicitly stated in Kinhill (1982) that Borefield A, developed and commissioned during in-

Fig. 6
Location of borefields *A* and *B* and Mound Spring complexes (Kinhill 1997)



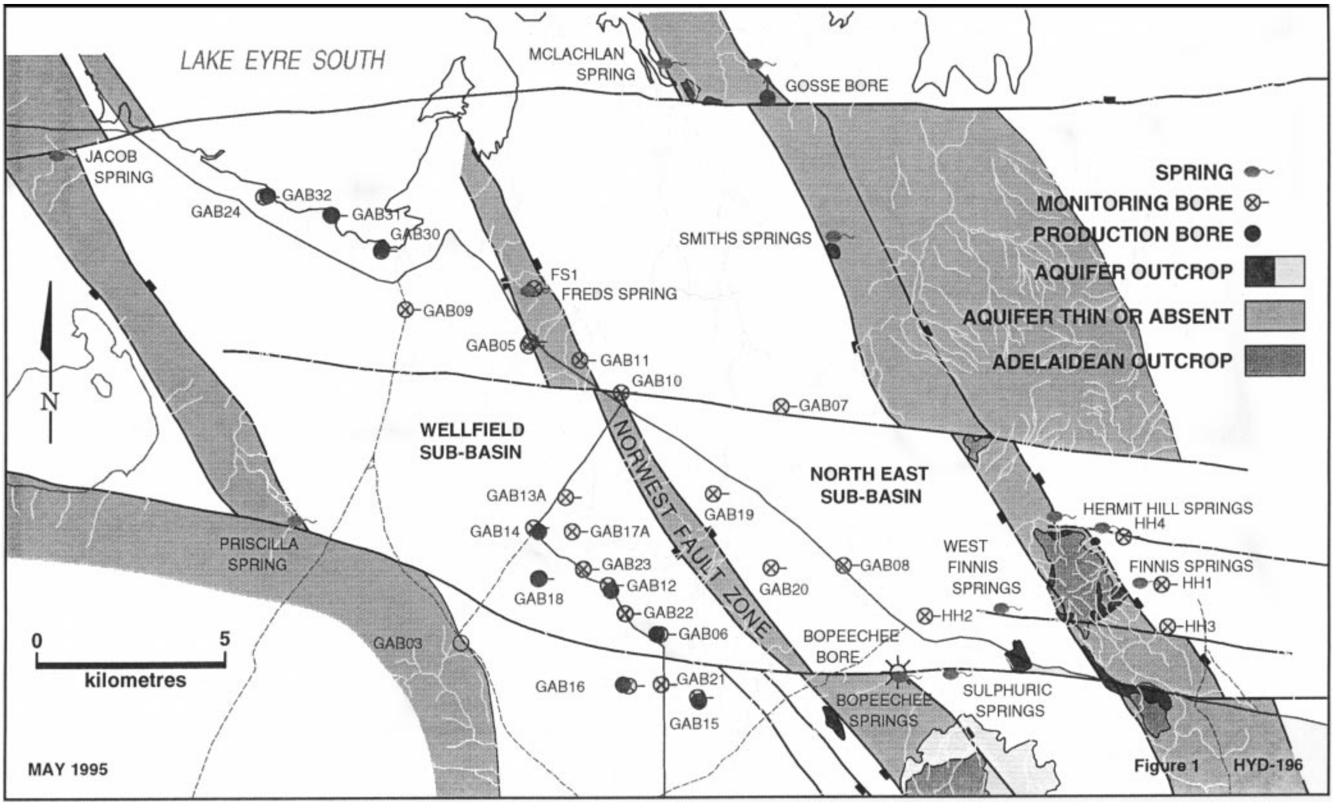


Fig. 7
Inferred and known faults in the borefield *A* region (Berry and Armstrong 1996)

itial mine construction in the mid-1980s, would not be able to supply the total demand for water of commercial mining operations and that Borefield B would be necessary for such a scale. The series of bores forming the southern and central regions of Borefield A were commissioned over 1987–1988, totalling about 10.8 ML/day (ODO 1992).

