The Great Artesian Basin, Australia

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The Great Artesian Basin occupies 1.7 × 10^6 km^2, or about one-fifth of Australia, extending across parts of Queensland, New South Wales, South Australia, and the Northern Territory. It underlies arid and semi-arid regions where surface water is sparse and unreliable. The discovery of the basin's groundwater resources around 1880, and their subsequent development, have allowed an important pastoral industry to be established. Pastoral activity and town water supplies are to a very large extent dependent on artesian groundwater. The groundwater basin consist of a multi-layered confined aquifer system, with aquifers occurring in continental quartzose sandstones of Triassic, Jurassic and Cretaceous age. The intervening confining beds consist of siltstone and mudstone; a thick argillaceous sequence of sediments of marine origin and Cretaceous age forms the main confining unit. The basin is, in places, 3000 m thick, and forms a large synclinal structure, uplifted and exposed along its eastern margin and tilted southwest. Recharge occurs mainly in the eastern marginal zone, and large-scale groundwater movement is generally towards the southwestern, western and southern margins. Natural discharge occurs from spring in these areas; most springs are connected with structural features. Minor recharge occurs in the western margin.

The potentiometric surfaces of the Triassic, Jurassic and Early Cretaceous aquifers are still above groundlevel in most areas of the basin. Considerable lowering occurred in heavily developed areas; from about 1880 to 1970, regional differences of up to 80 m were recorded, and in some areas waterwells ceased to flow. Waterlevels of some Cretaceous aquifers are below the groundsurface throughout most of the basin area. Hydraulic gradients of the main aquifers in the Lower Cretaceous-Jurassic sequence are about 1:2000, and of aquifers in the Cretaceous sequence 1:1800. Transmissivity values of the main aquifers in the Lower Cretaceous-Jurassic sequence, from which most flowing artesian wells obtain their water, usually are several tens to several hundreds m^2/day. Hydraulic conductivities range from 0.1 to 10 m/day, with a predominance in the lower part of the range. Storage coefficients, as interpreted from wire-line logs, average about 10^{-5}. Aquifer thicknesses range from several metres to several hundred metres. Average groundwater velocity in the eastern marginal parts is from 1 to 5 m/year. Environmental isotope analysis shows that the artesian water is of meteoric origin. About 4700 flowing artesian wells have been drilled to depths of up to 2000 m, but average 500 m. Individual flows exceeding 10 000 m^3/day have been recorded. About 3100 wells remained flowing during the early 1970s, when the accumulated artificial discharge was about 1.5 × 10^6 m^3/day, as compared to the maximum flow from the basin of about 2 × 10^6 m^3/day from about 1500 artesian wells around 1918. The high initial discharge in the early years of exploitation, which was caused by the release of pressure in the aquifers, gradually levelled off, and has now approached a steady-state condition, in which total basin discharge is roughly balanced by recharge. Non-flowing artesian water-wells mainly in the higher Cretaceous aquifers number about 20 000, and are generally shallow, up to several hundred metres deep, and are usually equipped with windmill-operated pumps, supplying on average about 10 m^3/day each. Most flowing wells occur in the marginal areas of the basin, as the main aquifers in the Lower Cretaceous-Jurassic sequence which they tap are too deep for economical abstraction in the central part of the basin. In the central part mainly non-flowing shallow wells are found.

Groundwater in the most widely exploited pressure aquifers in the Lower Cretaceous-Jurassic sequence generally contains about 500 to 1000 mg/l total dissolved solids, dominated by sodium bicarbonate. Water quality improves with increasing depth of aquifers in the sequence. Groundwater from the aquifers in the Lower Cretaceous-Jurassic sequence is of good quality and suitable for domestic and stock use, though it is generally unsuitable for irrigation because in much of the basin area it is chemically incompatible with the soil. Water from the upper, Cretaceous, aquifers has a higher salinity. More than 90 percent of the water from flowing artesian wells is wasted owing to seepage, transpiration and evaporation associated with the distribution of the water by open earth drains, many of which are tens of kilometres long.

Introduction

The Great Artesian Basin is a confined groundwater basin comprising aquifers in continental quartzose sandstones and confining beds of partly marine mudstone and siltstone of Triassic, Jurassic and Cretaceous age.

The Great Artesian Basin underlies 1.7 x 10^6 km^2, about 22 percent of the Australian continent and is one of the largest artesian basins in the world. It underlies parts of Queensland, New South Wales, South Australia and the Northern Territory (Fig. 1). The part described here lies south of latitude 20°S, an area of about 1.3 x 10^6 km^2.

Most of the groundwater basin area consists of low-lying interior plains, bounded in the east by tablelands and uplands of the Great Dividing Range. The

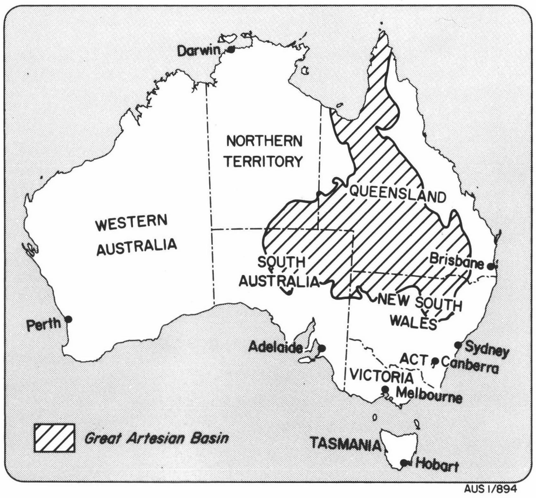

Figure 1. Location and extent of the Great Artesian Basin, Australia.

surface generally slopes towards the main depression near Lake Eyre in the southwest, an interior drainage feature up to 16 m below sea level. The summits of the Great Dividing Range vary from 600 to 900 m in Queensland, to 1200 to 1500 m in New South Wales. Ephemeral rivers draining the Range flow generally southwestward through stretches of plains, most of which lie below 150 m, and show very low relief of less than 30 m.

Bordering the main eastern divide, are "rolling downs", which consist of stony lowlands, erosional landscapes with mesas and tablelands capped by duricrust. The inner, low-lying parts of the interior lowlands are flood plains of anastomosing rivers, forming depositional landforms and dune fields of aeolian sand of the Simpson Desert.

The Great Artesian Basin is largely located in the arid and semi-arid parts of Australia. Very dry hot to warm climates predominate; a more temperate climate is present in the most eastern areas.

Average annual rainfall ranges from a minimum of about 100 mm in the Simpson Desert in the western part to maximum values of about 600 mm near the eastern marginal areas of the basin in the Great Dividing Range (Fig. 2). Rainfall variability follows this zonal distribution, with the more reliable rainfall coinciding with higher rainfall areas. Seasonal distribution is marked by a relative dry winter and wet summer.

Average annual temperatures throughout most of the basin range from 18° to 24°C; the highest average annual temperatures are in the north. An annual temperature range between highest monthly average maximum and lowest monthly average minimum temperature of more than 30° is common in most parts; extreme maximum air temperatures exceed 50°C in the central and western parts.

Evaporation throughout most of the basin area is very high and average annual tank evaporation reaches a maximum of about 3500 mm in the north of South Australia (Fig. 2).

Surface water

All streams in the basin area (Fig. 3) are characterised by extreme variation in discharge and flow duration. Very variable seasonal and annual streamflow patterns are caused by tropical cyclonic and summer monsoonal rainfall, and in most areas

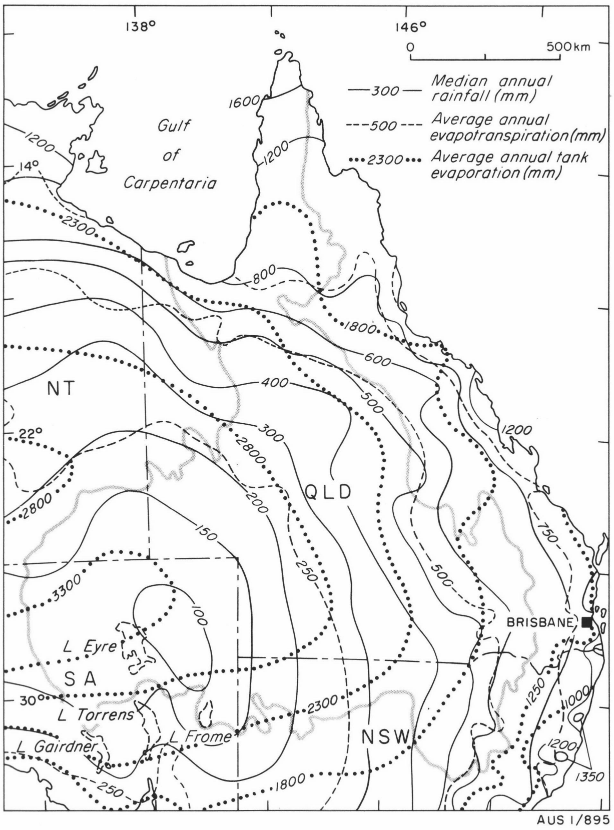

Figure 2. Median annual rainfall (mm), average annual evapotranspiration (mm) and tank evaporation (mm) (after Atlas of Australian Resources).

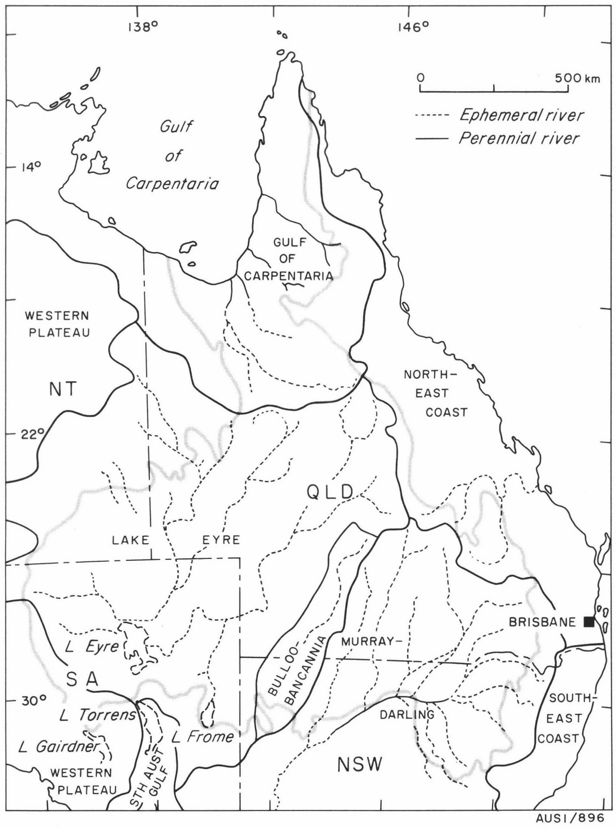

Figure 3. Surface water and drainage divisions (after Atlas of Australian Resources, and Australian Water Resources Council, 1976).

extended periods of droughts, some lasting for many years, alternate with major, long-lasting floods.

