



Review: The evolving understanding of the Great Artesian Basin (Australia), from discovery to current hydrogeological interpretations

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Abstract

The Great Artesian Basin (GAB) in Australia underlies semi-arid and arid regions across 1.7 million km² or one-fifth of Australia. The basin's groundwater resources were discovered around 1880 and their development allowed pastoral activities, homestead and town water supplies, and petroleum and mining ventures to exist. The GAB is a multi-layered confined aquifer system, with aquifers in Jurassic and Cretaceous continental sandstones and intervening confining beds of siltstone and mudstone of the constituent Eromanga, Surat and Carpentaria sedimentary basins. The basin is up to 3,000 m thick and forms a large synclinal structure, uplifted and exposed along its eastern margin and tilted southwest. Recharge to the exposed aquifers occurs in the eastern margin, an area of relative high rainfall. The western margin in Australia's arid centre receives minor recharge. Regional groundwater flow is towards the southern, south-western, western and northern margins. Flowing artesian springs discharge in the southwest margin and have produced carbonate mounds. Although lateral groundwater movement dominates, vertical upwards leakage is considered important. Potentiometric surfaces of the Jurassic and Lower Cretaceous aquifers are still above ground level throughout most of the basin, though pressure drawdowns of up to 100 m have been recorded in recent decades in highly developed areas, and consequently some artesian water boreholes and springs have ceased flowing. Government borehole rehabilitation programs have led to groundwater pressure recovery in some areas. This paper outlines the history of GAB exploration, scientific investigations (hydrogeology, hydrochemistry, isotope hydrology, groundwater modelling) and management, summarising the recent knowledge on the GAB.

Keywords Australia · History of hydrogeology · Hydrochemistry · Isotope hydrology · Review

Great Artesian Basin (GAB): Australia's largest groundwater resource

General geological and hydrogeological features

The GAB is a confined groundwater basin, underlying about 1.7 million km², around one-fifth of Australia, within New

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South Wales (NSW), Queensland (QLD), South Australia (SA) and the Northern Territory (NT); (Fig. 1). Most of the basin underlies arid and semi-arid regions with low rainfall, while the most northern parts have high tropical seasonal rainfall. The basin's artesian groundwater resources were discovered in 1878, and their development and exploitation allowed the establishment of an important pastoral industry. Pastoral activity for free range sheep (wool) and beef cattle farming, homestead and town water supplies in these Australian Rangelands since the 1880s, petroleum ventures since the 1960s and mining activity within and outside the basin area since the 1970s/1980s, are all totally dependent on artesian groundwater from the basin.

The GAB is a multi-layered confined aquifer system, with artesian aquifers in Triassic, Jurassic and Cretaceous fluvial, fluvio-lacustrine and other continental and shallow marine quartzose sandstones (Figs. 2 and 3). Intervening confining beds or aquitards consist of Jurassic siltstone and mudstone,

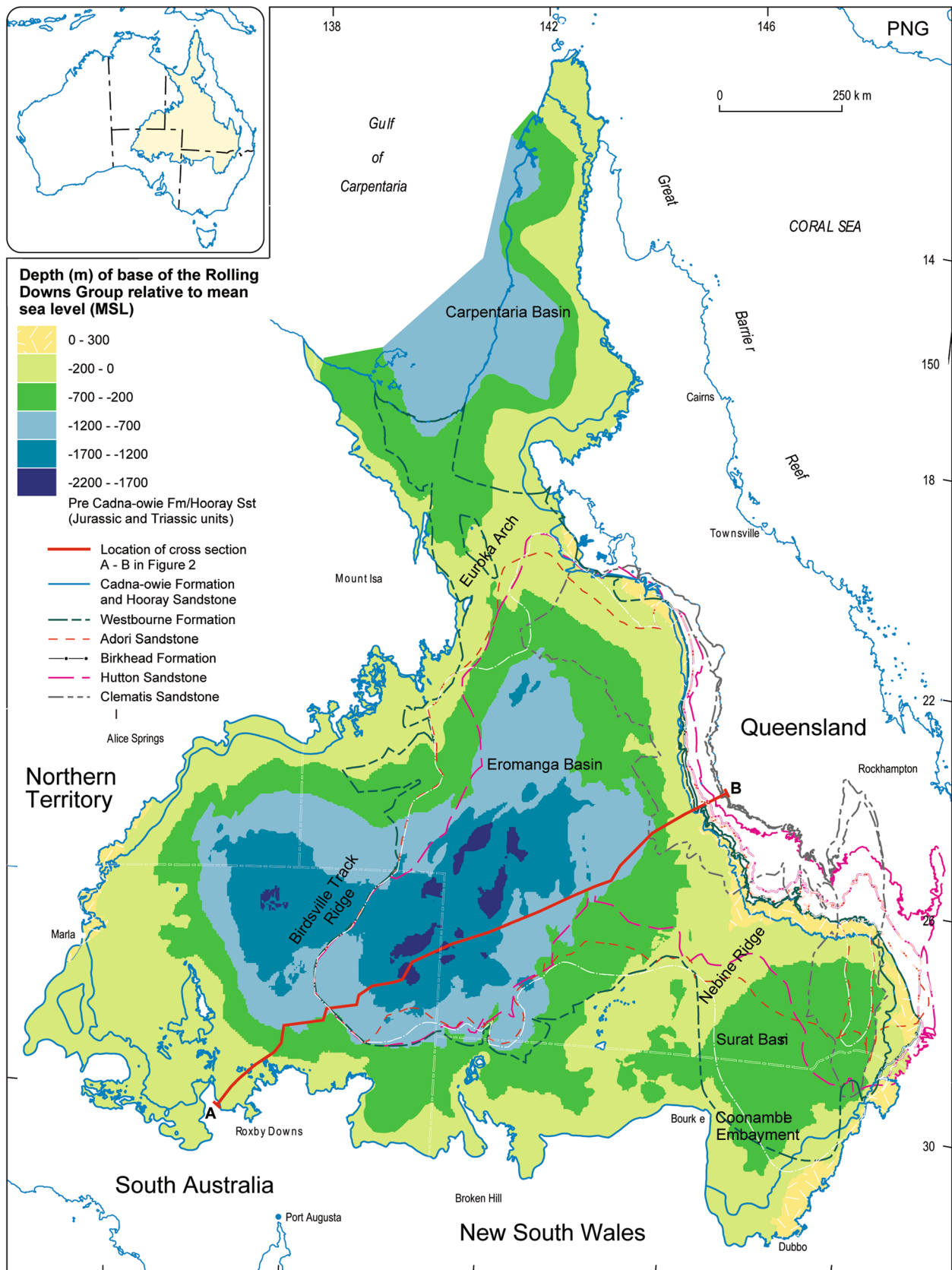


Fig. 1 Map of Australia showing the location of the Great Artesian Basin, extent of aquifers, and structure contours on the base of the Rolling Downs Group/top of the Cadna-owie Formation–Hooray Sandstone

(main tapped aquifer) and equivalents (after Habermehl 2001a, with permission from Geological Society of Australia)

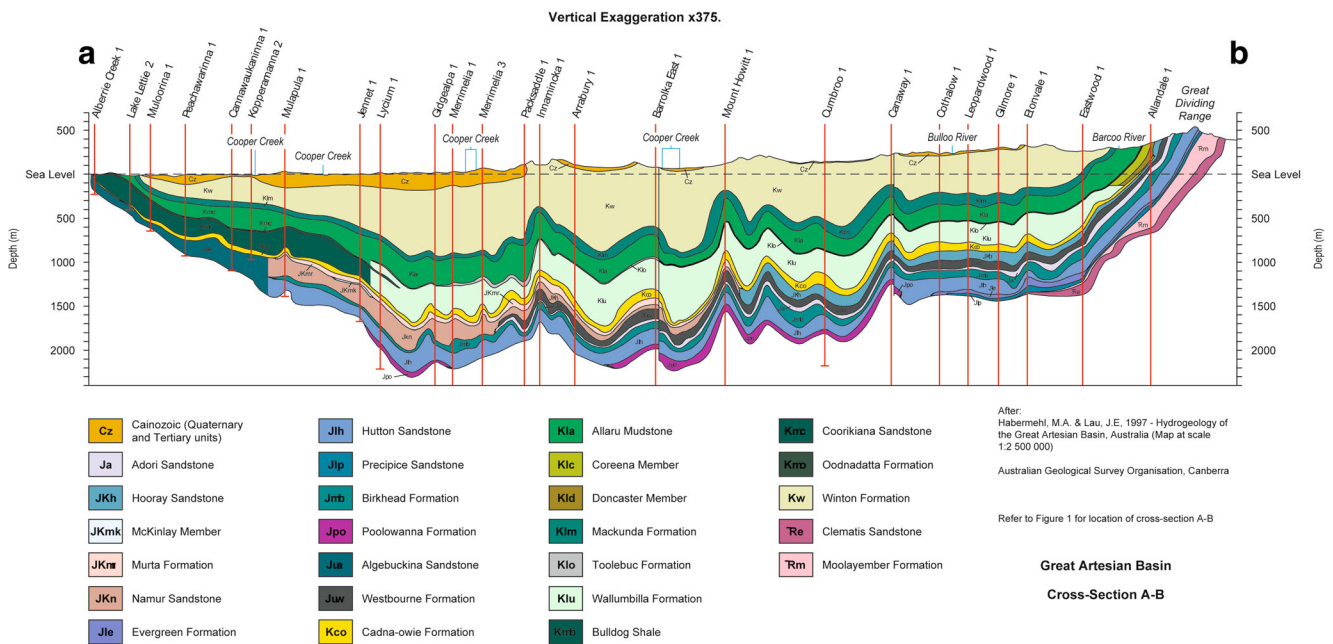


Fig. 2 Geological cross-section across the Great Artesian Basin (see Fig. 1 for location of the cross-section A–B) (after Habermehl and Lau 1997, with permission from Geoscience Australia)

and thick Cretaceous marine mudstone sediments form the main confining units (Habermehl 1980, 1986, 2001a, b, c; Habermehl and Lau 1997; Radke et al. 2000; Ransley et al. 2015; Smerdon et al. 2012b). The sedimentary sequence of the basin is up to 3,000 m thick, and forms a large synclinal structure, uplifted and exposed along its eastern margin since the Late Cretaceous and early Tertiary.

The GAB comprises the sedimentary Eromanga, Surat and Carpentaria basins, which represent individual depocentres (Figs. 1 and 4). Many of the sedimentary units, including the main aquifer units, extend across these basins and are connected across regional basement highs or ridges separating the sedimentary basins. The original correlation of the geological and hydrogeological units shown in Habermehl (1980), was updated by Habermehl and Lau (1997), Radke et al. (2000), Smerdon et al. (2012b) and Ransley et al. (2015).

Most recharge to the aquifers occurs predominantly in the eastern marginal areas, where the main aquifers are exposed or subcrop (McMahon et al. 2002; Kellett et al. 2003; Habermehl et al. 2009). This area, largely on the western slopes of the Great Dividing Range, has relative high rainfall (up to 500–600 mm median annual rainfall), whereas the western margin in the arid centre of the continent receives minor recharge (Keppel et al. 2013). Average annual Class A pan evaporation ranges from 2,000 mm in the eastern parts to 3,600 mm in the Simpson Desert area, in the western part. Regional groundwater movement in the aquifers (Fig. 5) is towards the southern, southwestern, western and northern margins, where artesian springs provide natural discharges (Fig. 4; Habermehl 2001a, Smerdon et al. 2012b). Vertical upwards leakage from the confined aquifers up into and through the confining beds is important. Many springs

produce sedimentary spring deposits, forming conical tufa carbonate mounds and extensive plateaus. Springs also occur in other parts of the basin and downgradient of the main recharge areas (Fig. 4). Many springs contain unique flora and fauna (Fensham et al. 2010, 2016; Gotch 2006, 2013) and were known to Aboriginals as assured sources of water in the arid areas.

Residence or travel times of artesian groundwater range from almost recent, in the recharge areas, to more than 1 million years near the centre of the basin. The artesian groundwater origin is meteoric, which mainly recharged the basin’s aquifers in the elevated eastern outcrop and subcrop areas (Bentley et al. 1986; Calf and Habermehl 1984; Hasegawa et al. 2016; Mahara et al. 2009; Torgersen et al. 1991).

Artesian springs and areas of seepage are abundant in the marginal areas of the basin, especially in the southern and southwestern discharge areas, and near the eastern recharge areas (Fig. 4). The largest concentration of springs and their sedimentary deposits, mainly tufa carbonates, occur near the southwestern margins (Fig. 4; Habermehl 1980, 1982b, 2001a; Keppel et al. 2011). Spring complexes have developed over several climatic cycles and age dating of spring deposits show age ranges up to 740,000 ± 120,000 years, with some springs probably being older (Prescott and Habermehl 2008; Priestley et al. 2018).

Groundwater exploitation

About 4,700 flowing artesian water boreholes (waterbores) were drilled up until the early 1970s into the main tapped Lower Cretaceous–Jurassic aquifers, i.e. the Cadna-owie Formation and Hooray Sandstone, which underlie the

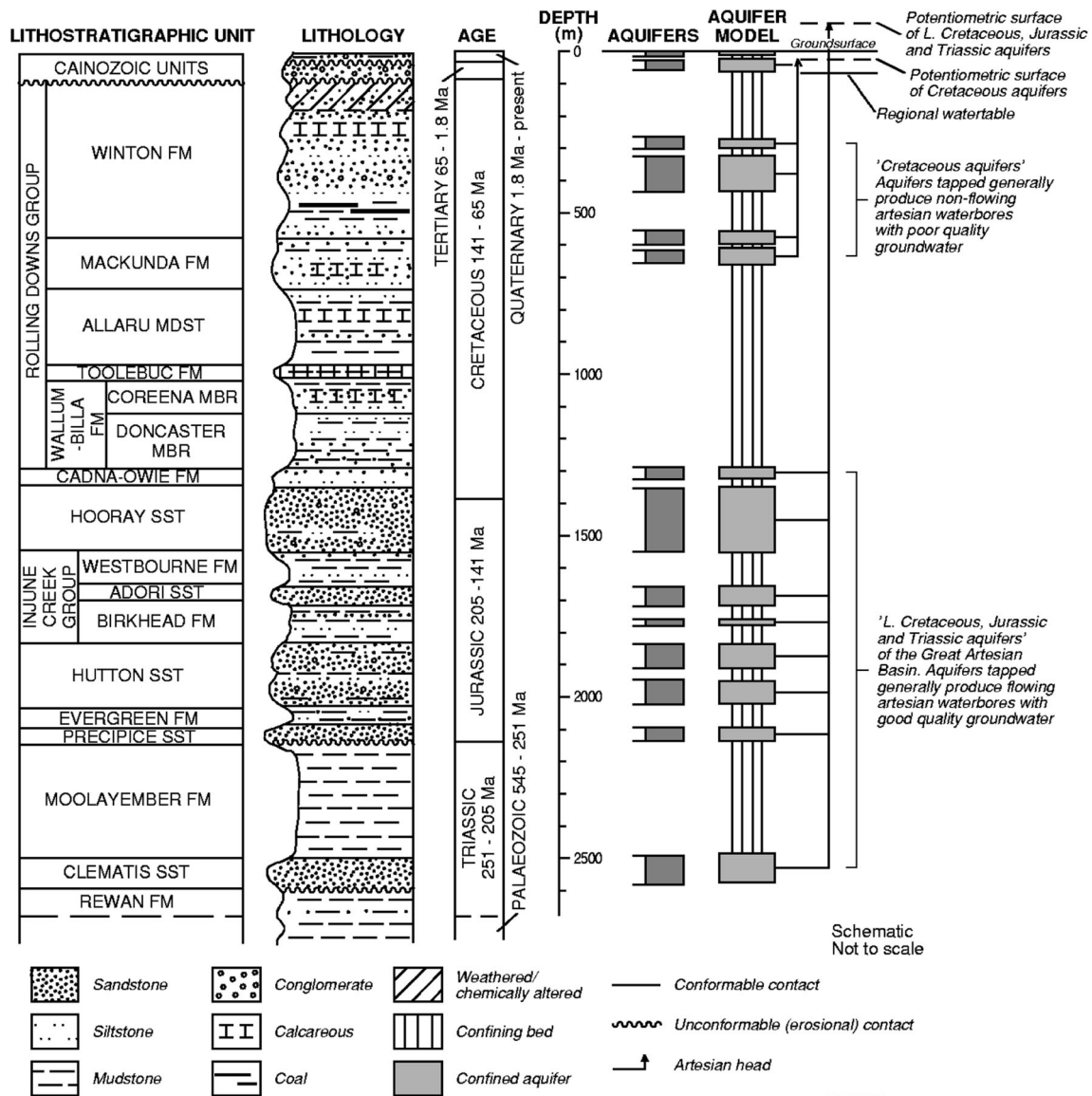


Fig. 3 Lithostratigraphic column and aquifers of the Great Artesian Basin, based on the central Eromanga Basin location (after Habermehl 1980, with permission from Geoscience Australia)