By the time of commissioning of the mine in August 1988, however, investigation, design and development of Borefield B was yet to begin. It was clear that the demand for water and the average extraction rate from Borefield A would exceed the original projection. A new proposal was approved by the South Australian government in 1991 to allow expansion of Borefield A with new limits on drawdowns at the designated boundary until construction of Borefield B (WMC 1995). Three new extraction bores were commissioned in January 1992 on the southern shores of Lake Eyre South (Kinhill 1995a).

Planning and investigation for the construction of Borefield B finally commenced in 1992 and field geophysics indicated that the original site would be unsuitable due to various constraints, such as no hydraulic barrier and excessive impacts on springs (Berry and Armstrong 1996). A new site was selected based upon existing exploration seismic data 50 km to the north-east of the original site (see Figure 6), where the GAB thickens and becomes more permeable (Berry and Armstrong 1996). Operation of the first bore from Borefield B began in November 1996, supplying approximately 9–10 ML/day and extraction from Borefield A was reduced to 5 to 6 ML/day (Kinhill 1997). A compilation of borefield extraction history is given in Table 3.

Predictive modelling of the impact of the borefields on the Lake Eyre region

There have been numerous computer modelling studies using the MODFLOW model (McDonald and Harbaugh 1988) that have attempted to predict and quantify the impacts of the various water-extraction scenarios imposed by the current borefields, and possible future borefield configurations. Although modelling on such a large regional scale presents many inherent complexities that are difficult to account for in numerical models, there are some important issues and aspects of the models that remain unresolved and these give rise to uncertainty in the predictions. These include:

- the approximation of the regional water table as a constant head layer, with no evaporative surface flux, despite this being known as a critical process around the southern extremities of the GAB – however, the inclusion of a variable water table influenced by floods and evaporative fluxes introduces significant errors in modelling (Berry and Armstrong 1995);
- there is very little quantitative field or laboratory assessment of the vertical permeability of the confining shale units, and thereby no accurate determinations of vertical leakage to verify model results;

Table 3
Average extraction rates from the Olympic Dam borefields (Kinhill 1997)

Years	Borefield A (Ml/day)				Borefield B (Ml/day)	Total (Ml/day)
	Southern	Central	Northern	Total		
1982–1986	1.30	0	0	1.30	0	1.30
1986–1987	2.30	0	0	2.30	0	2.30
1987–1988	2.34	2.08	0	4.42	0	4.42
1988–1989	4.27	4.56	0	8.83	0	8.83
1989–1990	5.68	4.30	0	9.98	0	9.98
1990–1991	6.25	4.39	0	10.64	0	10.64
1991–1992	5.67	4.39	1.57	11.63	0	11.63
1992–1993	5.60	3.98	3.01	12.59	0	12.59
1993–1994	4.50	3.14	4.46	12.10	0	12.10
1994–1995	4.72	4.37	4.43	13.52	0	13.52
1995–1996	4.67	5.40	4.92	14.99	0	14.99
1996–1997	n/a	n/a	n/a	6.9	7.8	15.20

- Borefield B is located deeper into the basin, and the regional water table which receives vertical leakage from GAB aquifers is subsequently deeper (usually at several tens of metres; Habermehl 1996b), indicating that the principle of harvesting vertical leakage otherwise lost to surface evaporation is fundamentally inappropriate. This deep phreatic surface conceals the vertical leakage (Habermehl 1996b). Woods (1990) clearly identified that diffuse discharge of vertical leakage only occurs in the marginal areas where the confining units are relatively thin, potentials are high and water tables shallow;
- impacts on spring flow are determined on the basis of reduction in artesian pressure only, not accounting for barometric effects or other factors known to influence spring flows. The Bopeechee and Hermit Hill spring complexes are fed from shallow and not deep GAB aquifers, and the assumption of artesian head driving spring flow may therefore be innaccurate (Berry 1995). Fatchen and Fatchen (1993) state that there is no clear relation between pressure head and spring flow.
- There is no discussion of how the Norwest Fault Zone is incorporated within the borefield model. Berry and Armstrong (1995) state that the hydraulic conductivity of the fault zone is thought to be approximately 2 m/day. The accurate treatment of faults generally requires the Horizontal Flow Barrier (HFB) package (Hsieh and Freckleton 1993).