Little rainfall occurs in the interior of the basin west of the main eastern divide. Heavy summer rain, usually restricted to the north results only in streamflow in the headwaters and middle reaches of the river-systems. Flows usually do not reach Lake Eyre because of the great distance, low gradient and high seepage, and evaporation losses. Generally this, and other lakes in the southwestern part of the basin, occur as flat, dry, salt-encrusted depressions.

In the southeast of the basin rivers discharge through the Murray-Darling system into the Southern Ocean. A few streams in the eastern marginal area flow out towards the Pacific Ocean (Fig. 3).

Average annual run-off in the basin area is much less than 10 mm and generally less than 5 mm.

Large natural waterholes are present in the channels of the network of ephemeral rivers which flow very infrequently, sometimes at intervals of several years. These waterholes provide permanent supplies in some locations.

No major surface water diversions or storage dams are present in the Great Artesian Basin area. Local farm dams and excavated earth tanks occur in large numbers, but most of these surface storages are of recent origin, and early development of the area was dependent mainly on artesian groundwater resources.

Vegetation

Natural vegetation shows a close interdependence with the zonal distribution pattern of climate and soil types. It is dominated by tussock grassland on grey and brown soils of heavy texture and red earth soils in the northeastern and central parts, low open-woodland with widely spaced hummock grasses in the northwestern and northeastern areas on skeletal and sandy soils. Woodland with trees and shrubs and hummock and tussock grasses occur in the eastern and southeastern parts. Generally dry creeks and rivers in the eastern recharge areas are commonly heavily lined by large phreatophytes. The central part of the basin area is surrounded by low open-woodland with tussock grasses, and the centre consist of open herbfields and some open grassland. Tall open-shrubland with hummock grass characterises the western parts, and low and tall open-shrubland with tussock grass occurs in the southwestern parts.

Large parts in the centre and southwest are covered by stony desert tablelands, with a continuous surface of wind-polished siliceous stones. The western and southwestern parts are covered by red sandhill deserts and ephemeral salt lakes.

Low soil moisture rather than low soil fertility is the production restraint in these arid and semi-arid regions. Low to very low carrying capacity in pastoral activity is probably all that can be expected, as in most areas no arable agriculture or sown pasture production is possible. Xerophytic tussock grass grazing lands (Mitchell Grass Downs) in the northern and central parts of the basin area are the most productive grazing lands in the arid regions. Introduced plants and fertilizers are only applied in small parts of the southeastern area.

Land use and economy

Almost all the non-desert parts of the Great Artesian Basin area are used for low intensity livestock grazing of sheep for wool and beef cattle (Fig. 4).

Physical conditions favourable for more intensive land use, including combined wheat-sheep farming, cereal production, and cotton, fruit and vegetables, only occur in the most eastern and southeastern parts. In the western part, the Simpson Desert is too dry and infertile 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 also occurred as watering points increased. Severe droughts in these arid and semi-arid parts caused declines in carrying capacity, as well as deterioration of the native pastures and soil erosion. Rabbit plagues and economic depressions were other contributing factors. Ultimately stable stocking rates were established after reassessment of the fact that droughts were the rule rather than the exception in this country, and of economic considerations.

The very variable rainfall forms the most important factor for provision of feed, and so adverse rather than favourable seasons significantly determine stocking rates. However, grazing capacity is also directly related to the distribution of watering points and with little surface water available, stock is mostly dependent on artesian wells and excavated tanks.

Changes in land use occurred from sheep to beef-cattle grazing in some areas, and to crop growing in the southeastern area. Irrigation water for the latter is obtained from surface water and from shallow groundwater in alluvial aquifers. Little irrigation development is expected as a result of artesian groundwater availability, mainly because of restrictions concerning chemical compatibility of the groundwater and the dominant soils, and of the quantities required.

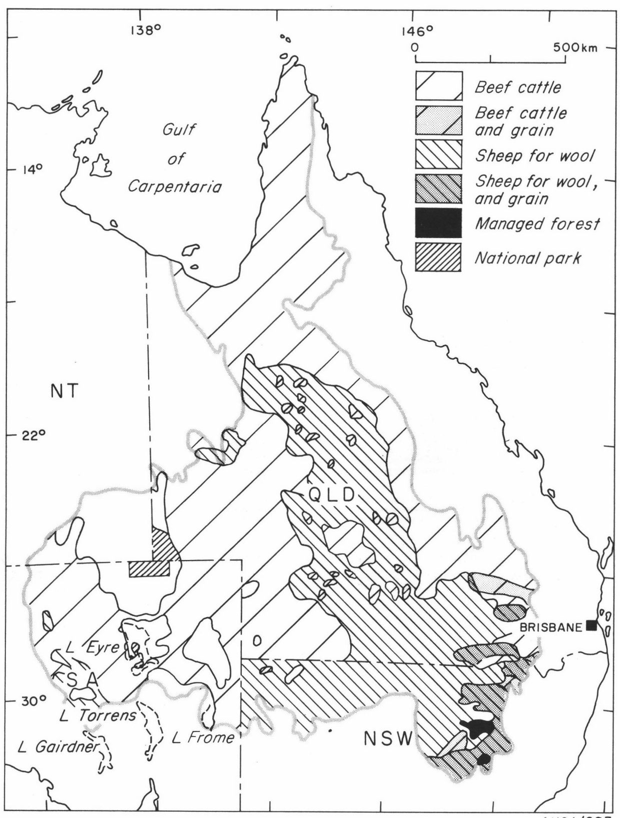

Figure 4. Dominant land use (after Atlas of Australian Resources).

The total population of the Great Artesian Basin area is probably not more than 100 000. This low density population is very unevenly distributed, with most of the twenty-five major centres being located in the eastern and southeastern areas of the basin in Queensland and New South Wales. About half of these urban centres are in Queensland and have on average a population of less than 2 500, the other half in New South Wales have a population of more than 5 000, and up to 10 000.

Access to most of the area is good, with bitumen roads leading into the basin area in the northern and eastern parts. Unsurfaced gravel roads serve the central, southern and marginal western areas. Many roads in the basin area quickly become impassable after rain, especially in the northern and central areas during summer. East-west railway lines penetrate the basin area as far as the east-central parts, and connect these areas and the southwestern margin with the coastal towns.

Investigations of the geology and hydrology of the basin

Early work around 1880 suggested that meteoric water infiltrated the western slopes of the Great Dividing Range, and that artesian springs near Lake Eyre indicated artesian water could be found across most of central and eastern inland Australia (Rawlinson, 1878; Russell, 1880, 1889; Tate, 1879, 1882). Geological investigations led Jack to conclude in 1881 and 1885 (Jack, 1895a, b; 1898), that a large synclinal trough existed in western Queensland, in which pervious beds occurred with artesian water.

Geological mapping of the intake beds along the Great Dividing Range in Queensland and New South Wales and along the northern, northwestern and southern margins by Brown, Cameron, David, Jack, Maitland, Pittman and Wilkinson (references in Pittman, 1914, Interstate Conference on Artesian Water, 1913), and waterwell information helped to outline the shape and size of the basin, so that by the end of the nineteenth century the basin was accepted by many as a classic artesian basin. Pressure data from field surveys confirmed the theory, though controversy remained as to whether the pressure head was hydraulic or hydrostatic. The difference in hydrodynamic conditions of the basin was important, as it would assist in predicting the effects of the already occuring decrease in flow and pressure of artesian wells. The interpretations of origin and movement of artesian water were attacked by Gregory (1901, 1906, 1911, 1914, 1923), who attributed the water in the Great Artesian Basin to connate and plutonic origins, and the movement as the result of heat, gas and rock pressure in the earth's crust, rather than a meteoric origin and movement under hydraulic conditions. Gregory's theories were supported by Symmonds (1912) and Du Toit (1917), but were skillfully refuted by defendants of the meteoric and hydraulic theory, notably Knibbs (1903), Pittman & David (1903) and Pittman (1907, 1914, 1915, 1917). The latter theory gained ground and became generally accepted; the controversy, however, inspired increased research in the basin.

Diminishing flows and pressures in artesian wells increasingly alarmed well owners, and ultimately State Governments became involved, whose attention had already been drawn to the wastage of water from many of the privately drilled wells. Once legislation was passed in the early 1900s to control the use of subsurface water, wells had to be licensed, detailed information provided and wells completed according to prescribed standards. State Water Authorities commenced systematic and periodical measurements which replaced the earlier intermittent data collection; information on wells has been collected since that time, and extensive surveys carried out.

Systematic investigations of the groundwater conditions in the basin increased markedly as a result of the five Interstate Conferences on Artesian Water, held between 1912 and 1928 (Interstate Conference on Artesian Water, 1913, 1914, 1922, 1925, 1929).

The conferences were originally called to study the serious reduction in pressure and diminution or cessation of flows, the extent of the basin, the origin and movement of artesian water, the corrosion problems of well casing and to inquire into a better utilisation of the groundwater.

The reports of the first and second conferences are mainly concerned with the collection of information and the verbal presentations by the (State) delegates and pastoralists, well owners, drillers, engineers, chemists and administrators. The reports of the third, fourth and fifth conferences record submissions by the State representatives (geologists and hydraulic engineers), who presented detailed data about the basin, the wells, and progress in local (State) investigations. The accompanying geological and potentiometric maps, cross-sections, tables with well data, water temperatures, chemical analyses results and other information, show the improvement of knowledge of the basin during the years.

Bibliographies relating to groundwater in Australia during and prior to the period, are included, as well as a detailed description of the deepest waterwell (QWRC Reg. No. 3489) in the basin, completed in 1921 at a total depth of 2136 m (7009 ft) in Queensland.

No further meetings were held until 1939, when an Interstate Conference on Water Conservation and Irrigation met in Sydney, which was concerned with most aspects of ground and surface water, and not confined to artesian water. Discussion concentrated on the diminution and control of flow from wells and the improvement in distribution. It was recognised that the wastage of water from flowing wells was the main problem.

Systematic surveys of the geology and of investigations of hydraulic characteristics continued to be carried out on a State basis. In New South Wales Kenny (references in Packham, 1969; Kenny, 1934, 1964), and Tandy (1939, 1940) completed several surveys during the 1920s and 1930s. The reports by Tandy concentrated on the southeastern parts of the Great Artesian Basin and contain maps, sections, potentiometric maps, graphs and diagrams and calculations and interpretations on well discharges, aquifer permeability, recharge and groundwater flowrates. Newer theories, including elastic storage, were applied. Recommendations were made on water conservation by the partially closing of wells and improved distribution methods. Dulhunty, Mulholland and Rade reported on the geology and groundwater aspects during the 1940s, 1950s and 1960s, (references *in* Packham, 1969; Dulhunty, 1973), whereas more recent studies and reviews occur in Williamson & Hind (1962), Griffin (1963), Williamson (1966), Hind & Helby (1969) and Water Conservation and Irrigation

Commission (1971). Hind & Helby (1969) described the geology and hydrology of the New South Wales part of the basin. Water movement is said to vary between 1.6 and 10 m/year in the Coonamble Embayment. It was reported that some 3000 wells obtain water from the basin in New South Wales, and that in 1968 682 were flowing artesian wells with a combined flow rate of 289 x 10^3 m^3/day. The remainder yield pumping supplies ranging from several tens m^3/day to 3.8 x 10^3 m^3/day.