predominantly mudstones of the Cretaceous Rolling Downs Group (Figs. 1, 2 and 3); bore depths are up to 2,000 m and average about 500 m. A census of all bores in the basin in 2015 (GABCC 2017) shows the total number of drill-holes into and through the basin at 50,508, with 75% (37881) being for water supply. There are 6,629 flowing artesian water supply bores drilled in artesian or previously artesian areas; however, 2,748 of these were drilled before 1960, prior to the requirements to cap flowing artesian supplies, and before pressure cementing of the steel bore casings was widely adopted. The latter bores could therefore be at risk of failure as the casings could corrode (GABCC 2017). Potentiometric surfaces of the Triassic, Jurassic and Early Cretaceous aquifers are still above ground level in most of the basin area, though pressure drawdowns of up to 100 m were recorded from the 1880s to the late 1900s and

early 2000s in some relatively densely developed areas (Habermehl 1980, 2001a, b, Habermehl and Lau 1997). Free flowing artesian waterbores of the pastoral industry, and for homesteads and town water supplies caused this drawdown. Bore discharges peaked at about 2,000 ML/day around 1918. About 3,100 controlled and uncontrolled flowing artesian waterbores (of the original 4,700) remained flowing with an accumulated discharge of 1,500 ML/day in the 1970–1980 period (Habermehl 1980). About 25,000 non-flowing artesian (so-called sub-artesian) waterbores (generally using windmill-, diesel- or solar-operated pumps) tap shallower Cretaceous and Jurassic aquifers with little or no artesian flows. Large-scale waterbore development and the ensuing lowered artesian pressures in many parts of the basin during the last 140 years resulted in some flowing artesian waterbores to cease flowing,

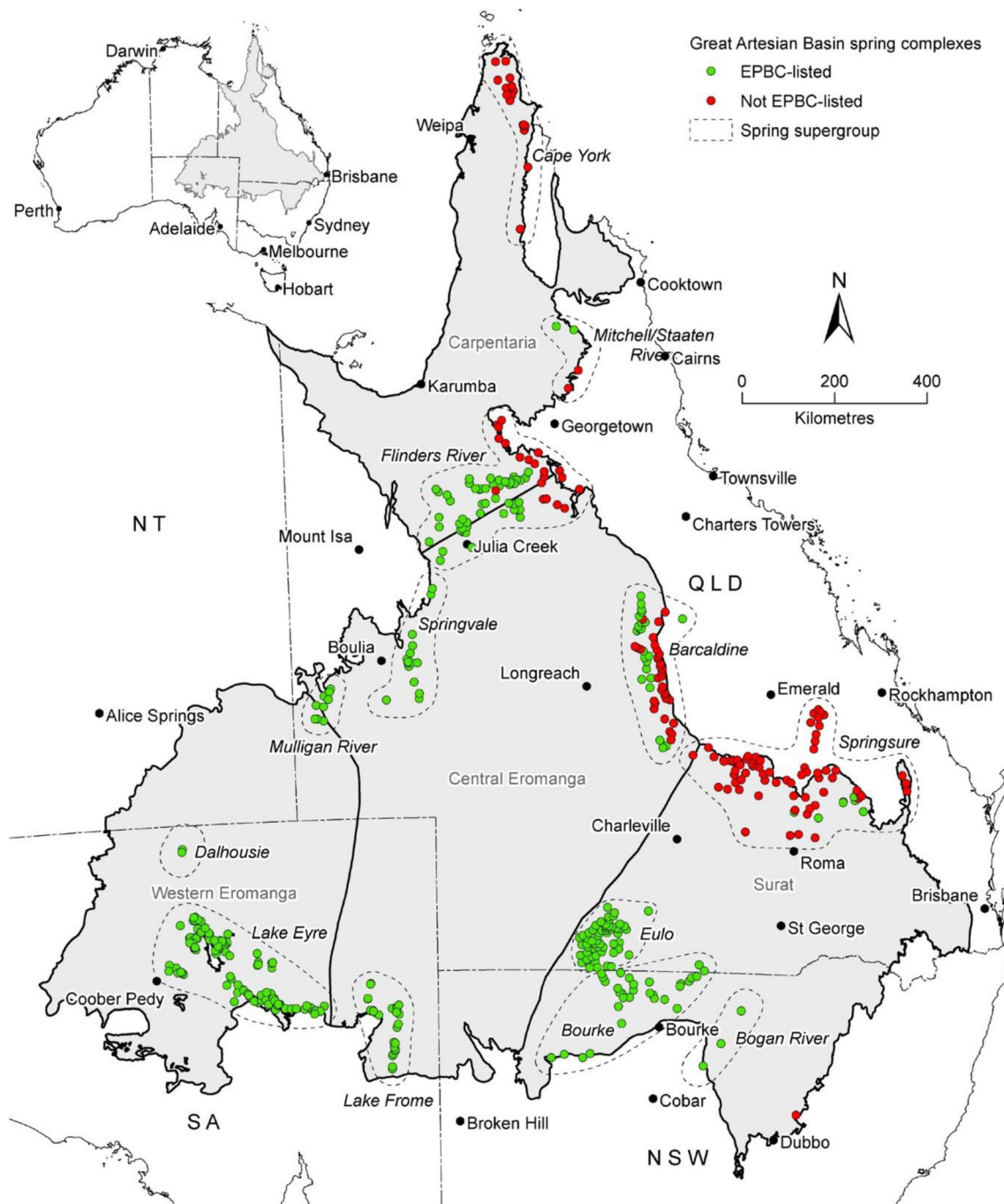


Fig. 4 Location of flowing artesian springs and spring groups. EPBC refers to the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 and 2013, which provides protection for the GAB spring. (after Smerdon et al. 2012a, b, with permission from CSIRO, CSIRO Australia)

requiring groundwater to be pumped. The wide-spread draw-downs also caused declines in spring discharges, and in some areas springs have ceased to flow.

Groundwater quality

Groundwater quality of the main Lower Cretaceous–Jurassic aquifers is characterised by low salinity at 500–1,500 mg/L total dissolved solids (Habermehl 2001a, Hasegawa et al. 2016;

Radke et al. 2000; Mahara et al. 2009). Groundwater in most of the basin is of the Na-HCO₃-Cl type (Fig. 6) and is suitable for town water supply, and domestic and stock use. It is unsuitable for irrigation in most areas, as the hydrochemistry of the groundwater and the montmorillonite clays at the ground surface in many parts of the basin are incompatible and lead to cementation of the surface. The southwestern part of the basin contains Na-Cl-SO₄ type water (Habermehl 1980, 1986, 2001a; Radke et al. 2000; Love et al. 2013). Total dissolved solids increase down-

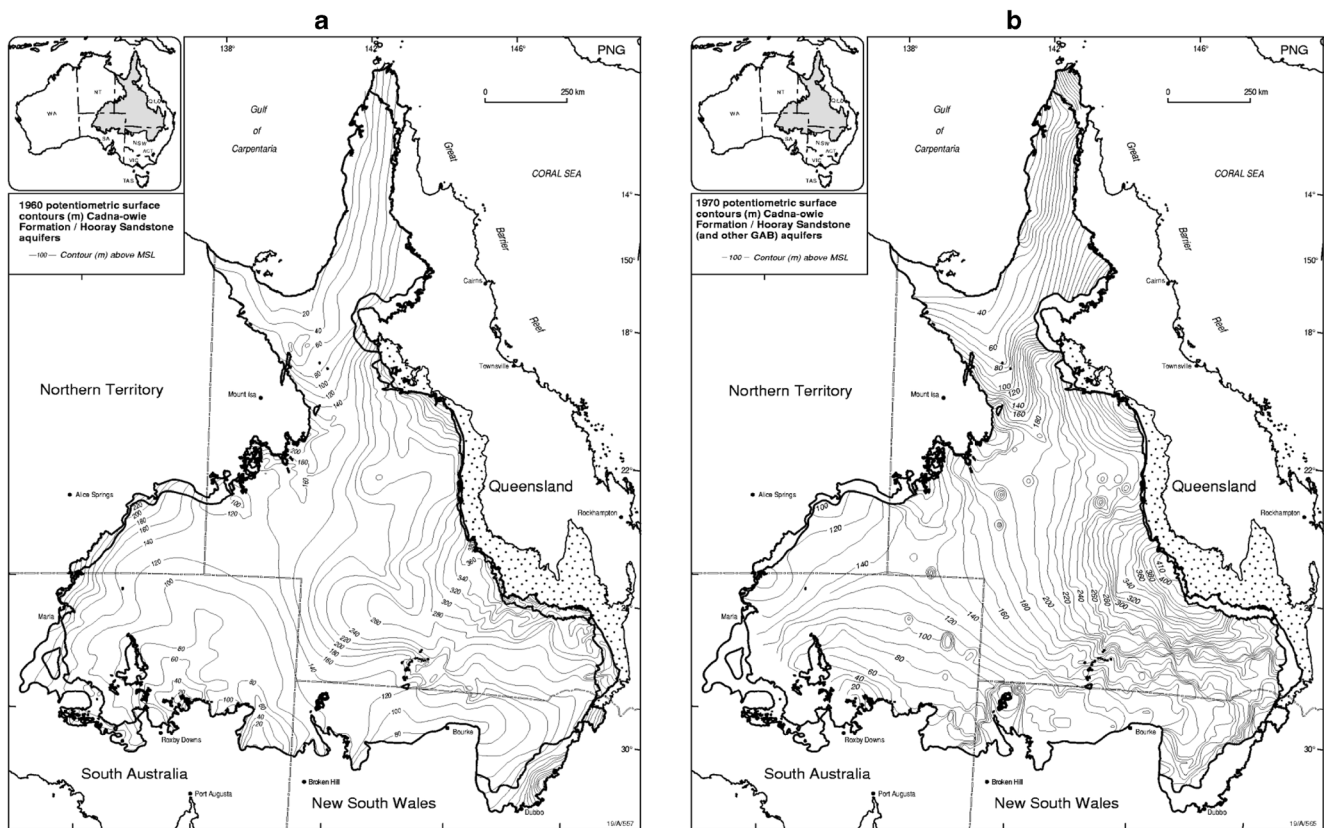


Fig. 5 **a** Potentiometric surface 1960, Cadna-owie Formation–Hooray Sandstone aquifers (after Welsh 2000, with permission from Aust. Govt. Dept. Agriculture and Water Resources). **b** Potentiometric surface

1970, Cadna-owie Formation–Hooray Sandstone aquifers (after Habermehl 1980, with permission from Geoscience Australia)

gradient along the groundwater flowlines. The main tapped artesian aquifers in the Lower Cretaceous–Jurassic sequence contain better quality groundwater than the Cretaceous aquifers, the latter of which have higher salinity water. Deeper aquifers in the Jurassic sequence contain low salinity quality groundwater.

Groundwater temperatures at the bore-heads range from 30 to 100 °C, and are potential geothermal energy sources (Habermehl and Pestov 2002)—for example, the town of Birdsville (in Queensland) has a geothermal electricity power plant. High-pressure flows from a number of flowing artesian bores at some pastoral stations (farms) in Queensland and SA have been equipped with turbines to generate electricity for households, buildings and for sheep shearing sheds. Artesian groundwater temperatures from springs range from about 20 to 45 °C.

Groundwater for domestic use, towns and pastoral industries, and petroleum and mining industries

The development of the artesian groundwater resources of the GAB since the 1880s include aspects of sustainable groundwater use, and groundwater and rangelands management (Cox and Barron 1998, GABCC 2000; Habermehl 2018). The extraction of artesian groundwater for the pastoral industries has affected the basin through large-scale drawdowns, reducing

artesian pressures, which had been up to 100–200 m above the ground surface in some areas (Radke et al. 2000), and reducing discharges from artesian springs and waterbores. These facts were recognised early in the twentieth century, but only effectively acknowledged, investigated and dealt with in the last few decades. Many of the artesian springs throughout the basin have unique flora and fauna and are easily affected by the drawdown of the potentiometric surface and reduced outflows or extinction (Fensham and Fairfax 2003; Fensham et al. 2010). Most of the artesian groundwater from pastoral waterbores was distributed through open earth drains (commonly referred to as “bore drains”). The bore drains are up to 100 km in length, and have a total length of approximately 34,000 km. The introduction of waterbores and bore drains provided a large amount of water, and this has had a significant impact on the flora and fauna in the region, with major changes to the biodiversity (Landsberg et al. 1997; Noble et al. 1998). The inefficient bore-drain distribution system causes wastage of more than 95% of the groundwater produced, and has resulted in land degradation, erosion, salinisation, the spread of introduced weeds, plants and trees, and large increases of feral and native animals. Polyethylene piping has replaced many bore drains during the last 30 years, particularly as part of government-initiated programs, which