Impacts on mound springs

By the early 1990s it was apparent that impacts on the mound springs were underestimated in Kinhill (1982), given in Table 4. By 1990 the spring vents at Priscilla and Venables had ceased flowing, and there were visible reductions in flows and wetland area at other spring complexes, notably Hermit Hill, Beatrice and Bopeechee (Keane 1997).

The assessment approach adopted by Kinhill (1997) for the expansion of Olympic Dam and the borefields was to compare all spring flow rates to 1996 levels, and not pre-borefield levels. It is unclear why this was done, but the relatively small changes presented do not compare favourably to the much larger changes from background flows. The predicted graphs of spring flows in Kinhill (1997) display downward trends after three years, with the relative reduction from 1996 levels ranging up to 17%.

Table 4
Reduction in Mound Spring flows – predicted and actual (Kinhill 1997). Predictions based on the northwest fault zone being impermeable or semi-permeable

Spring complex	Spring name	Predicted flow reductions (%)		Actual flow Reduction (%)
		Impermeable	Semipermeable	
Hermit Hill	Beatrice	100	100	40
	Bopeechee	<2	20	43
	Hermit Hill	<1	<1	36
	Old Finnis	<2	<2	Marginal increase
	Venable	100	100	100 (extinct May 1990)
Wangianna	Davenport	<1	<1	Close to 0
Lake Eyre	Emerald	3	3	Close to 0
	Fred	6	17	50
	Priscilla	75	60	100 (extinct late 1990)

Table 5
Select background and current spring flows (kL/day) compiled from Kinhill (1982), Lad (pers. comm.), and Annual Environmental Management Reports, (Mudd 1998). (Pastoral bores are adjacent to the former spring vents at Venables and Beatrice)

Spring	1974[a]	1981[b]	1985[c]	1988	1991	1992	1993	1996	1997
Venable (pastoral bore)	–	–	180	124	24.4	11.6	2.6	n/a	0.0
Hermit Hill Complex	130	30	45.4	31.1	36.3	36.9	37.1	30.2	–
Old Finnis	–	–	14.2	14.7	13.0	13.0	13.8	13.0	11.2
Beatrice (pastoral bore)	130	25	63.1	58.8	39.7	27.1	34.6	n/a	25.9
Bopeechee	130	25	54.4	42.5	33.7	33.5	31.7	24.2	13.9
Fred	40	10	15.6	4.3	9.1	4.7	12.0	n/a	–

[a] Includes flow and evapotranspiration
[b] Flow only
[c] Reference flows used for comparison

A comprehensive table has yet to be compiled comparing background, current and predicted flows from springs and bores, although background data is incomplete. A brief compilation is attempted in Table 5 for some of the more important springs, although it can only be considered indicative until a more thorough compilation of monitoring data is undertaken.

There are a number of complex mitigating factors in determining the reasons for the variability and reductions in spring flow. However, it is clear that the location and subsequent expansion of Borefield A in the midst of the springs hastened the demise of some springs and flow reductions in others.

Some key considerations in discerning the impact of Borefield A on the springs are:

- it was widely recognized at the time of the Draft EIS that there was a significant deficiency in the amount of knowledge and data on the hydrogeology of the southern margins of the GAB, especially the mound springs (e.g. Kinhill 1982; DEP 1983; DHAE 1983);
- original projections of spring flow reduction did not include a significantly expanded rate of extraction from Borefield A;
- flow across the northwest Fault zone was assumed to be impermeable, whereas operation of Borefield A demonstrated a degree of hydraulic connection (Berry and Armstrong 1995). It is hypothesised that the higher extraction rates created an increased pressure difference across the fault zone than early field testing and operation achieved, and thus the system was not stressed to the point of becoming permeable until Borefield A was expanded;
- the interpreted geological structure based on aerial photography presented in ODO (1993) shows that, like many springs across the GAB, several springs in the vicinity of Lake Eyre South are located directly above or near fault zones (e.g. McLachlan, Smith and Fred Springs) – suggesting that faults are at least semi-permeable across the region;
- the rehabilitation of pastoral bores in the Lake Eyre region is improving efficiency of water extracted for pastoral purposes, reducing demand from this source and associated impacts on spring flows (Sampson 1996);
- Woods (1990), using environmental isotope techniques to study the evaporative loss from the water table which receives vertical leakage from the GAB aquifer, concluded that the sustainable yield of Borefield A was approximately 9 ML/day (the average extraction during 1990 was 10.6 ML/day);
- pastoral bores are generally low yield bores spread diffusely across a large area while the borefields contain high yield bores in the concentrated region of the mound springs;
- the extraction of water by production bores is via pumps, thereby exacerbating drawdowns, whereas pastoral bores flow under natural artesian conditions;
- the volume of water extracted by the borefields represents a significant alteration to the water balance of the Lake Eyre region (see Table 2), with only 2 ML/day of spring flow and up to 15 ML/day for Borefield A. Further expansions of the borefields in the vicinity will exacerbate the impacts on the Lake Eyre region of the GAB.

The Bopeechee re-injection experiment

Due to the declining flow rates from the Bopeechee spring complex, near the southern bores of Borefield A, a limited re-injection experiment commenced in October 1995 (Kinhill 1997). The reason for the declining flow rates was thought to be hydraulic communication across the Norwest Fault Zone (Berry and Armstrong 1996). The flow decline at Bopeechee was sensitive to the total abstraction from Borefield A and not the location (Berry 1995).

The initial rate of re-injection was 2 L/S (173 kL/day), which was increased to 4.6 L/S (400 kL/day) in June 1996 (Kinhill 1997). Although there was a minor increase in artesian head in the general vicinity up to 1.43 m, this is masked by the reduction in extraction from Borefield A in late 1996 due to the startup of Borefield B. The flow rate at Bopeechee spring continued its decline until March 1996, but by June 1996 the flow was still only 6% higher than June 1995 (Kinhill 1997). At Bopeechee in 1997, it was observed that the number of spring vents had not increased and the wetland area still remained significantly reduced. The monitoring bores in the surrounding area also gave variable and ineffective conclusions (Kinhill 1997). The required environmental flows of the springs before the impact of the borefield were not achieved.

Alternative borefield configurations

It has long been recognized that continued overdevelopment of the GAB would lead to the extinction of flows at the mound springs. This scenario was first put forward by the Public Works Department in Queensland in 1954 when they assessed the sustainable supply of artesian water (DPW 1954), presented in Fig. 8 diagrammatically.
In other words, it suggests that before European development of the GAB, artesian pressures and spring flows were relatively high. As bores were developed around the margin of the GAB and gradually in the center, the overall artesian pressure begins to fall and spring flows decline, although initial artesian bore flows are reasonable. Finally, the GAB is developed with an extensive series of bores that each provide small relative flows, the artesian pressure of the GAB is exhausted and near ground level and there is no flow emanating from the mound springs.
The current situation in South Australia is approaching the final stage of the above prediction – one made 30 years before the construction of the Olympic Dam water supply borefields.
Despite the fundamental groundwater management principle outlined through Fig. 8, there is often very little focus on management of the resources of the Great Artesian Basin to sustain minimum environmental flows at the springs across the GAB. Hillier (1996) highlighted these concerns, although he also stressed that economics and high value uses of GAB water, such as pastoralism, mining and other industrial projects, would be the overriding management control.
There has been limited assessment of the effect of closing Borefield A on spring flow. These demonstrated that while Borefield B was still operating at full extraction capacity there would be no recovery of springs in the long-term, with flows predicted to remain low or decrease from 1996 levels by up to 17% (Kinhill 1995b; Berry and Armstrong 1995). This can be considered to be due to the decrease in artesian pressure to the north due to Borefield B and no effective recovery mechanism for artesian pressure around Borefield A.
The regional contours of transmissivity and GAB aquifer thickness presented in Berry and Armstrong (1995) and Armstrong and Berry (1997) show that a further 100–200 km to the north and northeast of Borefield B, the GAB aquifer is relatively thick at about 300–400 m, is more permeable and reaches a transmissivity of 3000–4000 m^2/day. The aquifer thickness and transmissivity at Borefield A ranges from 10 to 25 m and 20 to 200 m^2/day, respectively. A borefield located in this new region would likely result in relatively lower drawdowns and occupy a smaller area compared to that from Borefield A. The potential for drawdown effects on the springs is therefore smaller than the current location of Borefields A and B. A borefield located in this region would therefore be more sustainable for both spring flow and the long term life of the mine's water supply due to it's higher potential yield.
The prospect of a third borefield has been recognized with the current phase of expansion, and WMC will con-