In South Australia Jack (1915, 1923, 1925, 1930) studied the geology, groundwater hydrology and chemical characteristics, and Ward (1946), Chugg (1957), and Ker (1966) reported data on the Great Artesian Basin; a recent review is included in Sheperd (1977).

In Queensland a committee of geologists and hydraulic engineers was set up in 1939 to investigate the nature and structure of the Great Artesian Basin. A First Interim Report was presented by the committee in 1945 (Queensland Government, 1945), which mainly dealt with the geology, hydrology, use of water and diminution of flows and pressures. It emphasised the principles of recharge, elastic storage, the resulting diminution of flows and pressures and the gradual decrease in diminution, and the importance of water conservation by the control of wells. Another report by the Artesian Water Investigations Committee was produced in 1954, and formed the most comprehensive description of detailed investigation on the hydrogeology of the Queensland part of the basin (Queensland Government, 1954). Appendixes, which were published separately, provide detailed descriptions of the geology (Whitehouse, 1954) and hydrology (Ogilvie, 1954). The report described the nature and structure of the Queensland portion of the Great Artesian Basin, with emphasis on the quantity of water and its aquifer system, and the study of geological, physical and chemical aspects of the problem of diminishing supply. Recommendations concerned the proper use, regulation and control of water from wells, and the suggestion not to enter in the strict conservation of flows from existing wells.

In the Explanatory Notes to the 1:2 500 000 map of the Groundwater Resources of Queensland (Geological Survey of Queensland and Irrigation and Water Supply Commission, 1973) some new figures related to the 1954 report were published. In 1954 it was estimated that the increase in recharge which tended to offset the pressure losses, would reach a steady state in the year 2010, when the total discharge would equal the recharge. The general trends of the earlier (1954) work were confirmed in the 1973 publication, but it was estimated that the ultimate steady output of the wells in 2010 would be 590 x 10^3 m^3/day, underflow to other states at 90 x 10^3 m^3/day, and recharge at 680 x 10^3 m^3/day. The 1973 report further states that the pressure gradients steepened from an initial 1:2933 to about 1:1760, and that the computed total withdrawal from the basin up to 1973 was 35.1 x 10^9 m^3, 70 percent of which had come from elastic storage. The 1973 Queensland report reiterated that the most economical long-term policy to conserve the resource was not to undertake expensive reconditiong of old flowing wells and maintain the existing area of flowing wells, but rather to aim at an ultimate total withdrawal rate for flowing and pumped wells commensurate with natural recharge rates under equilibrium. Randal (1978) described the hydrogeology, including hydraulics and groundwater chemistry, of a small area near the northwestern margin of the basin.

A review of the Great Artesian Basin as a whole is given in David (1950), and more recent information, though on a State basis in — Groundwater resources of Australia (Australian Water Resources Council, 1975). In this publication discharge from the basin was reported to be about 540 x 10^6 m^3/year, subdivided into Queensland — 330 x 10^6 m^3/year, New South Wales — 130 x 10^6 m^3/year, South Australia — 75 x 10^6 m^3/year, and the Northern Territory — 1 x 10^6 m^3/year. Further information on the Great Artesian Basin is shown in the Review of Australia's Water Resources 1975 (Australian Water Resources Council, 1976), where the abstraction during 1974 is listed as 526 x 10^6 m^3, the estimated annual recharge 410 x 10^6 m^3, the estimated number of wells in 1974 at 22 770, and the range of common individual well yields from 0.4 m^3/day to 5.2 x 10^3 m^3/day.

From 1971 to 1979 a basin-wide hydrogeological study of the Great Artesian Basin was carried out by the Bureau of Mineral Resources, Geology and Geophysics (BMR) at the request of the Australian Water Resources Council's Technical Committee on Underground Water. Objectives of this hydrogeological study were to review the geological and hydrological data of the multi-layered confined aquifer system of the Great Artesian Basin and to develop and apply a mathematical, computer-based model to simulate the groundwater hydrodynamics.

An outline of the hydrogeology of the basin is given in this paper, and the digital model GABHYD based on the finite difference approach is described by Seidel (1980). Results of the digital computer simulation model predictions of the future hydraulic behaviour of the basin following management interventions can be used for assessment, planning and management purposes on a regional scale of the basin's artesian groundwater resources (Habermehl & Seidel, 1979). The model calibration and application are given in Seidel (1978a, b).

A joint study of the isotype hydrology of the Great Artesian Basin has been carried out with the Nuclear Hydrology Group of the Isotype Division of the Australian Atomic Energy Commission since 1974.

Data sources and data collection

Basic data for the present hydrogeological and model study included the results of geological surface mapping by BMR and State Geological Surveys obtained during the 1950s to early 1970s. Geological maps at scale 1:250 000 and their accompanying notes cover most of the Great Artesian Basin; geological maps at scale 1:1 000 000 cover the entire area except South Australia. Subsurface information was obtained from several hundred petroleum exploration wells. Stratigraphic drill-holes, both shallow and deep, drilled by BMR and the State Geological Surveys provided additional data, as did drillers logs of waterwells, which are available for most flowing artesian waterwells and for some non-flowing artesian waterwells.

Identification and correlation of hydrogeological units was further possible from wire-line logs of waterwells in the Great Artesian Basin. BMR logged about 1250 waterwells in the basin during the period 1960 to 1975; in the New South Wales part of the basin about 235 waterwells and in the South Australia part 17 waterwells were logged by the Geological Survey of those States. As almost all existing waterwells are lined with metal (steel) casing, the types of wire-line logs which can be run in the wells are restricted.

Hydrological data were obtained from the files and records of the Irrigation and Water Supply Commission (IWSC) (now Water Resources Commission) in Queensland, the Water Conservation and Irrigation Commission (WCIC) (now Water Resources Commission) in New South Wales and the Geological Survey of the Department of Mines in South Australia. Records on flowing artesian wells contain the bulk of the available hydrogeological data; these wells represent the most significant artificial discharge points in the basin, and periodic measurements on discharge, pressure, temperature and chemistry have been carried out since the early development of the basin. Non-flowing artesian (generally called sub-artesian) waterwells produce much smaller discharges, and information on these wells is generally restricted to basic data obtained at completion.

An automatic data-processing, storage and retrieval system was designed to contain the basic waterwell data from the Great Artesian Basin. The fixed format of the data base, consisting of thirteen data type cards, is described in Ungemach & Habermehl (1973). Data on nearly all 4700 flowing artesian waterwells was collected and listed on the Master, Well casing and screen, Aquifer description cards which contain fixed information, and further on the Well discharge, Head and temperature, Hydrodynamics, Pump or flow test, and Total dissolved solids cards with contain time variable data. These data form the basis of the GAB-ADP data bank, from which hydrogeological analysis and most input data for the digital simulation model was prepared.

The data were sorted according to location (State and 1:250 000 map sheet), identification (well number), and type of data (type of cards) and subsequently checked, as described by Krebs (1973). Manipulation of the basic data was carried out by a large set of processing programs, some of which were reported in Krebs (1974). The storage and retrieval system of the data was described by Seidel (1973).

Groundwater exploration and development

Early exploration of the basin

Artesian water in the Great Artesian Basin in a shallow, flowing waterwell was first discovered south-west of Bourke (NSW) in 1878. Many shallow and deep wells were soon drilled, first near springs at the margin of the basin, as in New South Wales and in

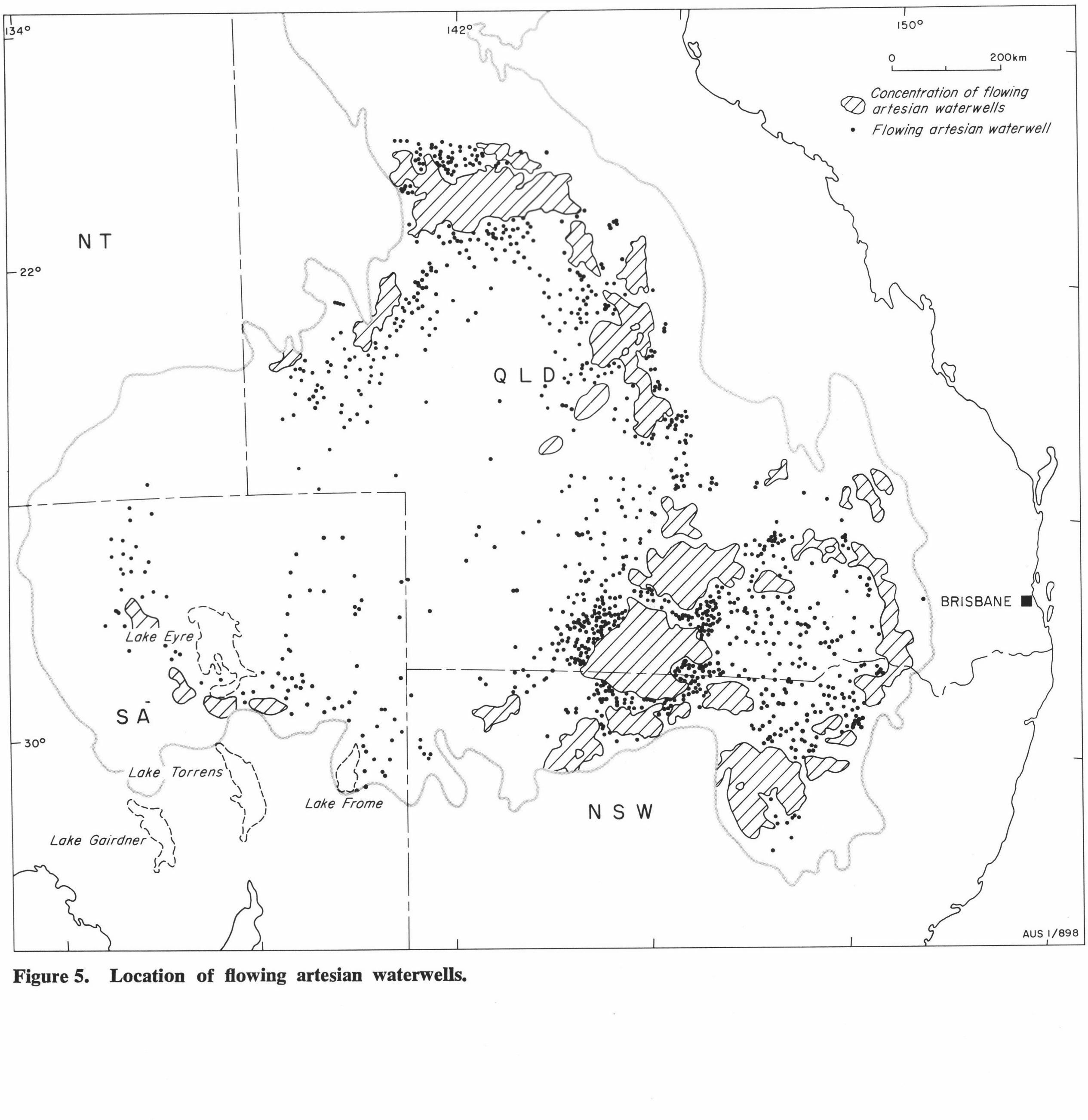

Figure 5. Location of flowing artesian waterwells.