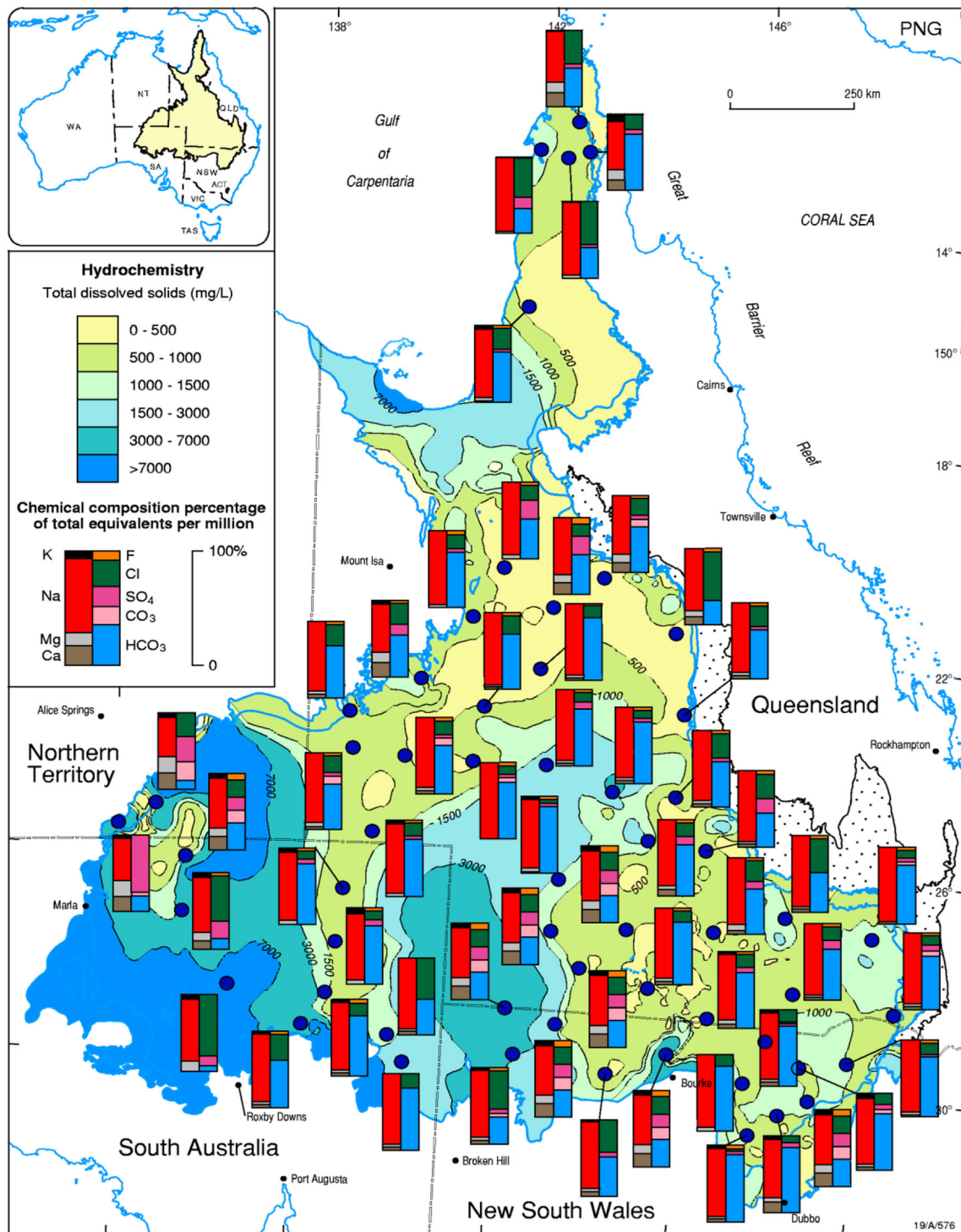


Fig. 6 Groundwater quality (total dissolved solids) and major ion hydrochemistry (chemical composition of groundwater) of selected flowing artesian waterbore in the Great Artesian Basin aquifer Cadna-

owie Formation–Hooray Sandstone (after Habermehl and Lau 1997, with permission from Geoscience Australia)

are described in detail later in the paper. These programs resulted in recovery of artesian pressures.

The Jurassic and Cretaceous sedimentary sequence in the basin and underlying Late Carboniferous to Triassic rocks of the underlying Cooper Basin comprise abundant hydrocarbon

reservoir and source rocks, and commercial and sub-commercial oil and gas is produced in north-eastern South Australia and southwestern and eastern Queensland. It was earlier assumed that the basin-wide groundwater through-flow had flushed out hydrocarbons from the Jurassic and

Cretaceous rocks (Habermehl 1986; Senior and Habermehl 1980; Williams and Moriarty 1986). The development of the petroleum resources in the basin since the 1960s added to the production and use of artesian groundwater, which is also extracted as part of oil and gas production (i.e. co-production). Prior to that date, artesian groundwater withdrawal was mainly for pastoral, homestead and town water supplies. More recently, coal seam gas (CSG) developments in southeast Queensland, since the early 2000s, co-produce groundwater mainly from the lower parts of the Jurassic, Triassic and Permian sequence of the Surat and Bowen Basins. CSG activities affect artesian groundwater flow to waterbores and springs in the area (Geoscience Australia and Habermehl 2010).

Mineral discoveries inside and outside the basin area since the mid-1970s and 1980s resulted in mining operations in mid-Proterozoic rocks and new (mining) towns using the artesian groundwater, in particular from the two GAB borefields of the Olympic Dam mine (copper, uranium, gold and silver) in SA. Other base metal mines using the basin's artesian groundwater include: the Cannington, Osborne and Ernest Henry mines (base metals, copper and gold) in northwest Queensland; bauxite mines near Weipa, in northern Queensland; copper, gold, uranium and silver mines located near the SW Basin margin (SA); and, small opal mines located in Queensland, NSW and SA.

Climate and land use

The GAB underlies low-lying interior plains, bounded in the east by tablelands and uplands of the Great Dividing Range, which runs from north to south inland of the east coast of Australia. Summits in the Great Dividing Range vary from 600 to 900 m above sea level in the northern areas and 1,200 to 1,500 m in the southern areas. The ground surface slopes towards the western and south-western regions, with the main depression of Lake Eyre (most of the time being a dry salt pan), which is at its deepest point 16 m below mean sea level, being the focus of the internal surface drainage of much of the basin area. Bordering the eastern divide are stony lowlands, erosional landscapes with mesas and tablelands capped by duricrusts. The inner, low-lying parts of the interior lowlands are flood plains of anastomosing rivers, forming depositional landforms and towards the south-west, dune fields of parallel aeolian sand ridges of the Simpson Desert. The GAB is partially overlain by surface-water basins, including for a large part by the river systems and lakes of the Murray-Darling Basin (MDB) in Queensland, NSW and SA and the river systems and lakes of the Lake Eyre Basin in Queensland, NSW, SA and NT.

The GAB is located in the arid and semi-arid parts of Australia, where very dry hot to warm climates predominate, with more temperate climates present in the eastern and southern parts. The most northern parts have high rainfall (tropical) in summer (December–February) and

are dry in winter (June–August). Average annual rainfall ranges from (less than) 100 mm in the Simpson Desert in the western part to 600 mm in the eastern Basin margin in the Great Dividing Range. Seasonal distribution is marked by a relatively dry winter and wet summer. Average annual temperatures throughout the basin area range from 18 to 24 °C, with highest temperatures in the north. The annual temperature range is usually more than 30 °C, and extreme air temperatures can reach 50 °C in the central and western parts. Annual average potential evaporation throughout the basin is high and reaches a maximum of about 3,600 mm/year in northern SA.

Ephemeral rivers draining the Great Dividing Range generally flow south-westwards through stretches of plains at below 150–100 m elevation, with very low relief of less than 30 m. Streams in the basin area show extreme variation in discharge and flow duration. Very variable seasonal and annual streamflow patterns are caused by occasional tropical cyclonic and summer monsoonal rainfall moving inland. In most areas, extended droughts, some lasting for many years, alternate with major, long-lasting floods.

Nearly all nondesert parts of the GAB area are used for low-intensity livestock grazing of sheep for wool and beef cattle. In the basin's most eastern and south-eastern parts more intensive land-use includes wheat and sheep farming, cereal and cotton production. The parallel sand dunes in the Simpson Desert in the western part are too dry and difficult terrain to access for any productive use. The early years of occupation were characterised by overestimation of the grazing capacity of the land, and rapid extension in stock numbers occurred as watering points (bores) increased. Severe droughts in these arid and semi-arid regions caused declines in carrying capacity, as well as deterioration of the native pastures and soil erosion. Stable stocking rates were established after reassessment of the fact that droughts were the rule rather than the exception. Very variable rainfall is the most important factor for provision of feed, and therefore adverse rather than favourable seasons determine stocking rates. Grazing capacity is also directly related to the distribution of watering points and, with little surface water available, stock is mostly dependent on artesian bores and excavated tanks. Crop growing in the south-eastern areas is dependent on surface water or shallow groundwater and irrigation water derived from surface water. Artesian groundwater is seldom used for irrigation, as the chemical compatibility of the groundwater and the dominant soil restricts its use, as well as the quantities required.

The basin has an estimated population of approximately 100,000 people. A total of 70 widely distributed towns, mainly in the eastern and south-eastern areas, have populations ranging from 100s to 10,000s of people. A small number of people live on the widespread cattle and sheep stations (farms), which are usually large in size (up to 30,000 km²).

Discovery in 1878, early development and emerging geological and hydrogeological knowledge

Discovery and development

Artesian water in the GAB area was first discovered in a dug shallow waterwell near the Wee Wattah spring at Kallara Station, southwest of Bourke, NSW, in 1878. It was also found at Anna Creek in 1881, west of Lake Eyre, SA, also near artesian springs. Drilling provided artesian flows at Thurrulgoonia near Cunnamulla, Queensland in 1887, at the towns of Barcaldine in 1887 and at Blackall in 1888 (Queensland Government 1954). Early work around the 1880s suggested that meteoric water infiltrated the western slopes of the Great Dividing Range (Rawlinson 1878; Russell 1880, 1889; Tate 1882; references in Habermehl 1980) and that artesian springs near Lake Eyre indicated artesian water could be found across most of central and eastern inland Australia (references in Habermehl 1980, 1982a). Geological investigations were led by Jack in 1881 and 1885 (references listed as ‘Jack 1895a,b’ and ‘Jack 1898’ in Habermehl 1980) to conclude that a large synclinal trough existed in western Queensland, in which pervious beds occurred with artesian groundwater. In Queensland, several non-flowing and flowing artesian bores were drilled in several locations during the 1880s, and bores were also drilled in SA along the Birdsville Track, and in NSW in the area west of Bourke. Drilling for stock, domestic and town water supplies expanded rapidly from the 1880s onwards (reference ‘Russell 1889’ in Habermehl 1980). Some general historical information is shown in Blake and Cook (2006) and Jeffcoat (1988).

Geological mapping of the intake beds in Queensland and NSW, and along the basin margins, was combined with the information from drill-holes. This enabled Pittman and others (reference ‘Pittman 1914’ in Habermehl 1980, 1982a) to establish that the Lower Cretaceous sedimentary sequence contained significant artesian groundwater supplies and assisted in the determination of the shape and size of the basin. By the end of the nineteenth century the basin was accepted by many as a classic artesian groundwater basin.

Pressure data obtained from flowing artesian bores during government field surveys confirmed the theory, though controversy remained as to whether the pressure head was hydraulic or hydrostatic. This difference in hydrodynamic conditions of the basin was important, as it would assist in predicting the effects of the already occurring decrease in artesian flow and pressure of artesian bores. The interpretations of the origin and movement of the artesian groundwater were attacked by Gregory (reference ‘Gregory 1906’ in Habermehl 1980), who attributed the groundwater having connate or plutonic origins, and the movement caused by heat, gas and rock pressure. His theories were supported by

several others, but were skilfully refuted by defendants of the meteoric and hydraulic theory. The latter theory gained ground and became generally accepted, though the controversy lasted almost 20 years during the first years of the twentieth century, and inspired increased research in the basin. However, in recent years, Mazor (1995) and Endersbee (2005) also provided alternative theories of groundwater movement of artesian groundwater, i.e. respectively stagnant aquifers, hydraulically isolated from each other, and a plutonic origin of the groundwater in the GAB. Both of these theories are also generally discarded.

Early legislation and control: late 1800s–early 1900s

The individual (sovereign) colonies changed to states in Australia when they federated under the “Commonwealth of Australia” in 1901. The Commonwealth has only been involved in the development of water resources in cooperation with the states since the Australian Water Resources Council (AWRC) was established in 1962. The Commonwealth’s role has expanded since, in cooperation with the states, particularly as a funding agent.

In Queensland an attempt was made in 1891 to introduce government control on groundwater, but the legislation was rejected and not passed until 1910. The delay was the result of insufficient knowledge on whether the resource was limited and would not last, or would be abundant. The initial private endeavours of developing bores by pastoralists in the far western undeveloped regions were against the proposed introduction of stringent provisions for water conservation by government authorities, and there were politicians on both sides of the arguments. It was eventually recognised that the state was the “owner” of all resources, and that much water was running to waste (Powell 1991).

In NSW control was attempted in acts introduced in 1894, 1897 and 1906, but was not achieved until 1912. Once legislation became effective, control was enforced and systematic measurements made by existing and newly formed State Water Authorities in Queensland and NSW, yet in SA no real control was exercised until a more comprehensive Water Resources Act was introduced in 1976 (GABCC 1998).

In the late 1800s to early 1900s information about artesian bores, especially concerning the diminishing flows, had already been gathered intermittently by state authorities, but was incomplete. Only after legislation had been passed did official regular inspection and collection of data begin, which continues to the present day. The new legislation provided for bores to be licensed, all relevant details to be submitted to the state authority, the casing and headworks to be completed according to prescribed standards, construction and purpose of the bore to be specified, and definition of volumetric allocation and distribution works. Bores were to be constructed by suitably licensed (artesian) drillers. Bore owners were

responsible for the maintenance of all bores, including casing, headworks and distribution networks. Nearly all bores in the basin are lined with steel casing, and privately owned.

Five interstate conferences on artesian water (ICAW) 1912–1928

Systematic investigations of the groundwater conditions in the GAB increased markedly as a result of the five interstate conferences on artesian water (ICAW) held in 1912, 1914, 1921, 1924 and 1928 (references in Habermehl 1980). The ICAW were originally called to study the reduction in pressure and diminution or cessation of artesian flows, the extent of the basin, the origin and movement of the artesian water, and the corrosion problems of bore casings and to inquire into better utilisation of the groundwater (Habermehl 1980, 1982a, 2018).

The reports of the first and second conferences are mainly concerned with the collection of information and the verbal presentations of the delegates and pastoralists, bore owners, drillers, engineers, chemists and administrators of the state authorities in Queensland, NSW and SA during this period. The reports of the third, fourth and fifth conferences record submissions by representatives of the state authorities (geologists and engineers), who presented detailed data about the basin, the bores, and progress in local (state) investigations. The accompanying geological and potentiometric maps, cross-sections, tables with bore data, groundwater temperatures, chemical analyses results and other information, show the improvement of knowledge of the basin during the years. The conferences provided a better scientific understanding and led towards issues of management and governance of the basin's groundwater resources (Habermehl 1980, 1982a, 2018).

No further meetings were held until 1939, when an Interstate Conference on Water Conservation and Irrigation (reference 'ICWCI 1939' in Habermehl 1980) met in Sydney, which was concerned with most aspects of surface and groundwater, and not confined to artesian water in Australia. Discussion concentrated on the diminution and control of flow from bores and the improvement in distribution. It was recognised that the wastage of water from flowing artesian bores was the main problem in the GAB (Habermehl 1980, 1982a, 2018).

Geology and groundwater hydrology investigations and reports by the states 1920s–1960s

Geology investigations

Systematic surveys of the geology and of hydrogeological investigations continued to be carried out by states. State

water authorities and state geological surveys in Queensland, NSW and SA participated during this period. Reports and publications contain geology, hydrogeology, groundwater hydrology and chemical characteristics, together with geological maps and sections, potentiometric maps, graphs and diagrams, calculations and interpretations on bore discharges, aquifer permeability, recharge and flowrates. Newer theories, which became available during this period, including elastic storage, were applied. Recommendations were made on water conservation by the partial closing of bores and improved distribution methods. Habermehl (1980, 1982a) provides a comprehensive review of the GAB as a whole, including all key references reflecting geological and hydrogeological investigations in the basin until then.