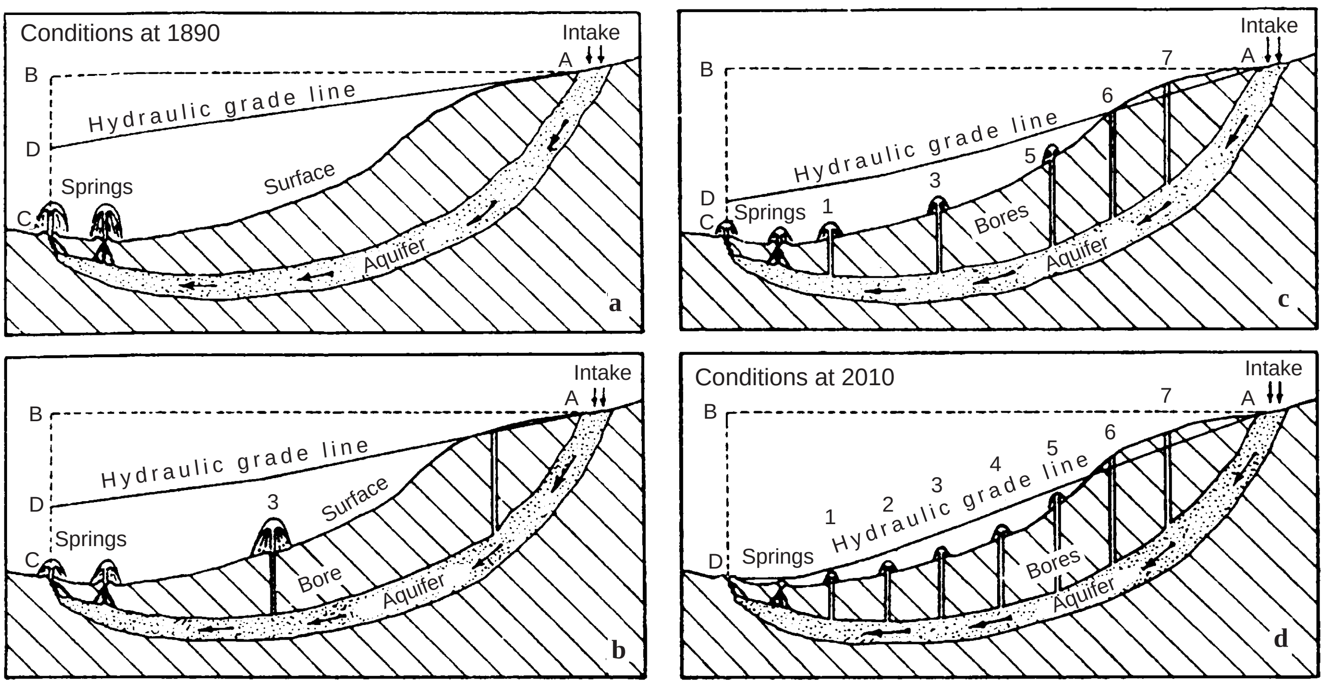


Fig. 8
GAB cross section: projection of bores, pressure and spring flow (DPW 1954)