South Australia west of Lake Eyre, but later further basinwards. Droughts and poor water supplies led to the drilling of the first deep artesian wells near the central Queensland towns of Cunnamulla and Barcaldine in 1887, and was followed by many others drilled for stock, domestic, and town water supplies. Drilling and geological investigations led to the discovery of artesian water nearly everywhere in the arid interior of the basin, and the extent of the artesian conditions was defined before the end of the nineteenth century.

Demand and utilisation of artesian groundwater

Flowing supplies of sufficient quantity and of good quality can be obtained from aquifers in most areas of the basin to support low density grazing. This pastoral activity requires relatively small amounts of water of acceptable quality for sheep and cattle from widely spaced watering points distributed over a large area.

Flowing artesian waterwells occur mainly in the northern, eastern and southern marginal areas of the basin, and in most of the south-central parts (Fig. 5). The economical drilling depths to the main artesian aquifers account for the relatively high well densities in these areas. Flowing artesian waterwells are almost absent in the central part of the basin, where the main aquifers occur at great depth. In these parts of the basin groundwater is obtained from shallower aquifers, though these aquifers produce more saline water under non-flowing conditions. In the eastern marginal parts there are many non-flowing artesian wells.

Most of the water derived from flowing artesian wells is distributed by open-earth drains or ditches, which in most areas run for many tens of kilometres through the flat countryside. The amount of the water distributed that is used by livestock is very low, much less than ten percent (Tandy, 1939, 1940); Queensland Government, 1954; Water Conservation and Irrigation Commission, 1971), or 1 to 2 percent (Ker, 1963).

Seepage and evaporation losses in these drains are considerable, and regular maintenance is required. The requirement in recent times to use polyethylene pipes for the distribution of water from new wells, in many cases in combination with metal tanks, automatic valves and windmill operated pumps, will probably assist in the wider distribution of water in a more efficient manner. Many government-operated wells and some privately owned wells are already equipped in this way.

Individual homesteads rely mostly on rainwater stored in metal tanks as a source for drinking water. If a waterwell tapping the main artesian aquifers is present near the homestead, then that water usually constitutes the main alternative supply for domestic purposes, with, in addition, possible storage in earth-tanks and permanent waterholes.

Nearly all towns in the Great Artesian Basin area are dependent for their water supplies on groundwater from the deeper aquifers in the basin. Although the flowing supplies are acceptable in quantity and quality, a minor inconvenience is the high water temperature, which needs to be reduced.

Pastoral, domestic and town water supplies are the main users of artesian water, and little if any other, including industrial applications, are found.

Groundwater from the Great Artesian Basin is generally chemically unacceptable for prolonged use for irrigation purposes on the soils in most areas, and State water authorities considered that stock and domestic requirements should have priority in water use, and that no artesian water should be used for irrigation.

Effects of development

The high initial discharge from individual wells — and from the basin as a whole — during the early years of exploitation, was mainly the result of the release at high pressure of water from elastic storage in the groundwater reservoir. This high flow rate gradually levelled off and diminished to a more steady artificial discharge rate, which approaches a steady-state condition (Fig. 6).

Approximately 4700 artesian waterwells in the basin originally flowed (about 3300 in Queensland, 1200 in New South Wales and 150 in South Australia). Many of these wells ceased flowing as the potentiometric surface fell below ground surface. At present about 2300 wells in Queensland, 650 in New South Wales and 150 in South Australia are still flowing. Most of the wells which ceased flowing are still in use, and being pumped (usually by windmill-operated pumps), as are most of the 20 000 original non-flowing artesian waterwells in the basin.

The potentiometric surface of the aquifers in the Lower Cretaceous and the Jurassic sequence was above the ground surface over the whole of the basin before exploitation began around 1880. Since then the regional potentiometric surface of the exploited aquifers in the Lower Cretaceous and Jurassic sequence has dropped by several tens of metres in many heavily developed areas (Fig. 7). Individual wells show falls of over 100 m. The heavy draw on the aquifers by the large number of freely or mainly freely flowing wells caused a marked lowering of the potentiometric surface in the immediate areas surrounding these wells. This process has been aggravated by the interference effect of relatively closely spaced wells, resulting in overlapping and accumulation of pressure drawdown cones and the resultant lowering of the regional waterlevels.

The potentiometric surface fell below the ground-surface in some highly developed areas near the margins and in the southeast-central part of the basin. As a result, flows from some flowing artesian wells ceased in those areas. However, in all areas where artesian waterlevels have been lowered below ground level, artesian water is well within economical pumping depths.

The significant change is that free-flowing wells ceased flowing, and that mechanically operated pumps had to be installed in these wells. The yield from pumped wells is usually very much less than from free-

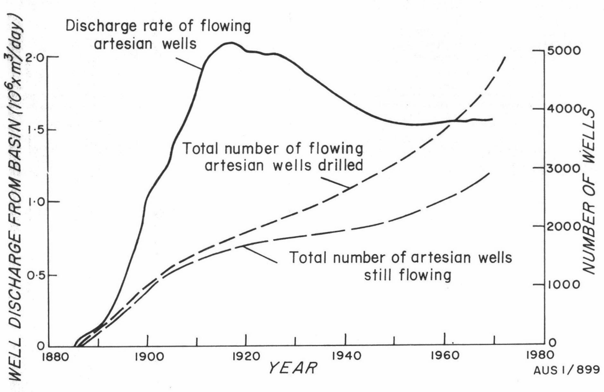

Figure 6. Discharge rate of flowing artesian wells, total number of initial flowing artesian wells drilled and total number of wells still flowing.

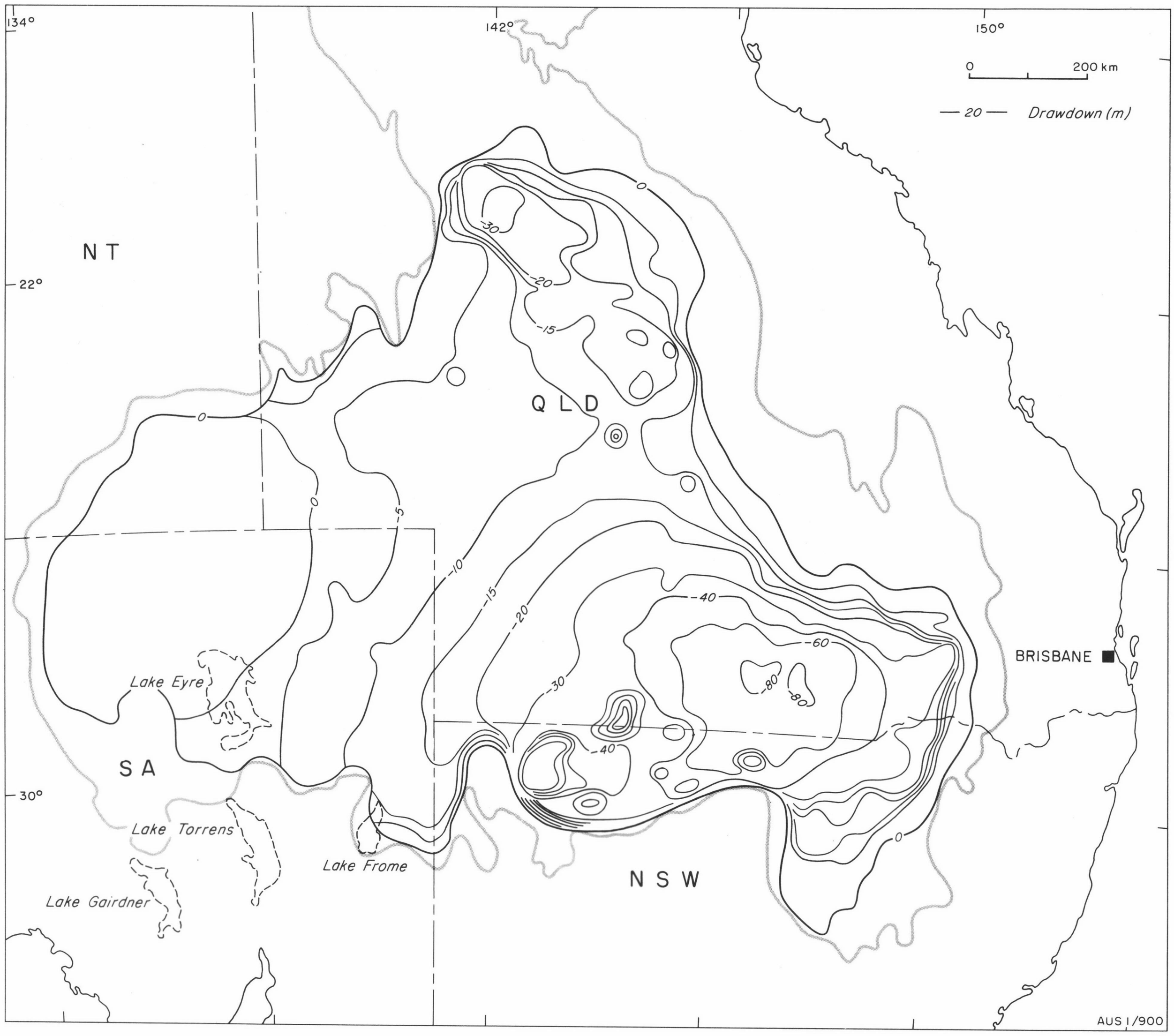

Figure 7. Regional drawdown (in metres) of the potentiometric surface of the main artesian aquifers in the Lower Cretaceous-Jurassic sequence following development during the period 1880 to 1970.

flowing wells, and no large-scale distribution system can be maintained by such wells.

The potentiometric surface of the aquifers in the upper part of the Cretaceous sequence has always been below the ground surface, consequently wells tapping these aquifers are non-flowing artesian, and have to be pumped. Because of their relative small discharge as compared with the high discharge from free-flowing artesian waterwells, the lowering of waterlevels in pumped wells is generally very much less . Regional drawdown in these aquifers is accordingly also much smaller. Data on waterlevels and exploitation rates of original non-flowing wells are sparse, in contrast to the amount of periodic measurements carried out on flowing artesian wells by State water authorities.

Exploitation of the basin's aquifers has caused significant changes in the rate of the various discharges in time (Fig. 6; Habermehl & Seidel, 1979, Seidel, 1980). Prior to development, the basin was in a natural steady-state condition, with an equilibrium between recharge and natural discharge, the latter by springs, vertical leakage and some lateral outflow. Following development, artificial discharge by wells became very prominent and vertical leakage and spring discharge diminished. A visible effect has been the diminution in flow from springs in the south-central and southwestern parts of the basin. Abstraction by wells caused a steepening of the hydraulic gradient and allowed more recharge water to enter the system.

At present a new steady-state condition has been reached in which total recharge and discharge are approaching equilibrium again (Fig. 6; Habermehl & Seidel, 1979; Seidel, 1980). Provided no new, major developments occur which will affect this equilibrium situation, discharge and potentials will not change significantly.