Groundwater investigations

In Queensland, which contains the largest part of the basin, a major investigation by geologists and hydraulic engineers started in 1939 on the GAB's nature and structure. They produced a first interim report in 1945 (reference 'Queensland Government 1945' in Habermehl 1980). The final report by the Artesian Water Investigation Committee was produced in 1954, and formed the most comprehensive description of detailed investigations on the hydrogeology of the Queensland part of the basin (reference 'Queensland Government, 1954' in Habermehl 1980). Appendices, which were published separately, provide detailed descriptions of the geology (reference 'Whitehouse 1954' in Habermehl 1980) and groundwater hydrology (reference 'Ogilvie 1954' in Habermehl 1980). That report includes recommendations concerning the proper use, regulation and control of groundwater from bores, and the suggestion not to enter into strict conservation of flows from existing bores. An assessment in the report of recharge and discharge by bores showed that the artesian diminution was not considered a threat, only a disability, as recharge occurred and groundwater would always be available at pumping depths where bores ceased flowing. The report also contains a summary of legislative history relating to the GAB artesian water in Queensland (references 'Queensland Government 1954' and 'Ogilvie 1954' in Habermehl 1980). Predictions were made about the number of bores which would cease flowing during the 50–60 years following the report date in addition to bores which already had stopped flowing, and the number of bores which would continue to flow forever with reduced yields. Restrictions on bore discharges, and the use of efficient distribution systems had already led to conservation of water, which would be improved even further by flow restrictions and bore re-conditioning, and by the use of piping.

The report states that the quality of the artesian groundwater (with its predominance of Na-HCO₃) is unsuitable for prolonged irrigation on most of the (montmorillonite) soils. It was considered that domestic and stock requirements should

have priority, and that no artesian groundwater should be used for irrigation unless surplus water was available. The report contents formed a basis upon which a state policy for the use and conservation of groundwater was defined, and led to recommendations stating the principles and methods by which the maximum benefits could be obtained from artesian groundwater supplies. However, a minority report criticised some aspects of the main report, and expressed doubts about the inadequate premises and conclusions reached. It also recommended studying the GAB as an entity, in combination with the other States involved.

Hydrogeological study of the GAB by the federal geological survey 1971–2010

Proposal for a hydrogeological study of the GAB

The Australian Water Resources Council (AWRC), established in 1962, comprised commonwealth and state ministers primarily responsible for water resources. The primary objective of the council was the provision of a comprehensive assessment on a continuing basis of Australia's water resources and the extension of measurement and research to provide a sound basis for the planning of future development. The AWRC resolved in 1964 that a committee of officers from the relevant state and commonwealth authorities should prepare a suitable hydrogeological programme for the study of the GAB and a statement of how the programme was to be carried out. The collation of results was to be undertaken by the Commonwealth Bureau of Mineral Resources, Geology and Geophysics (BMR), the federal government's geological survey. The programme included geological mapping, stratigraphy, aquifer characteristics, and hydrodynamics review and assessment. The Australian Geological Survey Organisation (AGSO) replaced BMR in 1992, and subsequently became Geoscience Australia (GA) in 2004. State geological surveys were involved in the geological mapping of their states, and BMR carried out NT's geological mapping (at scale 1:250000) including the GAB part, and jointly with the Geological Survey of Queensland for the geological mapping of Queensland.

The BMR commenced the GAB hydrogeological study in early 1971, with the main objectives of reviewing the geological and hydrogeological data of the multi-layered confined aquifer system, and developing and applying a digital computer-based model to simulate the groundwater hydrodynamics (Habermehl 1980).

Geological investigations

Basic data for the hydrogeological and modelling study included the results of geological surface mapping by BMR

and state geological surveys, with geological fieldwork carried out from the 1950s to the early 1970s. 1:250000 geological maps and geological cross-sections were published mainly during the 1960s and 1970s together with explanatory notes. The 1:1000000 Geological maps and structure contour maps on significant lithostratigraphic formations also covered GAB's Eromanga Basin (Senior et al. 1978), Surat Basin (Exon 1976), and Carpentaria Basin (Smart et al. 1980; Habermehl and Draper 1997). The GAB is covered by 158 geological maps at scale 1:250000 (map size 1° latitude and 1° 30' longitude, approximately 110 × 150 km) published by BMR and the state geological surveys. These maps include flowing artesian bores, pumped nonflowing artesian waterbores, wire-line logged waterbores, stratigraphic drill-holes by BMR and state geological surveys, (the latter holes) with depths of up to several 100s of metres, petroleum exploration and production wells and geophysical data (seismic lines, airborne aeromagnetics, regional gravity and Bouguer anomalies) from surveys carried out by BMR and petroleum companies.

Publications, reports and geological and hydrogeological maps are accessible from the websites of the BMR, AGSO, and Geoscience Australia (Australian Government 2019).

State geological maps which show the GAB include: Queensland 1:2500000, with a companion volume (Day et al. 1983), and a groundwater resources map (references 'Queensland Geological Survey 1975' and 'Geological Survey of Queensland & Irrigation and Water Supply Commission 1973' in Habermehl 1980); New South Wales 1:3000000 geological map (reference 'Packham 1969' in Habermehl 1980), and geology of the GAB (Hawke and Cramsie 1984); South Australia 1:2000000 geology map (Drexel and Preiss 1995), and a map of the groundwater resources of South Australia (reference 'Sheperd 1983' in Habermehl 1980). A hydrogeological map of the South Australia and NT parts of the GAB by Sampson et al. (2012) is included in Keppel et al. (2013). A BMR 1:2500000 geological map of Australia covers the whole GAB. An updated digital Geological Map Australia 1:1000000 was published by GA in 2008 (Raymond 2012).

Geophysical logs

Existing flowing artesian and nonflowing (subartesian) waterbores were geophysically logged by BMR to obtain information on the subsurface geology (for most flowing and to a lesser extent nonflowing artesian bores, driller's logs are available). The objective was to identify and correlate GAB geological and hydrogeological units in its constituent sedimentary basins, including the Eromanga, Surat and Carpentaria basins, and parts of the Bowen and Galilee basins (Figs. 1, 2 and 3). The geophysical logs or wire-line logs from about 1,250 waterbores from Queensland, NSW and NT parts

of the GAB, collected during the period 1960 to 1975, included natural gamma-ray, neutron-gamma ray, temperature, differential temperature, casing collar locator logs, caliper and flowmeter logs and from some bores with sufficient length of uncased hole, spontaneous potential, single point resistance, short normal resistivity, long normal resistivity and lateral resistivity logs (Habermehl 2001b). With these logs, but mainly with natural gamma-ray logs, many of the Cretaceous and Jurassic geological and hydrogeological units could be correlated across large parts of the basin, and aquifers and casing details could be identified. These logs were digitised during the early 1990s, and 3,875 logs from 1,235 waterbores are available electronically in the report of Habermehl (2001b). That report includes three 1:2500000 maps showing the waterbore locations, the type of logs acquired, and the availability of lithostratigraphic and hydrochemistry data. In addition to BMR, the Queensland, NSW, SA and NT Water and Geological Authorities logged waterbores during the period 1960s to 1990s (e.g. Hawke and Cramsie 1984).

Wire-line logs from petroleum exploration and production wells drilled in the GAB areas since the early 1960s were obtained, but not included in Habermehl (2001b). A large number of petroleum exploration wells was included in the Commonwealth Petroleum Search Subsidy Act (PSSA), introduced in 1957 and completed in 1974. The Commonwealth assistance to petroleum exploration resulted in well completion reports of the exploration wells to be available in BMR, and these reports and their geological and geophysical logs provided a significant source of information on the GAB geological sequence and deeper units. Some of this information is shown in the 1:250000 Geological Maps Explanatory Notes.

Hydrogeological investigations

The 1:2500000 GAB Hydrogeology map (Habermehl and Lau 1997) shows the significant hydrogeological aspects based on work carried out during the 1970s–1990s and earlier studies. This includes aquifers and confining beds, faults, and structure contours on the base of the Rolling Downs Group, which is the base of the main Cretaceous confining sequence. The latter is equivalent to the top of the main (tapped) artesian aquifer the Cadna-owie Formation–Hooray Sandstone and equivalents (Lower Cretaceous–Jurassic sequence). Further, the 1:2500000 GAB Hydrogeology map includes the 1970 potentiometric surface contours for the top of the latter aquifer, regional groundwater flow directions, locations of flowing artesian springs (Fig. 4), total dissolved solids contours, groundwater temperatures, isotope ages, industrial borefields, pipelines, oil and gas fields and mines using artesian groundwater. It also comprises lithostratigraphy and hydrostratigraphy tables, and a cross-section from recharge to discharge areas (Fig. 2). Smaller maps show locations of flowing and nonflowing artesian bores, wire-logged

waterbores and petroleum exploration wells. Several figures in Habermehl (1980 and 2001a, b) show similar maps. Five inset maps on the 1:2500000 GAB Hydrogeology map show rainfall, evaporation, runoff, topography, geological basins, depth to basement, extent of aquifers and confining beds, total dissolved solids contours, hydrochemical composition of the artesian groundwater and drawdown of the potentiometric surface for 1880–1970. The 1:5000000 Hydrogeology of Australia map by Jacobson and Lau (1987) shows the GAB's general hydrogeological features.

Waterbore data

The state water authorities provided much of the basic bore data information during BMR's GAB Project. Data were manually transcribed from 1972 to 1974 by BMR from state paper files of data collected during the 1800s and 1900s up to the 1970s, and input into a BMR-GAB digital database system (Habermehl 1980). The measurements and tests have been repeated at regular intervals of a few years for most flowing artesian bores, which represent the most significant artificial discharge points in the basin. Nonflowing artesian waterbores produce much smaller discharges, and information on these bores is generally restricted to basic data obtained on drilling and completion of the bores (Habermehl 1980).

Conceptual hydrogeology model

The data collection and analysis described in the preceding led to a conceptual hydrogeological model of the multi-layered aquifer system in the basin, and definition of the hydrodynamic characteristics described by Habermehl (1980) and numerical modelling by Seidel (1980). The processed data were used in digital computer-based models GABSIM during the BMR-BRGM study (Ungemach 1975; reference 'Audibert 1976' in Habermehl 1980) and GABHYD (Seidel 1980) during the 1970s to simulate the groundwater hydrodynamics of the basin. The GABHYD model allowed for predictions and assisted in the assessment, planning and management of the basin's artesian groundwater resources (Habermehl and Seidel 1979).

The GAB database was updated and converted several times during the 1980s and 1990s. The hydrogeological model of the multi-layered aquifer system in the basin was updated during that time from a simple layered model with two confined aquifers and two confining beds to a model with the individual formation units, based on the structure contour maps on the top of each of the lithostratigraphic formations. However, hydrogeological data from waterbores are limited for the units below the main tapped aquifer, the Jurassic-Lower Cretaceous Cadna-owie Formation–Hooray Sandstone aquifer and its equivalents. The early models (Seidel 1980) were updated and new models using MODFLOW were prepared and applied for management activities, and in particular for the GAB Sustainability Initiative

(GABSI) program during the 1990s and early 2000s by Welsh (2000, 2006).

Isotope hydrology and hydrochemistry

Isotope hydrology and hydrochemistry studies of the GAB were carried out from 1974 to 1998 by BMR and successors (AGSO), and from 1998 to 2009 by the Bureau of Rural Sciences (BRS) to where the GAB Project and its staff were moved to. These studies required significant field operations throughout the whole of the GAB, during substantial time periods, as selected sampling points (waterbores and springs) are separated by large distances in sparsely or unpopulated areas. Joint sampling by the Australian Atomic Energy Commission (AAEC; now Australian Nuclear Science and Technology Organisation, ANSTO) and BMR (by the author) for hydrochemistry, stable and radio-active isotopes, and gases from flowing artesian waterbores and springs across the whole of the basin started in the early/mid-1970s and continued until the late 1980s. Data for D/H, $^{18}\text{O}/^{16}\text{O}$, ^{13}C and ^{14}C have been reported by Airey et al. (1979, 1983), Calf and Habermehl (1984), Habermehl (1983, 1986), and were used to date the groundwater and interpret hydrochemistry, groundwater movement and recharge to aquifers. The results provided descriptions of hydrochemistry and groundwater ages or residence times, and confirmed groundwater flow patterns and the meteoric origin of recharge water. This was a contentious issue during the early 1900s. The D/ ^{18}O stable isotope data from the artesian groundwater in the GAB plot on or near the Meteoric Water Line, which confirms the origin of the artesian groundwater as meteoric (Airey et al. (1979), Calf and Habermehl (1984), Habermehl (1980, 2001a, 2009), Habermehl et al. (2009), Kellett et al. (2003), McMahon et al. (2002), Radke et al. (2000).

During the 1980s and 1990s, BMR/AGSO and AAEC/ANSTO investigators were joined in the field sampling by Australian National University (ANU), and USA, Swiss and later by Japanese scientists. This broadened the range of stable and radiogenic isotopes sampled and analysed, including ^3He , ^4He , ^{36}Cl , ^{129}I , $^{86}\text{Sr}/^{87}\text{Sr}$, and provided additional data on the hydrochemistry and groundwater ages throughout the basin—Allan et al. (1991); Bentley et al. (1986); Collerson et al. (1988); Cresswell et al. (1996); Fabrika-Martin et al. (1985); Habermehl (1996); Habermehl and Lau (1993); Habermehl et al. (1993, 1996, 1997); Hasegawa et al. (2010, 2016); Herczeg et al. (1987, 1991); Mahara et al. (2007, 2009); Shimada et al. (1997, 1999); Torgersen et al. (1987, 1989, 1991, 1992); Torgersen and Phillips (1993); Torgersen and Clarke (1985); Torgersen and Phillips (1993). Most hydrochemistry and isotope results are also shown in Radke et al. (2000) and in Figs. 6, 7 and 8. A list of unpublished reports for projects reported from

2003 to 2005 (including Habermehl 2003, 2004, 2005b), containing GAB hydrochemistry and isotope data, are included in the electronic supplementary material (ESM).

The origin of the ^{14}C and most of the ^{36}Cl in the GAB's groundwater is cosmogenic and can be used to determine artesian groundwater travel times. The results of these studies show that the artesian groundwater movement is in the order of 1 m/year, and in some areas up to 2.5 m/year. Groundwater ages and residence or travel times are up to 1–2 million years from the eastern recharge areas to the central and southwestern parts of the basin. Contours of ^{14}C percent modern carbon (pmC) data and $^{36}\text{Cl}/\text{Cl}$ ratio data compiled from these studies are shown in Radke et al. (2000) and Habermehl (2001a, 2002, and in ESM: Habermehl, 2003, 2004, 2005b). Hydrochemistry and isotope analyses results from almost 1,000 samples from GAB waterbores and springs were collected during the period from 1974 to 2005—including analyses results from repeated samples collected from several bores and springs, including more than 100 samples from Dalhousie Springs (SA) during the period from 1976 to 2003. The waterbores sampled, the samples collected (1974–1997) and analysis results are listed in Radke et al. (2000), including a digital copy of the dataset.

Until the early 2000s, BRS (by the author and technical assistants) continued hydrochemistry and isotope (^{36}Cl , ^{14}C , D/H, $^{18}\text{O}/^{16}\text{O}$) sampling of flowing artesian waterbores and springs across the basin. All of the hydrochemistry and isotope data up to the year 2000, including sampling and analyses aspects (Appendix 3 in Radke et al. 2000), are included in digital format in a publication that analysed, interpreted and reviewed the hydrochemistry, isotope hydrology, hydrogeology and hydrodynamics of the basin (Radke et al. 2000). This publication points to two flow regimes, a shallow regime of low to moderate flow rates, and a regime with older groundwater and very low flow in areas of deep aquifer burial. It also dealt with the regional variation and evolution of the hydrochemistry and isotopes.