sider constructing it further into the GAB (Kinhill 1997), as the properties just highlighted would suggest is appropriate. The data presented in Kinhill (1997) for water consumption at Olympic Dam suggest that water demand could range from 58 to 75 ML/day for the full expansion to the 350,000 tpa of copper level, almost twice the currently approved extraction rate (Keane 1997). This clearly suggests that there is a direct long-term need for a third borefield.

However, despite the more favourable hydrogeologic properties, a "Borefield C" would thus be at a further distance from the mine but the GAB aquifer is also deeper in this area. The overall costs of a new pipeline and deeper drilling could inhibit the timing and commitment by WMC to a new borefield. It is unclear whether Borefield A would be closed under this scenario.

To date there has been no public assessment of long-term impacts of the borefields on the resources of the Great Artesian Basin in the Lake Eyre region of South Australia for the probable duration of the Olympic Dam project. The modelling presented in Kinhill (1997) only examines a 20 year time frame. Olympic Dam is estimated to operate for at least 50–100 years, and the borefields are likely to remain its only economic source of water. Indeed, it is arguable that the project would not be viable if the GAB borefields were not avaiable. One pertinent point is that the spring flow projections in Kinhill (1997), at 20 years, are consistently declining as the impact of Borefield B dominates. There is a clear need for long-term modelling predictions to be made concerning impacts on spring flows, pastoral interests, and the time it would take for artesian pressures to recover in the region.

Conclusion and recommendations

The question of adverse environmental impacts on the springs from the operation of the water supply borefields for the Olympic Dam copper-uranium mine is complex. It is clear from available hydrogeologic data that the location of Borefield A in the midst of the Lake Eyre supergroup of mound springs has hastened the demise of some springs and exacerbated flow declines at others. No comprehensive data set yet exists documenting the long-term changes over recent time of the springs and the complex factors that influence spring behaviour. The 20-year projections of Kinhill (1997) still predict long-term flow decreases.

As the Olympic Dam Project is estimated to operate well in excess of 50 years, the environmentally sustainable supply of water for ongoing operations should be considered crucial in successful and pro-active environmental management. The construction of a large borefield in the midst of environmentally and culturally important mound springs, given the more hydrogeologically favourable sites to the northeast, should not be regarded as having environmental merit.

The way to ensure the long-term ecological integrity of mound springs and associated wildlife is to protect the quality and quantity of water flowing to individual springs – not based on averages over large spring groups which mask declines and impacts.

It is recommended that WMC :

- work towards the permanent and rapid closure of Borefield A;
- immediately commence studies into a new Borefield "C", located a further 100–200 km to the northeast of Borefield B;
- fund an independent assessment of the mound springs, including an extensive historical review and the impact of the borefields on the springs and GAB in the Lake Eyre region; and
- begin investigations for remedial options of all affected springs in the Lake Eyre region and initiate programs to ensure that background flows of all affected springs are achieved within a reasonable time frame.

This will ensure the ecological and mythological integrity of the mound springs for indigenous custodians and all future Australians, and that environmental flows and values are maintained sustainably.

Acknowledgements The author wishes to give special thanks to Ila Marks, Eric Miller, Linda Marks, Daniel Keane, David Noonan, Kevin Buzzacott, Kenny Buzzacott, Reg Dodd, Jan Whyte, Lyn Hovey, Al Lad, David Sweeney, Belinda Alexandrovics and Saleem Ali (MIT, USA) for their positive support of this research. Rien Habermehl (AGSO) helped with the water balance of the GAB, with much thanks. Steve Green (WMC) contributed internal WMC reports, with thanks. A helpful review by Samantha Meehan (Uni. of Melbourne) and Marie Westhaver (Baltimore, USA) helped to improve the clarity of the paper, and is gratefully acknowledged.

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