Geology

The Great Artesian Basin comprises the sedimentary Eromanga, Surat, and Carpentaria Basins and small upper parts of the Bowen and Galilee Basins (Fig. 8). Confined aquifers within the basin consist mainly of Triassic, Jurassic and Cretaceous continental sandstones. The aquifers alternate with low to very low permeability, confining beds consisting of siltstone and mudstone of continental or shallow-marine origin. The basins are mainly very broad synclinal structures trending northeast (Eromanga) or north (Surat and Carpentaria). They are contiguous across shallow ridges

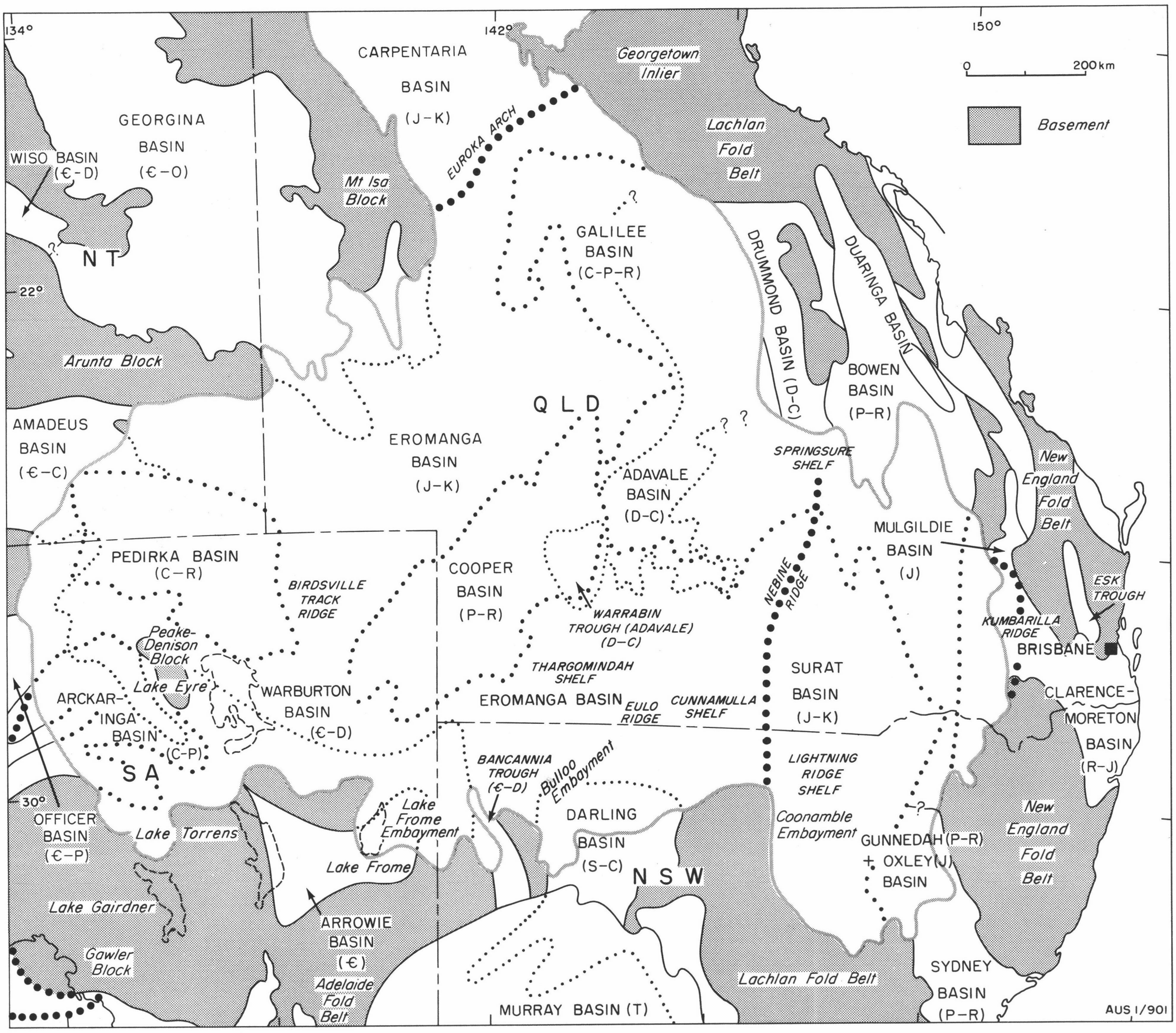

Figure 8. Constituent sedimentary basins, intermediate ridges and outlines of pre-Jurassic basins and their ages.

and platforms of older sedimentary, metamorphic or igneous rocks (Fig. 8). Similar rocks of pre-Jurassic age underlie the constituent sedimentary basins, and represent the impervious hydrogeological basement.

The Mesozoic sedimentary sequence present in the Great Artesian Basin reaches a maximum total thickness of about 3000 m in the central part of the Eromanga Basin. Marginal parts of the constituent geological basins have been partly eroded, particularly along the eastern rim which was uplifted during Cainozoic times. Sheet-like rock bodies are characteristic of the sedimentary basins, and persist relatively unchanged for hundreds of kilometres.

Notes on the constituent geological basins are given below:

Eromanga Basin. The Eromanga Basin (Fig. 8), which occupies about 1 x 10^6 km^2, consists of a conformable, almost horizontal sequence of Lower Jurassic to Upper Cretaceous sedimentary rocks (Parkin, 1969; Wopfner & others, 1970; Exon & Senior, 1976; Vine, 1976; Senior & others, 1978). The Jurassic sequence comprises continental quartzose sandstone, with lesser siltstone and mudstone. Siltstone, mudstone and lithic sandstone were laid down in shallow-marine environments during Early Cretaceous times. During the Late Cretaceous more sandy sediments were deposited in lacustrine and fluviatile environments. Most units crop out in the eroded eastern margin of the basin. Cretaceous outcrops in the central part are markedly weathered.

The Eromanga Basin is deepest where it overlies Palaeozoic and older Mesozoic sedimentary basins. The thinner sequences are present near the Nebine Ridge and Cunnamulla Shelf, where the Eromanga Basin connects with the Surat Basin, and across the Euroka Arch, where it connects to the Carpentaria Basin (Fig. 8). The Jurassic rock sequence thins and in places wedges out against these relatively shallow, buried basement structures near the southern part of the Eromanga, and also in the northern part.

Surat Basin. The southeastern part of the Great Artesian Basin is the sedimentary Surat Basin (Power & Devine, 1970; Exon, 1974, 1976; Allen, 1976; Exon & Senior, 1976) and occupies about 300 000 km^2 (Fig. 8). It consists of 2500 m of nearly horizontal sedimentary rocks of Jurrassic and Cretaceous age. The Jurassic sequence is an alternation of continental sandstone, siltstone and mudstone and some coal. The Cretaceous sediments consist of some continental, but mainly shallow-marine lithic sandstone and mudstone. Aquifers occur in many of the sandstone units; intake beds of these aquifers are present in exposures in the northern and eastern margins of the basin. The northern marginal area of the basin forms an erosional edge where Jurassic rocks unconformably overlie Triassic sediments of the Bowen Basin. Mesozoic sediments which connect the Surat and Eromanga Basins across the Nebine Ridge and Cunnamulla Shelf rest unconformably on Triassic sediments of the Bowen Basin and on the Palaeozoic sedimentary and igneous rocks of the Lachlan Fold Belt.

The Surat Basin intertongues with the Clarence-Moreton Basin across the Kumbarilla Ridge; this basin contains Triassic and Jurassic continental clastic sediments. Part of the eastern Surat Basin margin is controlled by a north-trending fault, but most of the northeastern, eastern and southwestern margins are bounded by Palaeozoic folded and faulted sedimentary and igneous rocks.

The Coonamble Embayment (Hind & Helby, 1969; Bourke & others, 1974; Hawke & others, 1975; Bembrick, 1976) forms the southern part of the Surat Basin, and is separated from the main part of the basin by the Lightning Ridge Shelf. The Jurassic rocks overlying the Gunnedah Basin in the most southeastern part of the Great Artesian Basin are referred to as the Oxley Basin (Bembrick & others, 1973; Bourke & others, 1974; Bourke & Hawke, 1977).

Carpentaria Basin. The northern extension of the Great Artesian Basin is the Carpentaria Basin (Doutch, 1976; Smart & others, in press), which occupies about 125 000 km² onshore and about 375 000 km² offshore in Queensland and the Northern Territory. It consists of continental rocks of Jurassic age, and mainly marine sedimentary rocks of Cretaceous age. The sequence is up to 1200 m thick and occupies a large north-trending syncline. Late Jurassic and Early Cretaceous rocks conceal the Euroka Arch, which is underlain by Proterozoic rocks (Smart, 1976).

Bowen and Galilee Basins. The uppermost sandstones in the Triassic sedimentary sequences of the Bowen and Galilee Basins contain aquifers which form part of the Great Artesian Basin; they are partly overlain by the Eromanga and Surat Basins. The Bowen Basin (Exon, 1974; Jensen, 1975; Paten & McDonagh, 1976) contains Permian and Triassic sedimentary rocks and forms an elongate, northerly trending basin. The main part is exposed in