Andrews and Fontes (1993) criticised the results reported by Bentley et al. (1986) and Torgersen et al. (1991) regarding the dilution of cosmic ^{36}Cl input by aquifer derived Cl. Torgersen and Phillips (1993) replied to this criticism, and later Mahara et al. (2007) also dealt with this matter.

Mass balance and equilibrium models for major dissolved species and stable carbon isotopes of dissolved inorganic carbon show that the chemical trends within the main aquifer in the basin are caused by mass transfer of cations involving cation exchange of Na for Ca-Mg, carbonate dissolution and reactions between Na and kaolinite to form Na-smectite (Herczeg et al. 1991).

The studies by Mahara et al. (2007, 2009), Hasegawa et al. (2010, 2016) and Habermehl (2003, 2004, 2005a, b) included sampling by the Japanese investigators jointly with BRS (the author and technical staff) for hydrochemistry and isotopes

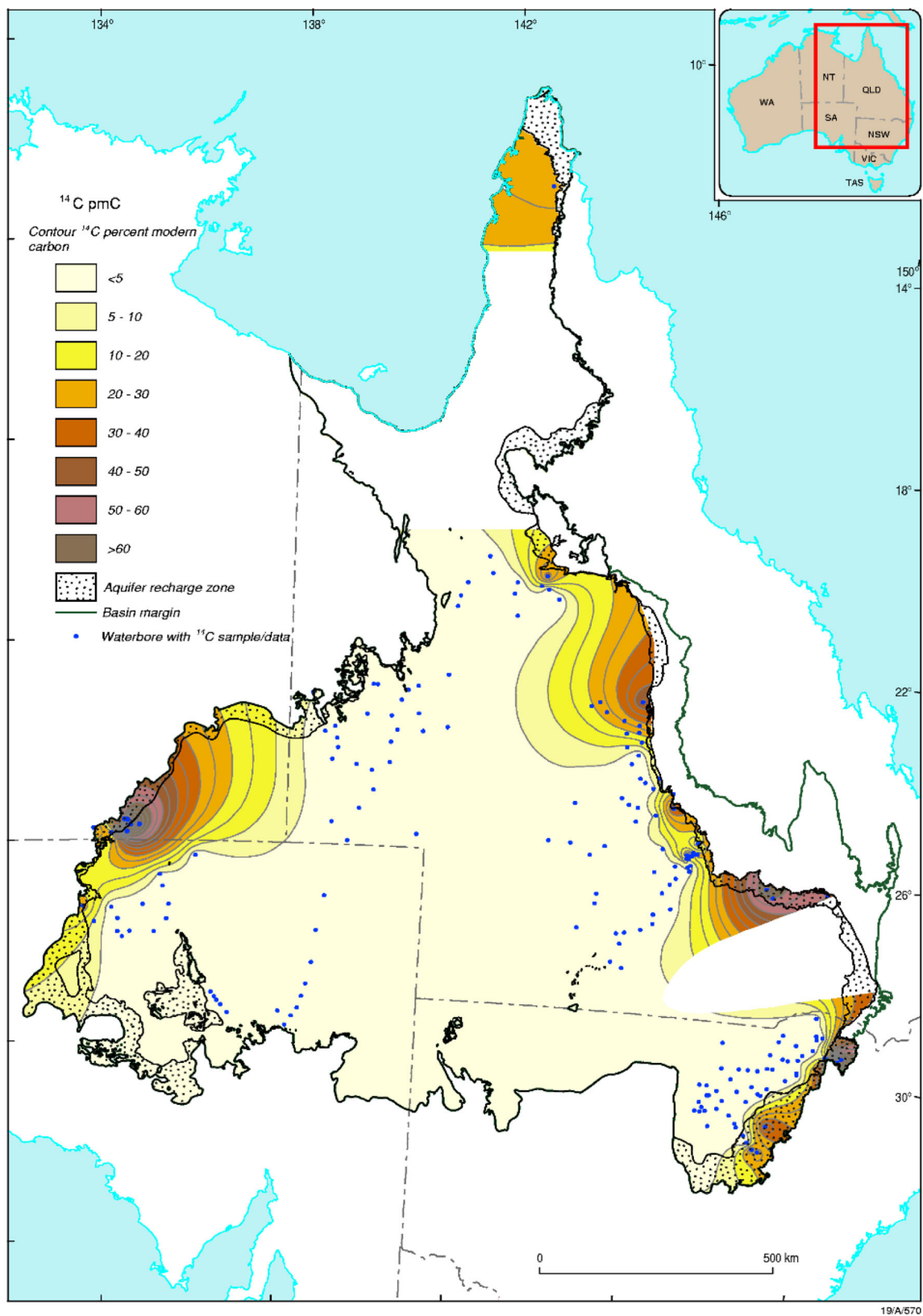


Fig. 7 Contours of ^{14}C pmC in the Great Artesian Basin Cadna-owie Formation–Hooray Sandstone aquifers (after Radke et al. 2000, with permission from Aust. Govt. Dept. Agriculture and Water Resources)

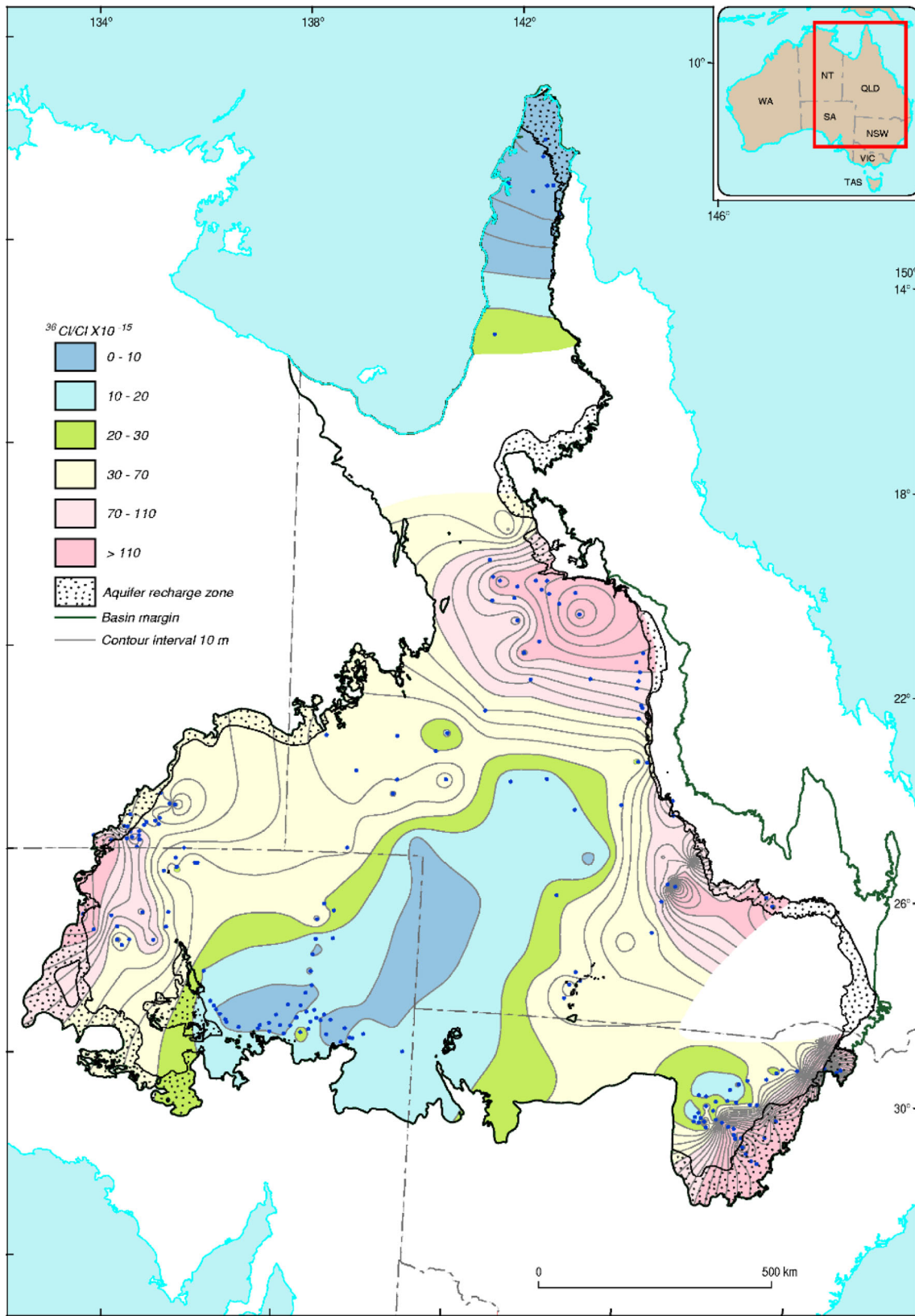


Fig. 8 Contours of $^{36}\text{Cl}/\text{Cl}$ ratios in the Great Artesian Basin Cadna-owie Formation–Hooray Sandstone aquifers (after Radke et al. 2000, with permission from Aust. Govt. Dept. Agriculture and Water Resources)

(D/H, $^{18}\text{O}/^{16}\text{O}$, ^{13}C , ^{14}C , ^{36}Cl , ^{37}Cl and ^4He , $^3\text{He}/^4\text{He}$, Ne) across the basin during 1996, 2002 and 2003 to estimate the residence times of the artesian groundwater. Two methods were used for dating of groundwater that cannot be reliably measured by ^{36}Cl alone, one based on groundwater flow velocity plus distance along a flow path and the other based on ^4He accumulation rates calibrated with ^{36}Cl dates.

The hydrogeological characteristics of the main confining aquitard overlying the main confined aquifer (the Cadna-owie Formation–Hooray Sandstone aquifer) were studied in detail (Hasegawa et al. 2016). As part of the latter study, two fully cored holes were drilled, (1) one downgradient from the basin's recharge area near Richmond, Queensland, with a depth of 264 m, and (2) one near the discharge margin of the basin near Marree, SA, with a depth of 197 m (in *ESM*: Habermehl, 2005a, b). ^{36}Cl and ^{37}Cl samples from the rock cores were used to characterise the hydrodynamics of the main confining bed, the Rolling Downs Group, and the main confined aquifer, the Cadna-owie Formation – Hooray Sandstone (Hasegawa et al. 2016). Results show that the groundwater flow in the confining layer is less than 10^{-5} m/year because diffusion is dominant.

Ransley et al. (2015) updated and extended the interpretation of the available data in the Hydrogeological Atlas of the Great Artesian Basin.

In addition to hydrochemistry and isotope analyses results by authors previously listed, data from other studies were published by Bethke et al. (1999), Beyerle et al. (1999), Collon et al. (2000), Lehmann et al. (2003), Love et al. (2000, 2013), and Pirlo (2004). References by Muller (1989), Quarantotto (1986, 1989) are shown in Habermehl (2001a).

Modelling studies by Ungemach (1975), Seidel (1980) and Welsh (2000, 2006) confirmed the basin-wide groundwater flow patterns determined from potentiometric surface information for the main Cadna-owie–Hooray Sandstone aquifer and equivalent aquifers (Fig. 5). They also showed the different groundwater travel-patterns in the basin.

The spreadsheet included (on CD) in Radke et al. (2000) contains the bore data and hydrochemistry and isotope analysis results of samples collected (1974–1997); further details can be found in the *ESM* for hydrochemistry and isotope analysis results of samples collected (2002–2005).

Groundwater temperatures and geothermal gradients

Groundwater temperatures of waterbores tapping the Lower Cretaceous–Jurassic aquifers range from about 30 to 100 °C and artesian spring temperatures range from about 20 to 45 °C. Geothermal gradients have a wide range and give a mean of about 39 °C/km, and a range of about 15 to 100 °C/km (Polak and Horsfall 1979, reference in Habermehl 1980).

Maps of groundwater temperatures in the basin and geothermal gradients are shown in Habermehl (2001b), Habermehl and Pestov (2002), Habermehl (2002). The GAB central and southwestern areas overlie a large area where estimated crustal temperatures between 180 and 300 °C occur at 5 km depth (Chopra and Holgate 2005).

Numerical modelling of the GAB

The modelling studies by BMR, AGSO, BRS and GA (Ungemach 1975; Seidel 1980; Welsh 2000, 2006) were of particular interest when a greater emphasis on management and regulation of the basin's artesian groundwater resources appeared since the 1990s. They were used in a number of management applications and reviews by commonwealth and state organisations and in particular in relation to GABSI and other management activities.

The MODFLOW-based GABFLOW (steady state) model by Welsh (2000), Welsh and Doherty (2005) predicted changes in artesian pressure in response to the rehabilitation and control of GAB waterbores and the plugging of abandoned petroleum exploration wells (converted to flowing waterbores) in the basin. A number of external models of small parts within the GAB have been constructed to evaluate the impact of specific water extraction projects for several of the mines in the southwestern and western margins (Welsh and Kellett in: Cox and Barron 1998). The GABFLOW model simulated the hydrodynamics of the whole basin (the Cadna-owie–Hooray Sandstone aquifer was explicitly modelled) at 1960 conditions. Model predictions show the pressure head distribution after the system reached equilibrium, but does not indicate the time required. The interactions between the aquifer layer and the aquitards are implicitly included in the model by leakage. The artesian aquifer layer is subdivided into 5 km × 5 km cells, resulting in 359 rows and 369 columns and over 60,000 active model cells.

The calibration of GABFLOW resulted in 90% of model cells having simulated heads within 7 m of observed heads and about half the cells within 3 m. Observed hydraulic heads were corrected for temperature and salinity. The model indicates that rainfall and rivers in the recharge areas represent the largest source for the groundwater system (60%, on average 1,937 ML/day). Upwards leakage from other aquifers provide the balance of the recharge (average 1,275 ML/day). Leakage into adjoining aquitards and aquifers causes the largest outflow at 1,715 ML/day. Discharge from springs and waterbores accounts for most of the remainder at 1,466 ML/day, and outflow to the Gulf of Carpentaria (north of Queensland) averages 32 ML/day. The estimated discharge rate from approximately 1,500 flowing artesian bores in the basin was, at its maximum around the year 1918, approximately 3,200 ML/day. Since then the flowrate has been in steady decline,

and was about 2,000 ML/day in 1960, and approximately 1,600 ML/day in 1980 (Habermehl 2001a; Reyenga et al. 1998), prior to the start of the GAB Bore Rehabilitation Program (GABBRP) in 1989 and the GABSI program in 1999. The flow rate from 3,100 bores was about 1,200 ML/day during the late 1990s. Drawdown then was more than 100 m in southern Queensland and around 40 m further north. GABFLOW predicted that it would be possible to achieve significant increases in artesian pressure heads if the groundwater wastage could be halted. By using tanks and troughs for water distribution to sheep and cattle, there could be a recovery of 36 m in the potentiometric head in the east-central part of the basin and lesser, but still substantial increases in other parts. Groundwater “saved” in such a scenario would be 122,000 ML/year, approximately 335 ML/day or 21% of the annual water use for the entire Basin (Welsh 2000).

A transient groundwater flow model of the basin by Welsh (2006) was constructed on MODFLOW-2000 building on the GABFLOW steady-state model (Welsh 2000; Welsh and Doherty 2005). The Cadna-owie–Hooray Sandstone aquifer, the most exploited aquifer, is modelled. It is a single confined layer model with 5×5 km² north–south-oriented cells, calibrated over the period 1965–1999 inclusive, with 1-year stress periods.

The model is parsimonious, using only the Recharge and Well package in addition to the standard MODFLOW packages. Because the GAB is large, and groundwater shows no seasonal variations, the recharge and vertical inter-aquifer leakage were held constant during the calibration period. Model changes in water levels were generated solely by temporal changes in discharge rates. The model was calibrated using a combination of automated and manual methods. Minimising vertical leakage was an additional objective because small amounts of vertical leakage over the large area of the basin could result in this component dominating the water balance. Performance measures of the resulting calibration are satisfactory according to Middlemis (2000).

The model water balance suggests that the basin is not in equilibrium, with outflows about 70% greater than inflows over the calibration period of 1965–2000. Some management scenarios were run with the model in predictive mode. Transient and steady-state predictions were compared and the two extreme scenarios, of no change to flows and all high flowing bores capped, were tested. Water level recovery due to rehabilitation of waterbores under phase 1 of GABSI was used to compare the transient and GABFLOW solutions. The main differences were: less recovery in SA due to inclusion of improved aquifer thickness information; less recovery in the Eastern-Central and Surat management zones due to reduced recharge rates; and more recovery in the north–north-eastern management zones due to different vertical leakage assumptions.

The magnitude and distribution of the water level recovery using the transient model correlates better with the GABSI flow savings than the equivalent GABFLOW scenario. Scenarios were also carried out to test the impacts to the year 2050, of not continuing the bore rehabilitations, and of rehabilitating all remaining high-flowing bores. The model estimates that over this time period, if no further works were undertaken after phase 1 of GABSI and no new bore were drilled, water levels would drop by more than 8 m over large areas of the basin. However, the rehabilitation in south-eastern NSW is predicted to maintain existing water levels in that area. If all remaining high-flowing waterbores were rehabilitated, the model predicts that the water levels would increase over most of the basin. In particular, water levels in the northern and east-central regions were estimated to increase by more than 20 m by 2050.

It was concluded that the model is acceptable by the standard statistical measures, but there are data deficiencies. The collection and incorporation of actual discharge rates from all bores and dense sets of accurate water pressures (and temperatures) from across the basin could be used to produce a better model. The parameter sets and water balance from the calibrated model add to the understanding of the hydrodynamics of the basin, and the improved discharge rate information is being used in GABFLOW. If used qualitatively, the model can be a useful tool for predicting the effects of changing groundwater extraction from the basin (Welsh 2000; Welsh and Doherty 2005).

Artesian springs in the GAB

Studies of GAB flowing artesian springs

These studies carried out by BMR and AGSO since the mid-1970s, concentrated initially on the distribution and hydrogeological characteristics of springs (Habermehl 1980, 1982b, 2001a, 2006). Springs and seepage areas are abundant in the marginal areas of the basin, mainly in the southern, south-western north-western and northern discharge areas (Fig. 4). Detailed hydrogeological and ecological studies have been carried out on springs near Lake Eyre as part of Environmental Impact Studies for the region near the Olympic Dam mine in SA, and for other mines and coal seam gas developments in Queensland, NSW and SA—Fairfax and Fensham (2003); Fensham and Fairfax (2003); Fensham et al. (2010, 2016); Gotch (2006, 2013); Ponder (1986). Springs also occur near recharge areas in the eastern margins, where many springs are the result of ‘overflow’ or ‘rejection’ of recharge into the aquifers, or result from the intersection of local topography and aquifers. Most springs are associated with structural features (such as faults, folds, monoclines and intersecting lineaments, and thin confining beds overlying

the aquifer) and abutment against basement rocks such as in the south-western parts of the basin. Most springs occur in groups, e.g. a 50 km straight NW–SE line of major springs runs from Strangways Springs to Horse and Buttercup Springs SW of Lake Eyre. Extensive studies were carried out during the early 2000s (2008–2012) on the springs in the western Great Artesian Basin in South Australia as part of a project on natural resources management and allocating water and maintaining springs in the Great Artesian Basin (National Water Commission 2013).

Springs hydrochemistry and isotopes

Hydrochemistry and isotope sampling of groundwater from springs throughout the basin was carried out by the author and assistants, and in particular of springs in the south-western part of the basin, southwest of Lake Eyre in SA, and from Dalhousie Springs, SA (Radke et al. 2000, Zeidler and Ponder 1989). Measuring equipment to determine spring discharges and meteorological equipment was maintained at the latter springs for more than a decade since 1990 (Habermehl 1990). Many of the springs deposit tufa carbonate sediments, and many of the active and older nonactive springs, particular springs in the south-western parts of the basin, have built up conical mounds several metres high and several metres or tens of metres in diameter, and large platform deposits.

Drill-holes in spring deposits

Drilling of 23 fully cored drill-holes through the fossil carbonate mound deposits south-west of Lake Eyre during 1985 by the author (Habermehl 2020), determined the thickness of the deposits and their lithology, which shows that the sediments generally consist of calcite and dolomite, occurring as tufa, travertine and very fine-grained or crystalline carbonate. They were deposited as a chemical precipitate out of the artesian groundwater and precipitated by a combination of chemical, algal and bacterial action (Habermehl 1986 and Keppel et al. 2011, 2013). Thicknesses of the drilled carbonate mound deposits range from almost 5 to 30 m. Analysis of the sedimentary petrology of the spring deposits based on the drill-core samples was carried out by B. M. Radke (Bureau of Mineral Resources, 'Petrology of mound spring complexes, Curdimurka 1:250 000 sheet, Great Artesian Basin', unpublished report (2 volumes), 1990). Keppel et al. (2011) and Keppel et al. (2013) described the sedimentological aspects of the tufa deposits and carbonate hydrochemistry of the mound spring environments in the Lake Eyre region.

Ages of spring deposits

Artesian springs and their deposits in the Lake Eyre region in the south-western part of the GAB range from topographically

high springs to younger, topographically low springs as a result of the lowering of the land surface and spring outlet levels in Quaternary times (Habermehl 1982b). The higher, older spring carbonates of no-longer-active springs cap circular mesas and hills and overlie pedestals of Cretaceous mudstones. Deposits of extinct older springs occur more than 40 m above the nearby present flowing springs, and neighbouring active springs occur at the present ground surface (Prescott and Habermehl 2008). This indicates that the potentiometric surface of the aquifers in the Lake Eyre region has declined considerably during recent geologic time (Habermehl 1982b, 2001a). The GAB artesian springs might have been flowing continuously since the onset of aridity in the Australian continent during the Quaternary, as many biological species have survived throughout that time.

The dated ages of spring deposits range up to 740,000 ± 120,000 years, with some palaeomagnetic studies for spring deposits probably being older. Ages of spring deposits sampled in 1993 in this area have been determined by thermoluminescence, with Elizabeth Springs (SA) showing a plus or minus age of 740,000 ± 120,000 years (Prescott and Habermehl 2008), and subsequent uranium series dating with ages for Beresford Hill at 466,000 ± 135,000 years and Dalhousie Springs at 465,000 ± 43,000 years (Priestley et al. 2018), as well as palaeomagnetic studies for Beresford Hill (M. Idnurm and M. A. Habermehl, unpublished data, 1993). The range of episodic ages of the travertine ages of spring deposits in several locations in the Lake Eyre region compare with wet periods in central and southern Australia and could indicate times of high regional rainfall in the recharge areas of the basin—Magee et al. (2004), Prescott and Habermehl (2008), Priestley et al. (2018). However, Ring et al. (2016) and Uysal et al. (2019), with comments by Priestley et al. (2018) propose an alternative explanation for the palaeohydrogeology and paleoclimate interpretation. These authors consider that CO₂ degassing from the earth mantle associated with active faulting played a major role in the spring travertine precipitation in the area southwest of Lake Eyre. Love et al. (2017) discuss a reappraisal of the hydrogeology of the western margin of the GAB, as its chemistry, isotopes and groundwater flow indicate evidence for active mantle to groundwater fluid linkage.

GAB water resources assessment (GABWRA) 2010–2012

A scientific assessment of the whole of the GAB

This 2010–2012 assessment was the first since the 1971–1980s, and showed the advances in understanding made in that 30-year period (Smerdon et al. 2012a, b; Ransley et al. 2015). GABWRA was conducted by CSIRO, Geoscience

Australia (GA) and consultants (including the author). It was requested by the Australian Government and provided an analytical framework to assist water managers in the basin to meet National Water Initiative (NWI) commitments and communicates the best available science to the Australian Government. The long-standing conceptualisation by Habermehl (1980) was reviewed and an advanced conceptualisation developed (Smerdon et al. 2012b). The assessment was a review of existing information and an update on the geology and hydrogeology, groundwater conditions and groundwater modelling, and modelling of the potential impacts of climate change and groundwater development from 2010 to 2070 (Smerdon et al. 2012b). The assessment of groundwater level maps for 20-year intervals beginning in 1900 clearly illustrates the decline in groundwater levels in the early part of the last century. An increase (recovery) of groundwater levels is evident for 2000–2010, resulting from bore capping under GABSI and previous GABBRP government programs (Reyenga et al. 1998; GABCC 2000; Macauley et al. 2009).

The GABWRA project also resulted in a paper by Smerdon and Turnadge (2015) that explored the effect of faulting of the main aquifer sequence and the creation of stagnant groundwater flow areas against faults, leading to the disruption of regional-scale groundwater flows and effects on the potentiometric surface. The principle of stagnation of groundwater flows and creation of stagnant compartments were limited to where aquifers were located opposite aquitards on opposite sides of faults, and had been recognised by Senior and Habermehl (1980), in the context of hydrocarbon migration and groundwater flow. The modelling by Smerdon and Turnadge (2015) shows that the effects on the potentiometric surface can be important, and that this has implications for groundwater management. It also could be of interest to the application of ^{36}Cl and ^4He age dating and the use of groundwater residence times related to groundwater flow, if waterbores sampled for those isotopes are located within a (local) stagnation or semi-stagnant compartment of regional groundwater flow. The present number of flowing artesian waterbores is however quite limited where faults were located.

Gaining control of hydrogeological conditions

The AWRC-GC, GAB-Sub-Committee, and GABBRP proposal in 1987

The AWRC-GC, the successor of the AWRC-TCUW, comprised commonwealth and state water authorities. In 1985, the GAB-Sub-Committee was established to review matters concerning the basin, and it identified considerable wastage of artesian water by the main users, the pastoral industry. This was mainly because of the distribution of artesian water from

flowing bores by open earth channels or drains, owing to seepage, transpiration and evaporation, causing wastage of more than 95% of the groundwater produced. It also concluded that a large number of waterbores were unserviceable. The report “Improved efficiency of artesian groundwater use, rehabilitation of bores and conversion from drains to piping” (Woolley et al. 1987), prepared by State and BMR hydrogeologists, recommended better management on a basin-wide basis, and proposed the GAB Bore Rehabilitation Program (GABBRP).

GABBRP 1989–1997

The GAB Bore Rehabilitation Program (GABBRP) and the subsequent GAB Sustainability Initiative (GABSI) aimed to recover artesian groundwater pressures. The GABBRP was a joint initiative of the commonwealth and state governments, carried out by the state government authorities of Queensland, NSW and SA. The GABBRP Program (Reyenga et al. 1998) commenced in 1989 and was completed in 1997, though in SA, rehabilitation of uncontrolled waterbores had already been underway since 1977, mainly because many of the bores in SA are government property. In NSW, rehabilitation of flowing bores took place from 1952 to 1976.

The GABBRP Program was partly funded by the commonwealth government, and the part of funding for rehabilitation was based on a 40:40:20 split of the costs by the commonwealth government, the respective state government and the bore-owner or landholder. Participation by the bore-owner/landholder was voluntary. In SA, the funding was on a 50:50 basis, with the commonwealth government and state government providing equal shares, with no landholder contribution, as most waterbores are government owned.

The rehabilitation or reconditioning of artesian waterbores under the GABBRP involved the installation of proper headworks, including control valves or the repair or replacement of the current headworks and pressure cementing of new steel casing (Habermehl 2009). As a result of these measures, the pressures in the groundwater system were expected to increase or be partially restored, and the basin-wide diminution in artesian pressures reduced. Artesian pressure increases have been confirmed since the GABBRP implementation, particularly in the eastern half of the basin in Queensland (Cox and Barron 1998; Macauley et al. 2009; Smerdon et al. 2012b).

Replacement of the open earth bore drains by polythene piping combined with float-valve-controlled concrete or metal tanks or polypropylene tanks and trough systems, resulted in more efficient use of water. Piping of the water also reduced the environmental effects caused by the introduction of large amounts of water and watering points in the semi-arid and arid landscape. The availability of bore water in these areas has resulted in land degradation, the spread of introduced weeds

and dense shrubs lining the drains, and animals attracted by the water, and it affected the biodiversity around waterbores and bore drains, and near artesian springs, with reduced outflows (Noble et al. 1998).

In the period 1989 to 1997, 40% of 1,192 uncontrolled artesian waterbores, or waterbores with corrosion or maintenance problems in Queensland, NSW and SA were rehabilitated, representing a water “saving” of around 46,000 ML/year. Much of the water which was previously wasted is now conserved in the aquifer. Continued use of some of the bore drains means that a significant proportion of the groundwater was still wasted. Changes in artesian pressures or water levels as a result of rehabilitation of water-bores have been noteworthy. Artesian pressures have risen in several areas where large numbers of waterbores were rehabilitated, to the extent that previous flowing artesian waterbores which had ceased flowing, have begun flowing again. Major increases in pressure heads of several metres have been recorded in several large regions as a result of rehabilitation (GABCC 1998; Macaulay et al. 2009; Smerdon et al. 2012b). The replacement of bore drains by piping following rehabilitation led to the largest changes in artesian pressures, as less groundwater is extracted from the bores (Habermehl 2001a, 2018).

GABSI 1999–2018

The GABSI (GAB Sustainability Initiative) Program followed GABBRP in 1999 to accelerate bore rehabilitation and bore drain replacement by piping. GABSI continued to be delivered through state agencies and the Australian Government made its contributions jointly with state governments and bore owners. GABSI was completed in 2018.

Under GABSI, the Australian Government invested almost AU\$125 million over 18 years (1999–2018) to the NSW (\$48.7 million), Queensland (\$64.7 million) and SA (\$11.4 million) governments to accelerate work on the repair and rehabilitation of uncontrolled or corroded artesian bores and equip them with control valves (Habermehl 2009), and the replacement of open earth bore drains with piped water reticulation systems using polyethylene pipes. Under GABSI, state and territory expenditure matched Australian Government expenditure, which represented a substantial level of assistance to landholders (most properties are leasehold from State Governments and bores are privately owned).

During GABSI, 759 bores were controlled and 21,391 km of open bore drains were deleted for the period 1999–2017, and 31,552 km of piping was installed for the period 1999–2018. The estimated artesian groundwater “savings” achieved under GABSI works carried out over the period 1999–2018 was 253,640 ML/year.

The GABSI Initiative assisted with the implementation of key actions of the Strategic Management Plan 2000 (SMP 2000) prepared by the GAB Consultative Council (GABCC 2000).

SMP 2000 is a long-term strategic framework for responsible groundwater and related natural resource management in the GAB, and the use of the GAB groundwater resources, including springs (GABCC 2000; Fensham et al. 2010). The plan provides for the restoration of the environmental assets of the GAB with an emphasis on springs. Basin-wide groundwater modelling (Welsh 2000, 2006) contributed to the management planning and implementation (Habermehl 2001a, b, c, 2018).

Additional GAB Governance provisions since 1997: GABCC (1997–2004), GAB Management Plan (2000) and GABCC (2004–2018)

The Great Artesian Basin Consultative Council (GABCC) was established in 1997 by GAB stakeholders. The council had 17 representatives from various stakeholder groups, including federal, state and local governments; pastoral, petroleum and mining industries; traditional owners, bore owners, community and conservation groups. The GAB Technical Working Group consisting of hydrogeologists from state government water authorities and the Australian Government, provided technical support to the council.