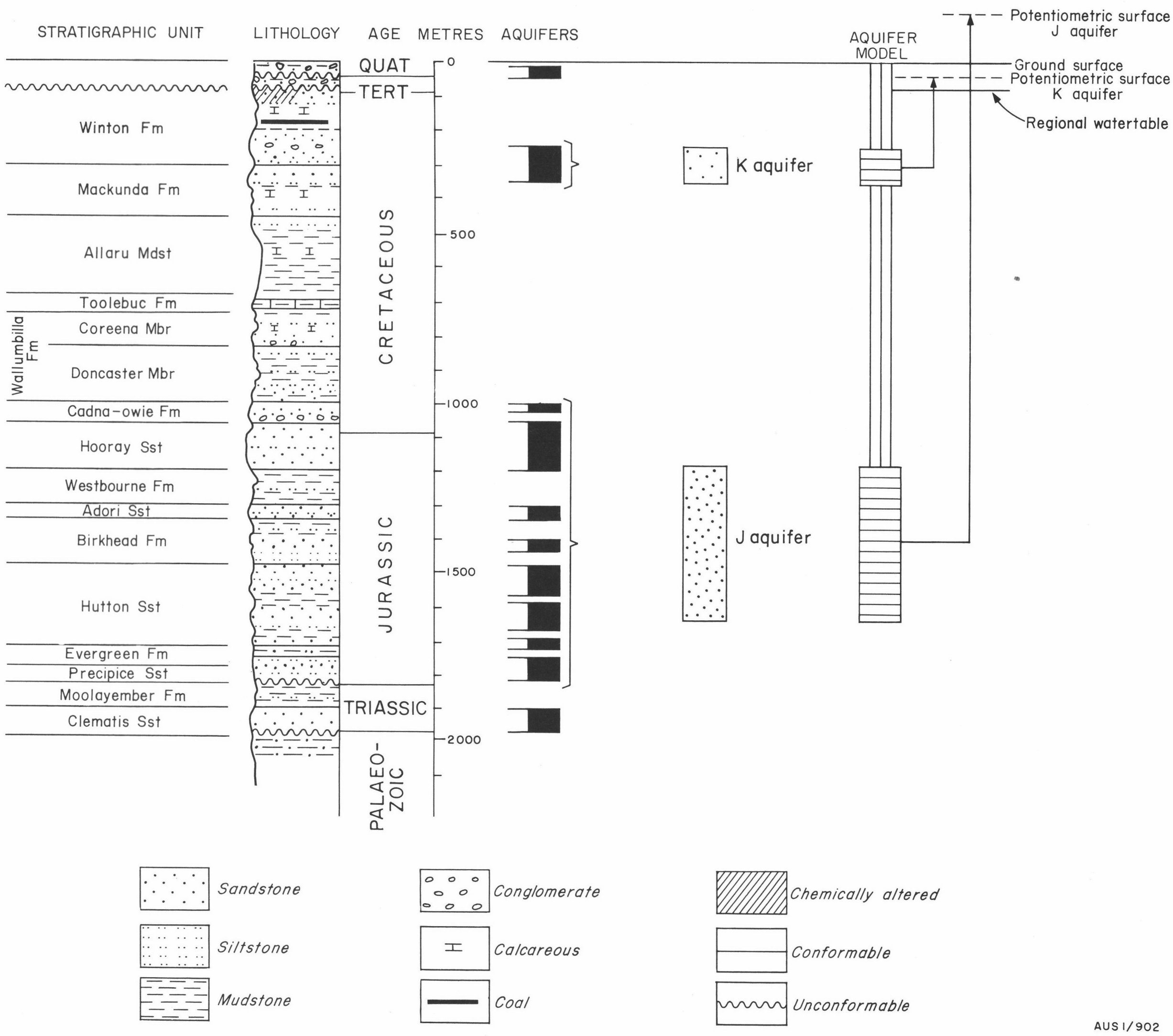

Figure 9. Schematic lithostratigraphic column of the Great Artesian Basin, simplified aquifer groups and potentials of the main (model) aquifers.

the north, the southern part is concealed beneath the Surat Basin. The Permian sediments consist of shallow-marine and continental deposits, and some volcanics; the Triassic sediments are continental. The Bowen Basin is bounded by older Palaeozoic rocks. The Narrabri Structural High separates the Bowen Basin from the Gunnedah Basin; the latter forms the transition to the Sydney Basin. The Bowen Basin intertongues with the Galilee Basin across the Springsure Shelf and the Nebine Bridge (Senior, 1971).

The Galilee Basin (Vine, 1976) contains up to 3000 m mainly of continental sediments of Late Carboniferous to Triassic age, which overlie older Palaeozoic sedimentary basins (Drummond, Adavale Basins) and Proterozoic rocks. Rocks are exposed along the eastern margin, but the main part of the Galilee Basin is concealed by the Eromanga Basin.

Cainozoic rocks. The Great Artesian Basin is partly concealed by Cainozoic continental sedimentary rocks as much as 150 m thick. These deposits mainly occur in the northeastern and southwestern parts of the Eromanga Basin, and cover almost the whole of the Surat and Carpentaria Basins (Wopfner & Twidale, 1967; Wopfner & others, 1974; Wopfner, 1974).

In the northeastern part of the Eromanga Basin, the northern part of the Surat Basin and in the eastern part of the Coonamble Embayment, Tertiary basalts cover some areas of Mesozoic rocks.

Stratigraphy

The stratigraphic succession present in the hydrogeologic Great Artesian Basin is given in summary form, excluding local marginal facies equivalents and minor units, in Figure 9 and Table 1. The distribution and correlation of these rock units of Middle or Early Triassic to Late Cretaceous ages in the sedimentary Bowen, Galilee, Eromanga, Surat and Carpentaria Basins, which constitute the hydrogeologic Great Artesian Basin are given in Figure 10.

Detailed descriptions of the lithostratigraphic units, their nomenclature and associated information is given in Hind & Helby (1969), Wopfner (1969), Wopfner & others (1970), Hawke & others (1975), Senior & others (1975), Exon (1976), Exon & Senior (1976), Smart (1976), Senior & others (1978) and Smart & others (in press).

Generally thin Cainozoic sediments (several tens of metres thick) overlie parts of the Great Artesian

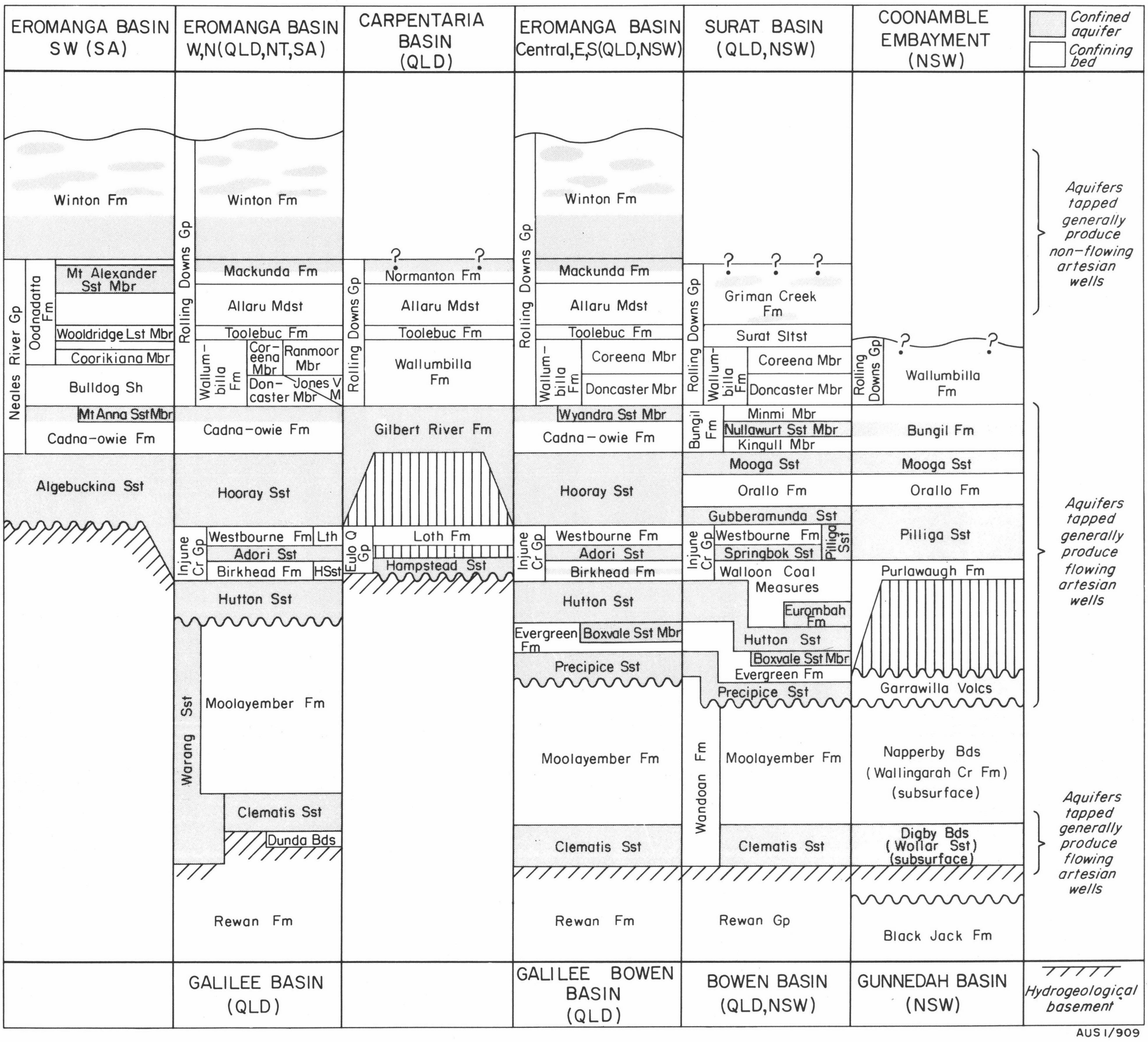

Figure 10. Correlation of hydrogeological units in the Great Artesian Basin.

Basin, and form shallow basins as much as 150 m deep. They rest on the deeply weathered erosional surface of the Cretaceous sediments; the older, Tertiary, sediments are also partly weathered and silicified, Quaternary sediments are mostly unconsolidated.

Structure

The Great Artesian Basin is an asymmetrical basin, elongated northeast-southwest, and tilted towards the southwest. The southern and northeast margins have slopes of about 2°, but in the west and southwest the regional dip increases to about 5°.

Tertiary uplift along the eastern margin, and subsidence in the central and southwestern parts, led to the basin's asymmetry and the present dominant southwesterly groundwater flow.

The broad structures in the basin are shown in Figure 11, a structure contour map of the top of the upper main aquifer producing flowing artesian wells (the base of the Rolling Downs Group, see Fig. 10) in the Jurassic-Cretaceous sequence in the Eromanga and Surat Basins.

Subsurface basement rises separating the Triassic and Jurassic-Cretaceous sedimentary basins are shown in Figure 8.

Many of the near-surface folds, particularly monoclinal features, grade downwards into faults and are the product of draping and differential compaction of the sediments over basement faults and fault-bounded basement blocks. Major fault and fold systems extend across the basin, sometimes forming in en echelon structures. Throws along major faults, affecting major aquifers, are as much as 300 m in the Eromanga Basin, and up to 150 m in the Surat Basin. Displacement of Jurassic-Cretaceous sediments along normal faults is usually much less, but considerable in some Permo-Triassic (1000-2000 m in the Bowen Basin) and older sediments.

Hydrodynamic conditions in the Great Artesian Basin, if considered on a basin-wide scale, will generally not be greatly influenced by the fold displacement of the sedimentary sequence. The faults are locally significant, in that they not only disconnect aquifers, and also give rise to hydraulic connection between different aquifers, but also act as preferential pervious or impervious structures, either to horizontal or vertical groundwater movement. However they do not significantly affect the broad regional flow patterns.