GABCC prepared a GAB Resource Study (GABCC 1998; Cox and Barron 1998), which dealt with most aspects of the basin, including physical aspects, hydrogeology, traditional use, water extraction, values associated with the groundwater resource, sustainability and environmental issues, policy framework for basin management, current management and research Habermehl (1998).

The council coordinated GAB management policy and provided advice to state and commonwealth governments on a strategic framework for sustainable use of the basin. The council also developed a GAB Strategic Management Plan (SMP) in 2000 (GABCC 2000), to address basin-wide management issues, sustainable development and use of the artesian groundwater. State advisory committees were established and were an important link between water users, state governments and the council, with a key role in advising on implementation and helping facilitate cooperative arrangements between all partners and stakeholders.

The Great Artesian Basin Coordinating Committee (GABCC) replaced the Great Artesian Basin Consultative Council (GABCC) in 2004, with its primary role to provide advice to relevant Australian and state and territory ministers on the sustainable whole-of-basin resource management, and to coordinate activity between stakeholders. A new Strategic Management Plan was developed in 2018 (Habermehl 2018). The state governments implemented groundwater resource sharing, operations and allocation plans in New South Wales (NSW Dept Water & Energy 2009), Queensland (Queensland Govt. Natural Resources and Water 2007) and South Australia (South Australian Arid Lands Natural Resources Management Board 2009).

Commonwealth and state activities under national water reforms

During the 1980s and 1990s the commonwealth government increased its involvement by introducing policy matters dealing with surface water and groundwater, and cooperation with the state governments. Several federal programs provided funding for added investigations, research and works by commonwealth and state organisations, including through the Federal Water Resources Assistance Programme (FWRAP), the Natural Heritage Trust (NHT) and the National Landcare Programme (NLP), the latter a key part of the Commonwealth commitment to natural resource management (Habermehl 2018).

Aspects of commonwealth and state legislation

The Commonwealth Environment Protection and Biodiversity Conservation Act (EPBC) 1999 and 2013 provides environmental protection for the GAB springs, and is the main regulation tool for (larger) developments by the states and commonwealth throughout Australia, in particular for mining and petroleum developments. Amendments to the EPBC Act became law in 2013, making water resources a matter of national environmental significance in relation to coal seam gas and large coal mining development. This significantly increased the influence of the EPBC Act (and the federal government) on groundwater (Habermehl 2018).

In many states, waterbores required by the oil and gas industry are not regulated under state water resources acts, but rather under petroleum acts. In particular, co-production of groundwater as part of oil and gas production can be substantial. In contrast, artesian groundwater resources for mineral mining projects, including for the Olympic Dam mine in SA, with borefields in the GAB are regulated under state water resources acts, and pumping rates and/or volumes are measured, recorded and reported.

Acknowledgements This paper draws on many of the studies and papers listed in the text and references, and the author's studies of the hydrogeology of the Great Artesian Basin since 1971 within: the Bureau of Mineral Resources, Geology and Geophysics; Australian Geological Survey Organisation; Bureau of Rural Sciences and Geoscience Australia, Canberra, ACT, Australia. Some repetition and overlap of these studies, their results and published texts quoted in this compilation are inevitable and is acknowledged.

References

Airey PL, Calf GE, Campbell BL, Habermehl MA, Hartley PE, Roman D (1979) Aspects of the isotope hydrology of the Great Artesian Basin, Australia. *Isotope Hydrology 1978, International Symposium on Isotope Hydrology*. IAEA, Vienna, pp 205–219

- Airey PL, Bentley H, Calf GE, Davis SN, Elmore D, Gove H, Habermehl MA, Phillips F, Smith J, Torgersen T (1983) Isotope hydrology of the Great Artesian Basin, Papers of the International Conference on Groundwater and Man. Australian Government, Canberra, pp 1–11
- Allan GL, Fifield LK, Bird JR, Smith AM, Ophel TR, Habermehl MA (1991) The use of accelerator mass spectrometry measurements of ^{36}Cl in the interpretation of hydrological processes. In: *International Hydrology and Water Resources Symposium*, Perth, 2–4 October 1991, Australia National Conference Publ. 91/22, pp 750–754
- Andrews JN, Fontes J-C (1993) Comment on “Chlorine 36 dating of very old groundwater. 3. Further results on the Great Artesian Basin, Australia” by T. Torgersen et al. (1991). *Water Resour Res* 29(6): 1871–1874
- Australian Government (2019) Geoscience Australia website. <http://www.ga.gov.au/>. Accessed August 2019
- Bentley HW, Phillips FM, Davis SN, Habermehl MA, Airey PL, Calf GE, Elmore D, Gove HE, Torgersen T (1986) Cl-36 dating of very old groundwater: 1. the Great Artesian Basin, Australia. *Water Resour Res* 22:1991–2001
- Bethke CM, Zhao X, Torgersen T (1999) Groundwater flow and the 4He distribution in the Great Artesian Basin of Australia. *J Geophys Res* 104(B6):12999–13011
- Beyerle U, Asschenbach-Hertig W, Peeters R, Kipfer R, Puttschert R, Lehmann BE (1999) Noble gas data from the Great Artesian Basin provide a temperature record of Australia on time scales of 10^5 years. *Proceedings of International Symposium on Isotope Techniques in Water Resources Development and Management*, IAEA-SM-361/25, IAEA, Vienna
- Blake T, Cook M (2006) Great Artesian Basin historical overview. Queensland Government: Natural Resources, Mines and Water, Brisbane, Australia, 89 pp
- Calf GE, Habermehl MA (1984) Isotope hydrology and hydrochemistry of the Great Artesian Basin, Australia. In: *Isotope Hydrology 1983*, IAEA, Vienna, pp 397–413
- Chopra PN, Holgate F (2005) A GIS analysis in the Australian crust. *Proceedings of the World Geothermal Congress*, Antalya, Turkey, April 2005, 7 pp
- Collerson KD, Ullman WJ, Torgersen T (1988) Ground waters with unradiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the Great Artesian Basin, Australia. *Geology* 16:59–63
- Collon P, Kutschera W, Loosli HH, Lehmann BE, Purtschert R, Love A, Sampson L, Anthony D, Cole D, Davids B, Morrissey DJ, Sherrill BM, Steiner M, Pardo RC, Paul M (2000) ^{81}Kr in the Great Artesian Basin, Australia: a new method for dating very old groundwater. *Earth Planet Sci Lett* 182:103–113
- Cox R, Barron A (1998) Great Artesian Basin Resource Study. Great Artesian Basin Consultative Council, Brisbane, Australia, 235 pp
- Cresswell RG, Fifield LK, Keywood MD, Habermehl MA, Kellett JR, Jacobson G, Wischusen J (1996) Theory, rainfall and recharge: a chlorine-36 story. *EOS Trans Am Geophys Union* 77(22):W44
- Day RW, Whitaker WG, Murray CG, Wilson IH, Grimes KG (1983) Queensland geology: a companion volume to the 1:2 500 000 scale geological map (1975). Publ. 383, Geological Survey of Queensland, Brisbane, Australia, 194 pp
- Drexel JF, Preiss WV (1995) The geology of South Australia, vol 2: the Phanerozoic. Bulletin 54, Geological Survey of South Australia, 347 pp (includes Geological Map South Australia scale 1:2,000,000)
- Endersbee LA (2005) Voyage of discovery: a history of ideas about the earth, with a new understanding of the global resources of water and petroleum, and the problems of climate change. Endersbee, Tasmania, Australia, 264 pp
- Environment Protection and Biodiversity Conservation Act (EPBC) (1999) and (2013) Commonwealth of Australia, Canberra
- Exon NF (1976) Geology of the Surat Basin in Queensland. Bulletin 166, Bureau of Mineral Resources, Canberra, Australia

- Fabryka–Martin J, Bentley H, Elmore D, Airey PL (1985) Natural iodine-129 as an environmental tracer. *Geochim Cosmochim Acta* 49:337–347
- Fairfax RJ, Fensham RJ (2003) Great Artesian Basin springs in southern Queensland 1911–2000. *Mem Queensland Museum* 49:285–293
- Fensham RJ, Fairfax RJ (2003) Spring wetlands of the Great Artesian Basin, Queensland, Australia. *Wetl Ecol Manag* 11:343–362
- Fensham RJ, Ponder WF, Fairfax RJ (2010) Recovery plan for the community of native species dependent on natural discharge of groundwater from the Great Artesian Basin. Queensland Department of Environment and Resource Management, Brisbane, Australia
- Fensham RJ, Silcock JL, Powell O, Habermehl MA (2016) In search of lost springs: a protocol for locating active and inactive springs. *Groundwater* 54(3):374–383
- GABCC (Great Artesian Basin Consultative Council) (1998) Great Artesian Basin Resource Study, GABCC, Canberra, 235 pp
- GABCC (Great Artesian Basin Consultative Council) (2000) Great Artesian Basin Strategic Management Plan. Great Artesian Basin Consultative Council for the Australian Government Department of Agriculture, Fisheries and Forestry, Canberra, 60 pp
- GABCC (Great Artesian Basin Coordinating Committee) (2017) Summary of past drilling activity within the Great Artesian Basin, Canberra, 27 pp
- Geoscience Australia and Habermehl MA (2010) Advice in relation to the potential impacts of coal seam gas extraction in the Surat and Bowen basins, Queensland: phase one final report. Summary Report 29, Australian Government Department of the Environment, Water, Heritage and the Arts, Canberra, Australia, 106 pp
- Gotch T (2006) Great Artesian Basin and Great Artesian Basin Springs bibliography. In: Gotch TB, Defavari J (eds) Proceedings of the 6th Great Artesian basin Springs Researcher's Forum, Adelaide, 23–24 February 2006, South Australian Arid Lands Natural Resources Management Board, Adelaide, Australia
- Gotch T (2013) Allocating water and maintaining springs in the Great Artesian Basin, vol 5: groundwater dependent ecosystems of the Western Great Artesian Basin. National Water Commission, Canberra, 180 pp
- Habermehl MA (1980) The Great Artesian Basin, Australia. *BMR J Aust Geol Geophys* 5:9–38
- Habermehl MA (1982a) Investigations of the geology and hydrology of the Great Artesian Basin, 1878–1980. Report 234 (BMR Microfiche MF 169), Bureau of Mineral Resources, Geology and Geophysics, Canberra, Australia
- Habermehl MA (1982b) Springs in the Great Artesian Basin, Australia: their origin and nature. Report 235 (BMR Microfiche MF 179), Bureau of Mineral Resources, Geology and Geophysics, Australia, Canberra
- Habermehl MA (1983) Hydrogeology and hydrochemistry of the Great Artesian Basin, Australia. Invited Keynote Paper. In: Papers of the International Conference on Groundwater and Man. Sydney, 5–9 December 1983, Australian Water Resources Council (AWRC) Conference Series, no. 8, vol 3, 83–98 pp. Australian Government, Canberra
- Habermehl MA (1986) Regional groundwater movement, hydrochemistry and hydrocarbon migration in the Eromanga Basin. In: Gravestock DI, Moore PS, Pitt GM (eds) Contributions to the geology and hydrocarbon potential of the Eromanga Basin, vol 12. Special Publ., Geological Society of Australia, Hornsby, Australia, pp 353–376
- Habermehl, MA (1990) Hydrogeology of the Great Artesian Basin. In: BMR 90: yearbook of the Bureau of Mineral Resources, Geology & Geophysics. BMR, Canberra, pp 65–67
- Habermehl MA (1996) Groundwater movement, hydrochemistry and isotope hydrology of the Great Artesian Basin, Australia. In: Report of Special Research Project on Global Environmental Change, vol 4. University of Tsukuba, Ibaraki, Japan, pp 97–114
- Habermehl MA (1998) Geology and hydrogeology of the Great Artesian Basin. In: Cox R, Barron A (ed) Great Artesian Basin Resource Study. Great Artesian Basin Consultative Council, Brisbane, pp 33–59
- Habermehl MA (2001a) Hydrogeology and environmental geology of the Great Artesian Basin, Australia. In: Gostin VA (ed) Gondwana to greenhouse: Australian environmental geoscience. *Geol Soc Austral Spec Publ* 21:127–143, 344–346
- Habermehl MA (2001b) Wire-line logged waterbores in the Great Artesian Basin, Australia: digital data of logs and waterbore data acquired by AGSO. Bureau of Rural Sciences, Canberra and Australian Geol Surv Org Bull 245, 98 pp (Report + data CD + 3 maps at scale 1:2,500,000)
- Habermehl MA (2001c) Hydrogeology of the Great Artesian Basin, Australia. Invited Keynote Address. In: Proceedings of the International Conference Regional Aquifer Systems in Arid Zones: Managing Non-Renewable Resources, Tripoli, 20–24 November 1999, IHP-V, Technical documents in Hydrology 2001, Libyan Arab Jamahiriya and UNESCO-IHP, Paris, pp 123–142
- Habermehl MA (2002) Hydrogeology, hydrochemistry and isotope hydrology of the Great Artesian Basin, Australia. In: Proceedings of the IAH conference, Balancing the Groundwater Budget, IAH, Goring, UK, 17 pp on CD
- Habermehl MA (2006) Artesian springs of the Great Artesian Basin. In: Gotch TB, Defavari J (eds) (2006) Proceedings of the 6th Great Artesian Basin Springs Researchers' Forum, 23–24 February 2006, Adelaide. South Australian Arid Lands Natural Resources Management Board, Adelaide, Australia, pp 1–12
- Habermehl MA (2009) Inter-aquifer leakage in the Queensland and New South Wales parts of the Great Artesian Basin. Final report for the Australian Government Department of Environment and Water Resources, Heritage and Arts, Bureau of Rural Sciences, Canberra, Australia, 33 pp + 22 appendices
- Habermehl MA (2018) Groundwater governance in the Great Artesian Basin, Australia, chapt 21. In: Villholth KG, López-Gunn E, Conti K, Garrido A, van der Gun J (eds) Advances in groundwater governance. Taylor and Francis, London, 594 pp. <http://gripp.iwmi.org/2019/01/11/book-on-advances-in-groundwater-governance-now-open-source/> and <https://www.un-igrac.org/news/open-access-book-groundwater-governance>. Accessed September 2019
- Habermehl MA (2020) Artesian springs of the Great Artesian Basin: hydrogeology, hydrochemistry and age dating of artesian (spring) groundwater and spring deposits. In: Rossini R, Arthington A (eds) Proceedings of the Royal Society of Queensland – Springs Special Issue 2020, vol 12. Royal Society of Queensland, St. Lucia, Australia
- Habermehl MA, Draper JJ (1997) Groundwater. In: Bain, JHC, Draper JJ (eds) North Queensland Geology. AGSO Bull 240, AGSO, Canberra and Queensland Geology 9, GSQ, Brisbane, pp 391–392
- Habermehl MA, Lau JE (1993) Fluoride in groundwater of Cape York Peninsula. *AGSO J Aust Geol Geophys* 14:316–317
- Habermehl MA, Lau JE (1997) Hydrogeology of the Great Artesian Basin, Australia. Australian Geological Survey Organisation, Canberra, Map at scale 1:2,500,000
- Habermehl MA, Pestov I (2002) Geothermal resources of the Great Artesian Basin, Australia. *Geo-Heat Center Q Bull* 23(2):20–26
- Habermehl MA, Ransley T (1997) Groundwater: groundwater quality, groundwater hazard and groundwater levels. In: Bain JHC, Draper JJ (eds) 1997 Atlas of North Queensland Geology 1:3 Million scale. Maps 35, 36 and 37, AGSO, Canberra and GSQ, Brisbane, pp 75–79
- Habermehl MA, Seidel GE (1979) Groundwater resources of the Great Artesian Basin. In: Hallsworth EG, Woodcock JT (eds) Proceedings of the Second Invitation Symposium Land and Water Resources of Australia: Dynamics of Utilisation. Australian Academy of Technological Sciences, Sydney, pp 71–93

- Habermehl MA, Lau JE, Mackenzie DE, Wellman P (1996) Sources of fluoride in groundwater in North Queensland, Australia. 13th Australian Geological Convention, Canberra. Geol Soc Austral Abstr 41:176
- Habermehl MA, Devonshire J, Magee J (2009) Sustainable groundwater allocations in the intake beds of the Great Artesian Basin in New South Wales (Recharge to the New South Wales part of the Great Artesian Basin). Final report, National Water Commission, Canberra, 44 pp + 5 appendices
- Hasegawa T, Mahara Y, Nakata K, Habermehl MA (2010) Verification of ^4He and ^{36}Cl dating of very old groundwater in the Great Artesian Basin, Australia. In: Taniguchi M, Holman IP (eds) Groundwater response to changing climate. IAH Selected Papers on Hydrogeology 16, Taylor and Francis, London, pp 99–111
- Hasegawa T, Nakata K, Mahara Y, Habermehl MA, Oyama T, Higashihara T (2016) Characterization of a diffusion-dominant system using chloride and chlorine isotopes (^{36}Cl , ^{37}Cl) for the confining layer of the Great Artesian Basin, Australia. *Geochim Cosmochim Acta* 192:279–294
- Hawke JM, Cramsie JN (1984) Contributions to the geology of the Great Australian Basin in New South Wales. Bull 31, Geological Survey of New South Wales, Maitland, Australia, 295 pp
- Herczeg AL, Torgersen T, Chivas AR, Habermehl MA (1987) Geochemical evolution of groundwaters from the Great Artesian Basin, Australia. *EOS Trans Am Geophys Union* 68:1275–1276
- Herczeg AL, Torgersen T, Chivas AR, Habermehl MA (1991) Geochemistry of ground waters from the Great Artesian Basin, Australia. *J Hydrol* 126:225–245
- Jacobson G, Lau JE (1987) Hydrogeology of Australia. Map at scale 1:5 000 000. Bureau of Mineral Resources, Geology and Geophysics, Canberra
- Jeffcoat K (1988) More precious than gold: an illustrated history of water in New South Wales. NSW Department of Water Resources, Sydney, 180 pp
- Kellett JR, Ransley TR, Coram J, Jaycock J, Barclay DF, McMahon GA, Foster LM, Hillier JR (2003) Groundwater recharge in the Great Artesian Basin intake beds, Queensland. Queensland Department of Natural Resources and Mines, Brisbane, Australia
- Keppel M, Clarke JA, Halihan T, Love AJ, Werner AD (2011) Mound springs in the arid Lake Eyre South region of South Australia: a new depositional tufa model and its controls. *Sediment Geol* 240:55–70
- Keppel M, Karlstrom KE, Love AJ, Priestley S, Wohling D, De Ritter S (2013) Allocating water and maintaining springs in the Great Artesian Basin, vol 1: hydrogeological framework of the western Great Artesian Basin, National Water Commission, Canberra, 7 vols, 121 pp
- Landsberg J, James CD, Morton SR, Hobbs TJ, Drew A, Tonway H (1997) The effects of artificial sources of water on rangeland biodiversity. *Environment Australia & CSIRO Wildlife and Ecology*, Canberra, 208 pp
- Lehmann BE, Love AJ, Purtschert R, Collon P, Loosli HH, Kutschera W, Beyerle U, Aeschbach-Hertig W, Kipfer R, Frappe SK, Herczeg A, Moran J, Tolstikhin IN, Gröning M (2003) A comparison of groundwater dating with ^{81}Kr , ^{36}Cl and ^4He in four wells of the Great Artesian Basin, Australia. *Earth Planet Sci Lett* 211:237–250
- Love A, Herczeg AL, Sampson L, Cresswell RG, Fifield LK (2000) Sources of chloride and implications for ^{36}Cl dating of old groundwater, southwestern Great Artesian Basin, Australia. *Water Resour Res* 36:1561–1574
- Love AJ, Wohling D, Fulton S, Rousseau-Guétin P (2013) In: De Ritter S (ed) Allocating water and maintaining springs in the Great Artesian Basin, vol 2: groundwater recharge, hydrodynamics and hydrochemistry of the western Great Artesian Basin. National Water Commission, Canberra, 238 pp
- Love AJ, Shand P, Fulton S, Wohling D, Larlstrom KE, Crossey L, Rousseau P, Priestley SC (2017) A reappraisal of the hydrogeology of the Western margin of the Great Artesian Basin: chemistry, isotopes and groundwater flow. *Procedia Earth Planet Sci* 17(2017): 428–431
- Macaulay S, Carey H, Habermehl MA (2009) Artesian pressure trends within the Great Artesian Basin. Technical report, Bureau of Rural Sciences, Canberra, 123 pp
- Magee JW, Miller GH, Spooner NA, Questiaux D (2004) Continuous 150 k.y. monsoon record from Lake Eyre, Australia: insolation-forcing implications and unexpected Holocene failure. *Geology* 32:885–888
- Mahara Y, Habermehl MA, Miyakawa K, Shimada J, Mizuochi Y (2007) Can the ^4He clock be calibrated by ^{36}Cl for groundwater dating? *Nuclear Instruments and Methods in Physics Research B* 259, Proceedings AMS 10, pp 536–546. <https://doi.org/10.1016/j.nimb.2007.01.198>
- Mahara Y, Habermehl MA, Hasegawa T, Nakata K, Ransley TR, Hatano T, Mizuochi Y, Kobayashi H, Ninomiya A, Senior BR, Yasud H, Ohta T (2009) Groundwater dating by estimation of groundwater flow velocity and dissolved ^4He accumulation rate calibrated by ^{36}Cl in the Great Artesian Basin, Australia. *Earth Planet Sci Lett* 287:43–56
- Mazor E (1995) Stagnant aquifer concept, part 1: large-scale artesian systems—Great Artesian Basin, Australia. *J Hydrol* 173:219–240
- McMahon GA, Ransley TM, Barclay DF, Coram J, Foster LM, Jaycock J, Hillier JR, Kellett JR (2002) Aquifer recharge in the Great Artesian Basin of Queensland, vol 11. Proceedings International Association of Hydrogeologists International Groundwater Conference, Darwin, Australia, May 2002
- Middlemis H (2000) Groundwater flow modelling guideline. Murray-Darling Basin Commission, Canberra, 72 pp + appendices
- National Water Commission (2013) Allocating water and maintaining springs in the Great Artesian Basin, vol VII. Summary of findings for natural resource management of the western Great Artesian Basin, National Water Commission, Canberra, 70 pp
- New South Wales Department of Water and Energy (2009) Water Sharing Plan NSW Great Artesian Basin Groundwater Sources. NSW Government, Sydney
- Noble JC, Habermehl MA, James CD, Landsberg J, Langston AC, Morton SR (1998) Biodiversity implications of water management in the Great Artesian Basin. *Rangel J* 20(2):275–300
- Pirlo MC (2004) Hydrogeochemistry and geothermometry of thermal groundwaters from the Birdsville Track Ridge, Great Artesian Basin, South Australia. *Geothermics* 33:743–774
- Ponder WF (1986) Mound springs of the Great Artesian Basin. In: De Deckker P, Williams WD (eds) *Limnology in Australia*. Springer, Dordrecht, The Netherlands, pp 403–420
- Powell JM (1991) Plains of promise, rivers of destiny: water management and development of Queensland 1824–1990. Boolarong, Brisbane, Australia, 395 pp
- Prescott JR, Habermehl MA (2008) Luminescence dating of spring mound deposits in the southwestern Great Artesian Basin, northern South Australia. *Aust J Earth Sci* 55:167–181
- Priestley SC, Karlstrom KE, Love AJ, Crossey LJ, Polyak VJ, Asmerom Y, Meredith KT, Crow R, Keppel MN, Habermehl MA (2018) Uranium series dating of Great Artesian Basin travertine deposits: implications for palaeohydrogeology and palaeoclimate. *Palaeogeogr Palaeoclimatol Palaeoecol* 490:163–177
- Queensland Government Natural Resources and Water (2007) Great Artesian Basin Resource Operations Plan, Queensland Government Natural Resources and Water, Brisbane, Australia, 43 pp
- Radke BM, Ferguson J, Cresswell RG, Ransley TR, Habermehl MA (2000) Hydrochemistry and implied hydrodynamics of the Cadnawowie–Hooray Aquifer, Great Artesian Basin, Australia. Bureau of Rural Sciences, Canberra, 229 pp

- Ransley TR, Radke BM, Feitz AJ, Kellett JR, Owens R, Bell J, Stewart G, Carey H (2015) *Hydrogeological Atlas of the Great Artesian Basin*. Geoscience Australia, Canberra, 134 pp
- Raymond OL (2012) *Surface Geology of Australia 1:1 000 000 dataset*. Geoscience Australia, Canberra
- Reyenga PJ, Habermehl MA, Howden SM (1998) *The Great Artesian Basin: bore rehabilitation, rangelands and groundwater management*. Bureau of Resource Sciences, Canberra, 76 pp
- Ring U et al (2016) Recent mantle degassing recorded by carbonic spring deposits along sinistral strike-slip faults, south-central Australia. *Earth Planet Sci Lett* 454:304–318
- Sampson L, Wohling D, Jensen-Schmidt B, Fulton, S (2012) South Australia and Northern Territory Great Artesian Basin (Eromanga Basin) hydrogeological map: part 1 and part 2. Department of Environment, Water and Natural Resources, South Australian Government, Adelaide
- Seidel GE (1980) Application of the GABHYD groundwater model of the Great Artesian Basin, Australia. *BMR J Aust Geol Geophys* 5: 39–45
- Senior BR, Habermehl MA (1980) Structure, hydrodynamics and hydrocarbon potential of the central Eromanga Basin, Queensland, Australia. *BMR J Aust Geol Geophys* 5:47–55
- Senior BR, Mond A, Harrison PL (1978) *Geology of the Eromanga Basin*. Bulletin 167, Bureau of Mineral Resources, Canberra, Australia
- Shimada J, Habermehl MA, Mahara Y, Kayane I, Miyaoka K, Tanaka T (1997) A 100,000 year paleohydrological information from artesian groundwater in the Great Artesian Basin, Australia. *International Workshop on Global Change and Terrestrial Environment in Monsoon Asia*, Tsukuba, Japan, pp 156–159
- Shimada J, Habermehl MA, Mahara Y, Kayane I (1999) Use of ^{36}Cl to compile the recent 200 K year paleohydrological information from artesian groundwater in the Great Artesian Basin, Australia. In: *Proceedings of the International Symposium on Groundwater in Environmental Problems*, Chiba University, Japan, pp 125–131
- Smart J, Grimes KG, Douth HF, Pinchin J (1980) *The Mesozoic Carpentaria and Cainozoic Karumba Basin*, Queensland. Bulletin 202, Bureau of Mineral Resources, Canberra
- Smerdon BD, Rousseau-Guetin P, Love AJ, Taylor AR, Davies PJ, Habermehl MA (2012a) Regional hydrodynamics, chap 7. In: Ransley TR Smerdon, BD (eds) *Hydrostratigraphy, hydrogeology and system conceptualisation of the Great Artesian Basin*. Technical report, CSIRO Water for a Healthy Country Flagship, Canberra
- Smerdon BD, Ransley TR, Radke BM, Kellett JR (2012b) *Water resource assessment for the Great Artesian Basin: a report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment*. CSIRO Water for a Healthy Country Flagship, Canberra, 45 pp
- Smerdon BD, Turnadge C (2015) Considering the potential effect of faulting on regional-scale groundwater flow: an illustrative example from Australia's Great Artesian Basin. *Hydrogeol J* 23:949–960
- South Australian Arid Lands Natural Resources Management Board (2009) *Water Allocation Plan for the Far North Prescribed Wells Area*. Natural Resources Centre SA Arid Lands, Augusta, Australia, 64 pp
- Torgersen T, Clarke WB (1985) Helium accumulation in groundwater. I: an evaluation of sources and the continental flux of crustal ^4He in the Great Artesian Basin, Australia. *Geochim Cosmochim Acta* 49: 1211–1218
- Torgersen T, Phillips FM (1993) Reply to “Comment on ‘Chlorine-36 Dating of very old groundwater 3. Further results on the Great Artesian Basin, Australia’ by T. Torgersen et al.” by J.N. Andrews and J.C. Fontes. *Water Resour Res* 29:1875–1877
- Torgersen T, Habermehl MA, Clarke WB (1987) Helium isotope evidence for recent subcrustal volcanism in eastern Australia. *Geophys Res Lett* 14:1215–1218
- Torgersen T, Kennedy BM, Hiyagon H, Chiou KY, Reynolds JH, Clarke WB (1989) Argon accumulation and the crustal degassing flux of ^{40}Ar in the Great Artesian Basin, Australia. *Earth Planet Sci Lett* 92: 43–56
- Torgersen T, Habermehl MA, Phillips FM, Elmore D, Kubik P, Jones BG, Hemmick T, Gove HE (1991) Chlorine-36 dating of very old groundwater 3. Further studies in the Great Artesian Basin, Australia. *Water Resour Res* 27:3201–3213
- Torgersen T, Habermehl MA, Clarke WB (1992) Crustal helium fluxes and heat flow in the Great Artesian Basin. *Chemical Geology (Isotope Geoscience Section)* 102:139–152
- Ungemach P (1975) *Great Artesian Basin Groundwater Project: explanatory note on digital model package, Great Artesian Basin Simulation Model (GABSIM)*. Record 1975/169, Bureau of Mineral Resources, Geology and Geophysics, Canberra
- Uysal IT, Ring U, Unal-Imer E, Yüce G, Imer A, Italiano F, Zhao J-X (2019) Comment on “Uranium series dating of Great Artesian Basin travertine deposits: Implications for palaeohydrogeology and palaeoclimate” by Priestley et al. 2018
- Welsh WD (2000) *GABFLOW: A steady state groundwater flow model of the Great Artesian Basin*. Bureau of Rural Sciences, Canberra
- Welsh WD (2006) *Great Artesian Basin transient groundwater model*. Bureau of Rural Sciences, Canberra, 58 pp
- Welsh WD, Doherty J (2005) *Great Artesian Basin groundwater modelling*. Engineers Australia 29th Hydrology and Water Resources Symposium, Canberra, February 2995, 8 pp
- Williams T, Moriarty K (1986) Hydrocarbon flushing in the Eromanga Basin: fact or fallacy? In: Gravestock DI, Moore PS, Pitt GM (eds) *Contributions to the geology and hydrocarbon potential of the Eromanga Basin*. *Geol Soc Austral Spec Publ* 12:377–384
- Woolley DR, Habermehl MA, Palmer J, Sibenaler X, O'Neill D (1987) Improved efficiency of artesian groundwater use, rehabilitation of bores and conversion from drains to piping. Report to the Australian Water Resources Council-Groundwater Committee (AWRC-GC) by the Great Artesian Basin Sub-Committee. AWRC-GC, Canberra, 18 pp
- Zeidler WF, Ponder WF (eds) (1989) *Natural history of Dalhousie Springs*. South Australian Museum, Adelaide, Australia, 138 pp