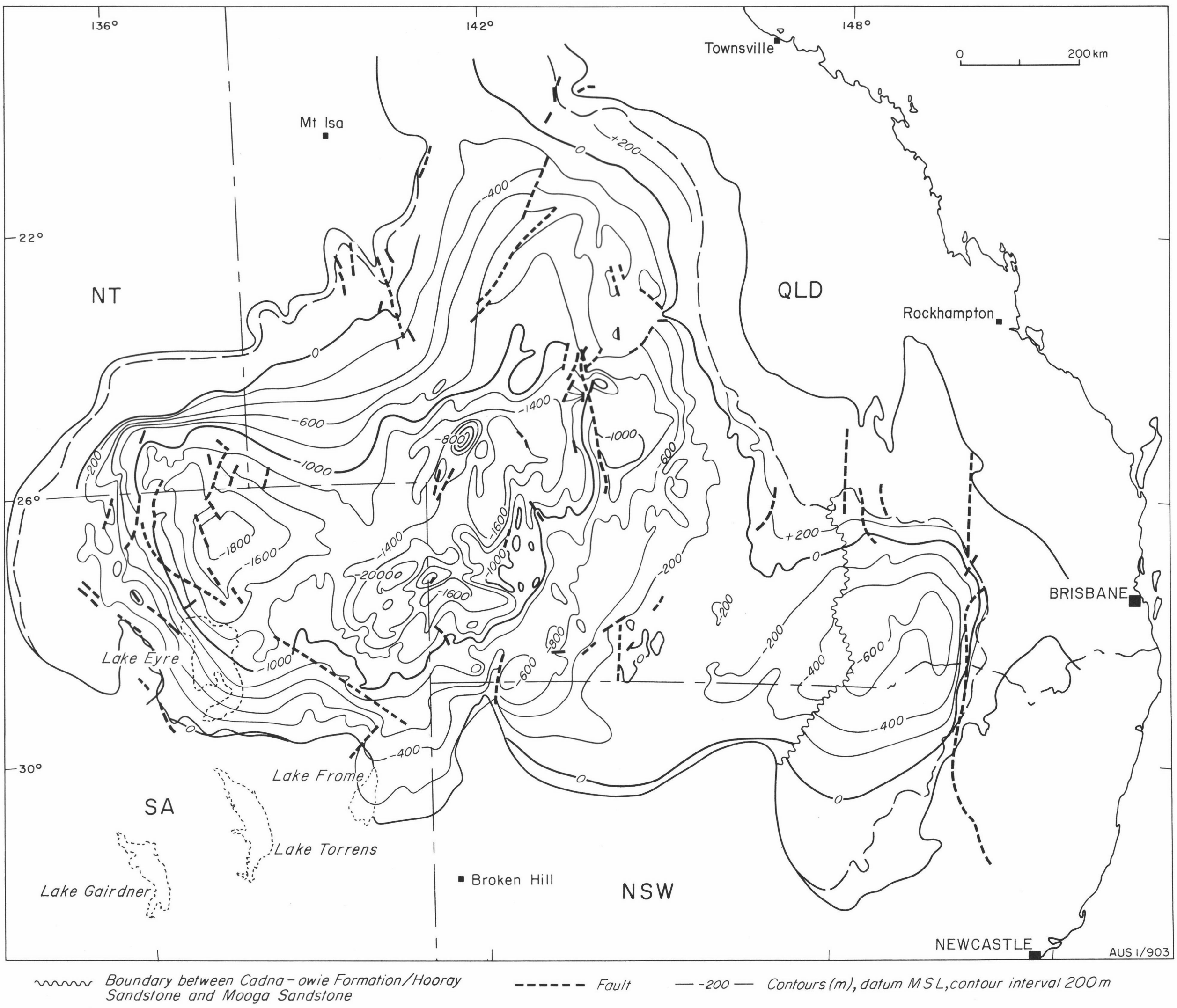

Figure 11. Structure contour map of the base of the Rolling Downs Group (Table 1 and 2) and top of the upper main aquifer producing flowing artesian wells in the Lower Cretaceous-Jurassic sequence.

Lithostratigraphic unit *Age*	*Thickness Average min.-max. (m)*	*Major lithology (environment of deposition)*	*Hydrogeologic characteristics, recharge, discharge, wells, yield and quality*
WINTON FORMATION Late Cretaceous Cenomanian	500 200-1200	Lithic sandstone, siltstone, mudstone. (Continental, fluviatile and lacustrine.) Upper part erosional surface, weathered and silicified	Confined aquifer, lenticular. Upper aquifer in Great Artesian Basin. Recharge in extensive outcrop areas; natural discharge from eroded anticlinal structures. Many shallow non-flowing artesian wells in central part of basin, wells pumped, low to moderate yield, water quality poor
MACKUNDA FORMATION Early Cretaceous Late Albian	60 30-250	Lithic sandstone, siltstone, mudstone. (Shallow marine to paralic.)	Confined aquifer, lenticular. Recharge in outcrop, no natural discharge. Many shallow non-flowing artesian wells in central part of basin, wells pumped, low yield, water quality poor
ALLARU MUDSTONE Early Cretaceous Late Albian	200 30-370	Mudstone, siltstone. (Shallow marine)	Confining bed. Thick uniform mudstone sequence. Extends across most of Eromanga Basin
TOOLEBUC FORMATION Early Cretaceous Late Albian	15 5-75	Bituminous and calcareous shale. (Shallow marine)	Confining bed. Excellent marker-bed because of organic-rich argillaceous sediments (in lithological logs and strong positive gamma-ray anomaly in gamma-ray logs). Outcrops near western, northern and southern margins of Eromanga Basin; extends across most of Eromanga Basin, and southern part Carpentaria Basin
GRIMAN CREEK FORMATION Early Cretaceous Middle to Late Albian	300 480	Lithic sandstone, siltstone, mudstone. (Shallow marine, grading from beach to fluviatile)	Confined aquifer, interbedded with confining layers. Sandstone aquifer small proportion of thickness. Recharge in northern margin of Surat Basin, in central part covered by Quaternary sediments, which form in part confining bed. No connection with pervious beds in Eromanga Basin. Shallow non-flowing artesian wells, pumped, low yield, water quality poor
SURAT SILTSTONE Early Cretaceous Early to Middle Albian	100 150	Siltstone, mudstone. (Shallow marine)	Confining bed, insignificant aquifer. Restricted to Surat Basin
OODNADATTA FORMATION Early Cretaceous Albian	150-600	Siltstone, mudstone. (Marine)	Confining bed, minor aquifers (Mt Alexander Sandstone Member). Restricted to southwestern part of Eromanga Basin
COREENA MEMBER (Wallumbilla Formation) Early Cretaceous Early to Middle Albian	100 25-200	Siltstone, mudstone. (Shallow marine and paralic)	Confining bed, minor aquifers. Recharge in outcrop in eastern margin of Eromanga Basin and Surat Basin. Shallow non-flowing artesian wells in eastern and southeastern Eromanga Basin and western Surat Basin; wells pumped, low yield, water quality poor
DONCASTER MEMBER (Wallumbilla Formation) Early Cretaceous Late Aptian	150 120-270	Mudstone, siltstone. (Shallow marine)	Confining bed, minor aquifers. Permeable sandstone beds at base. Recharge in outcrop in eastern margin Eromanga Basin and Surat Basin. Shallow non-flowing artesian wells in eastern and southeastern Eromanga Basin and western Surat Basin; wells pumped, low yield, water quality poor
BULLDOG SHALE Early Cretaceous Aptian/Albian	200-500	Mudstone, shale. (Marine)	Confining bed. Southwestern part of Eromanga Basin
CADNA-OWIE FORMATION Early Cretaceous Neocomian to Early Aptian	60 15-80	Quartzose and lithic sandstone, siltstone. (Paralic to shallow marine)	Upper part good confined aquifer, lower part poor aquifer or confining bed. Recharge in subsurface from aquifers in connecting Hooray Sandstone. Cadna-owie Formation restricted to subsurface in Eromanga Basin, except for outcrops in southwestern margins, where spring discharge occurs. Many shallow and deep flowing artesian wells, high yield, water quality good
WYANDRA SANDSTONE MEMBER (Cadna-owie Formation) Early Cretaceous Late Neocomian to Early Aptian	15 3-20	Quartzose sandstone with quartz pebbles. (Shallow marine, beach)	Good confined aquifer. Restricted to subsurface of central and eastern Eromanga Basin. Recharge in subsurface through lateral conection with Hooray Sandstone. Usually first aquifer in Eromanga Basin producing flowing artesian wells. Majority of flowing wells tap this aquifer; except in centre, because of depth. High yield, water quality good
BUNGIL FORMATION Early Cretaceous Neocomian to Early Aptian	150 100-300	Lithic and quartzose sandstone, siltstone, mudstone. (Paralic)	Confined aquifers and confining beds. Recharge in northern and eastern margins of Surat Basin. Many flowing artesian wells obtain water from these aquifers in northern Surat Basin. Moderate to good yields, water quality good
MINMI MEMBER (Bungil Formation) Early Cretaceous Early Aptian	20-70	Quartzose and lithic sandstone, siltstone, mudstone. (Paralic)	Confining bed, minor aquifers. Some flowing artesian wells
NULLAWURT SANDSTONE MEMBER (Bungil Formation) Early Cretaceous Early Aptian	20-30	Quartzose and lithic sandstone, siltstone. (Paralic)	Confined aquifer. Flowing artesian wells

Table 1. Main lithostratigraphic and hydrogeologic units in the Great Artesian Basin.

Lithostratigraphic unit Age	*Thickness Average min.-max. (m)*	*Major lithology (environment of deposition)*	*Hydrogeologic characteristics, recharge, discharge, wells, yield and quality*
KINGULL MEMBER (Bungil Formation) Early Cretaceous Neocomian	30-50	Lithic and quartzose sandstone, clayey. (Paralic)	Confining bed
GILBERT RIVER FORMATION Early Cretaceous Late Jurassic Neocomian	45 30-140	Quartzose and lithic sandstone. (Continental and shallow marine)	Confined aquifer. Recharge in eastern margins of the northern Eromanga Basin and Carpentaria Basin. Springs present in southeastern Carpentaria Basin. Flowing artesian wells, good yields and good water quality in northern Eromanga Basin, and (most wells) in southern Carpentaria Basin
HOORAY SANDSTONE Early Cretaceous Late Jurassic	150 45-400	Quartzose and lithic sandstone, siltstone, conglomerate, mudstone, coal. (Fluviatile, paralic, littoral)	Good, confined aquifer. Permeable throughout. Good permeability (intrinsic permeability several 100-several 1000 md) and porosity (average 25 percent). Transmissivity several 10 to several 100 (up to 1000) m^2/day, hydraulic conductivity 0.1 to 10 m/day. Recharge mainly in outcrop in eastern margin and small area of western margin of Eromanga Basin, northwestern Surat Basin. Discharge from springs in western margin and south-central part of Eromanga Basin. Most flowing artesian wells in Eromanga Basin obtain water from this aquifer. Good, to very good, yield (exceeding flows of 10 000 m^3/day), water quality good (500-1000 mg/l total dissolved solids, better quality than water from aquifers in Cadna-owie Formation. Wells tapping this aquifer throughout the basin; however, few in centre because of depth of aquifer
MOOGA SANDSTONE Early Cretaceous Neocomian	100 30-300	Quartzose and lithic sandstone, siltstone. (Fluviatile)	Confined aquifer. Recharge in outcrop in northern and eastern margins Surat Basin. Many flowing artesian wells obtain water from this aquifer in Surat Basin. Moderate to good yield. Water quality good
ORALLO FORMATION Late Jurassic	200 140-270	Lithic sandstone, siltstone, mudstone. (Fluviatile, lacustrine)	Confined aquifer in sandstone beds, more than half of total thickness is confining bed. Recharge in northern and eastern margins Surat Basin. Few wells in Surat Basin.
GUBBERAMUNDA SANDSTONE Late Jurassic	100 45-300	Quartzose to lithic sandstone, siltstone, mudstone. (Fluviatile)	Confined aquifer; aquifers more than half of total thickness. Recharge in northern and eastern margins Surat Basin. Many flowing artesian wells in Surat Basin obtain water from this aquifer. Good yield and water quality good
ALGEBUCKINA SANDSTONE Late Jurassic	25 20-350	Quartzose sandstone, conglomerate. (Fluviatile)	Good, confined aquifer. Generally permeable throughout. Good permeability and porosity. Restricted to southwestern part of Eromanga Basin. Recharge in western margin but main recharge by lateral connection with Hooray Sandstone in subsurface. Many mound springs in southwestern marginal area provide natural discharge. Most flowing artesian wells in southwestern part obtain water from this aquifer. Good, to very good yield (flow exceeding 5000 m^3/day), water quality good to very good
WESTBOURNE FORMATION Late Jurassic	100 60-200	Siltstone, mudstone. (Fluviatile, lacustrine, shallow marine)	Confining bed; minor confined aquifers in part of Surat Basin
ADORI SANDSTONE Middle to Late Jurassic	50 25-70	Lithic to quartzose sandstone. (Fluviatile)	Confined aquifer. Recharge in aquifer outcrop in eastern margin Eromanga Basin and northwestern Surat Basin. Some flowing artesian wells in eastern part of Eromanga Basin. Good supplies and water quality good
LOTH FORMATION Late Jurassic	60 50-100	Quartzose sandstone, siltstone. (Fluviatile)	Confining bed, minor aquifers. Few wells in northern Eromanga Basin and southern Carpentarian Basin
SPRINGBOK SANDSTONE Middle to Late Jurassic	60-250	Lithic sandstone, siltstone, mudstone. (Fluviatile, deltaic)	Interbedding of minor aquifers and confining layers. Recharge in northern and eastern margins Surat Basin. Few flowing artesian wells northern and central parts Surat Basin
BIRKHEAD FORMATION Middle Jurassic	100 30-130	Lithic sandstone, siltstone, mudstone. (Fluviatile, lacustrine)	Confining bed, some minor aquifers

Table 1 (cont.).

Lithostratigraphic unit Age	*Thickness Average min.-max. (m)*	*Major lithology (environment of deposition)*	*Hydrogeologic characteristics, recharge, discharge, wells, yield and quality*
PILLIGA SANDSTONE Middle to Late Jurassic	-300	Quartzose sandstone, conglomerate. (Fluviatile)	Good, confined aquifer. Permeable throughout. Good to very good permeability (intrinsic permeability 100-several 1000 md), good porosity (25 percent). Transmissivity several 10 to several 100, up to 1000 m^2/day, hydraulic conductivity 0.1 to 10 m/day. Recharge in outcrop of aquifers in eastern margin of Surat Basin. Very few springs in the western part of the Coonamble Embayment. Many flowing artesian wells (most wells in Coonamble Embayment) obtain water from this aquifer. Good to very good yield (exceeding 5000 m^3/day). Water quality good (500-1000 mg/l total dissolved solids), better quality than water from aquifers in higher aquifers
HAMPSTEAD SANDSTONE Late Jurassic	40 30-60	Quartzose sandstone, siltstone. (Fluviatile)	Confined aquifer. Recharge northeastern margin Eromanga Basin, southeastern Carpentaria Basin. Flowing artesian wells in northern Eromanga Basin and southern Carpentaria Basin
WALLOON COAL MEASURES Middle Jurassic	-650	Lithic sandstone, siltstone, mudstone. (Lacustrine, fluviatile)	Confining bed
PURLAWAUGH FORMATION Early to Middle Jurassic	10-120	Mudstone, sandstone, siltstone. (Fluviatile, lacustrine)	Confining bed
HUTTON SANDSTONE Early to Middle Jurassic	150 120-250	Quartzose and lithic sandstone, siltstone, mudstone. (Fluviatile, lacustrine)	Good, to very good confined aquifer. Most of formation is permeable. Moderate to good permeability (intrinsic permeability several 10-several 1000 md), good porosity (25 percent). Recharge eastern margins of Eromanga Basin, and northern and eastern margins Surat Basin (partly east of surface water divide). Some flowing artesian wells mainly near northern, northeastern and eastern basin margins, restricted elsewhere by depth. Good yield (flows 5000 m^3/day) and good quality. Water quality better than for water from higher (Jurassic and Cretaceous) aquifers (lower total dissolved solids values)
EVERGREEN FORMATION Early Jurassic	10-260	Siltstone, mudstone. (Fluviatile, lacustrine, deltaic, shallow marine)	Confining bed. Northern and central Surat Basin, eastern Eromanga Basin
BOXVALE SANDSTONE MEMBER (Evergreen Formation) Early Jurassic	45-90	Quartzose sandstone, siltstone. (Fluviatile, lacustrine)	Confined aquifer. Recharge in eastern margin Eromanga Basin, northern margin Surat Basin. Some flowing artesian wells and artesian wells near basin margins. Good yield and good quality
PRECIPICE SANDSTONE Early Jurassic	45-150	Quartzose sandstone, siltstone. (Fluviatile, lacustrine)	Good, confined aquifer, especially lower, coarser sandstone. Good to very good permeability (intrinsic permeability several 10-20 000 md), good porosity (20 percent). Recharge in outcrop in eastern margin Eromanga Basin, northern margin Surat Basin. Some springs 'overflow' in margin of northern Surat Basin. Flowing artesian and artesian wells near basin margins. Good yield and water quality good
GARRAWILLA VOLCANICS Late Triassic to Early Jurassic	-180	Trachyte and trachy-basalt lavas, tuff. (Interbedded lavas, sills)	Confining bed
MOOLAYEMBER FORMATION Middle Triassic	200-1500	Siltstone, mudstone. (Fluviatile, lacustrine, deltaic, shallow marine)	Confining bed
NAPPERBY BEDS Middle Triassic	15-200	Siltstone, mudstone. (Fluviatile)	Confining bed
CLEMATIS SANDSTONE Middle to Early Triassic	20-300	Quartzose to lithic sandstone. (Fluviatile)	Good, confined aquifer. Lowest aquifer in the Great Artesian Basin. Permeable throughout. Moderate to good permeability (intrinsic permeability 5-3000 md), moderate to good porosity (20 percent). Recharge in aquifer outcrop eastern margin Galilee Basin and northern margin Bowen Basin (east of topographic watershed). Flowing artesian and artesian wells near eastern margins of the basin. Good yield and water quality good
DIGBY BEDS Early Triassic	200	Quartzose sandstone, siltstone. (Fluviatile)	Confined aquifer. Few wells
WARANG SANDSTONE Middle to Early Triassic	-700	Quartzose sandstone, siltstone. (Fluviatile)	Confined aquifer
REWAN FORMATION/GROUP (Middle to) Early Triassic	-3500	Mudstone, siltstone, lithic sandstone. (Fluviatile, lacustrine, aeolian)	Confining bed

Table 1 (cont.).

Groundwater hydrology

Hydrogeological units

The Great Artesian Basin consist of confined aquifers and confining beds throughout the Middle Triassic to Late Cretaceous sedimentary sequence in the constituent sedimentary Bowen, Galilee, Eromanga, Surat and Carpentaria Basins. Confined aquifers are present within a rock sequence, which, where complete, is bounded by the Rewan Group at the bottom, and the Winton Formation at the top (Table 1; Figs. 9, 10).

Aquifers are present in the Clematis, Precipice, Boxvale, Hutton, Adori and Hooray Sandstones, and in the Cadna-owie Formation and their equivalents, as well as in the Mackunda and Winton Formations (Table 1; Figs. 9 and 10). Most of the aquifers are continuous and hydraulically connected across the constituent geological basins. Aquifers in Tertiary and Quaternary sedimentary rocks and sediments, which are partly confined, but mostly unconfined, with a discontinuous distribution, are not considered part of the Great Artesian Basin.

The major confining beds consist of the Rewan Group, Moolayember, Evergreen, Birkhead, Westbourne, Wallumbilla and Toolebuc Formations, and their equivalents, as well as the Allaru Mudstone, and parts of the Mackunda and Winton Formations (Table 1; Figs. 9, 10).

Hydrogeological basement comprises impervious sedimentary, metamorphic or igneous rock, and this basement forms in part an aquiclude or aquifuge.

The aquifers of the Great Artesian Basin are generally well separated from high salinity water in Permian and older units, except in the southwestern part, where Permo-Triassic strata are in direct contact with Jurassic aquifers (Youngs, 1975a, b). Confining beds further north separate aquifers in the Hooray Sandstone from higher salinity water in Cambrian and Ordovician carbonate sediments of the Georgina Basin (Randal, 1978). In part of the Galilee Basin, the Clematis Sandstone extends further westward than the overlying and confining Moolayember Formation, resulting in a hydraulic connection between the aquifer in the Clematis Sandstone and the aquifers in the Hutton or Precipice Sandstones. As a result of the onlapping nature of the Jurassic and Lower Cretaceous sedimentary sequence, migration of water occurs from aquifers in the lower part to aquifers higher in the sequence, where these units subcrop against impervious basement, as along the northern margin of the Thargomindah and Cunnamulla Shelves.

Most sandstones in the Triassic, Jurassic, and Cretaceous sedimentary sequence in the Great Artesian Basin are aquifers. Separate aquifers within individual sandstone units, though distinguished in drillers and geophysical well logs, were not studied in this regional hydrogeological study. Instead groups of aquifers were considered, which correspond broadly to aggregates of individual aquifers occurring in lithostratigraphic units (Table 1; Figs. 9, 10). Most of the lithostratigraphic units which contain a significant component of sandstone, represent the major aquifers of the Great Artesian Basin. Confining beds are represented by rocks with relatively low permeabilities and consist of mudstone and siltstone.

Most of the lithostratigraphic units have a rather uniform geometry, lithology, structure, texture, and depositional origin throughout the basin. Similar generalities apply to the hydraulic characteristics of the aquifers and the confining beds; in detail, however, the hydraulic properties, including the permeability and porosity of the rocks, show marked differences laterally and vertically.

Hydraulic characteristics of the aquifers and the confining beds

Transmissivity values determined from test data generally range from 1 to 2000 m^2/day: low values, usually less than 10-20 m^2/day, predominate in the south-central and most eastern parts of the basin. Higher values, in the order of 10s and 100s m^2/day, are present in the northern and southern parts.

Transmissivity values were calculated from data derived from periodical systematic tests carried out by the State water authorities since the early development of the basin, on flowing artesian waterwells in the Queensland and New South Wales parts of the basin. Hydraulic tests include recovery (static pressure) tests for wells which were found flowing, and constant drawdown (flow recession) tests for wells which were found with the headwork valves completely or partially closed. Step drawdown (dynamic) tests, being either an opening dynamic test for a closed well or a closing dynamic test on a flowing well were also carried out by these organisations. Transmissivity values include results from approximately 200 step drawdown tests on flowing artesian wells in Queensland which were analysed by R. N. Eden and C. P. Hazel of IWSC (now QWRC), unsing a modified version of the Sternberg method (Kruseman & De Ridder, 1970, Eden & Hazel, 1973).

Field data from recovery and drawdown tests in New South Wales were transcribed and transmissivity values determined using the modified Jacob method (Kruseman & De Ridder, 1970). Hydraulic conductivity values generally range from 0.1 to 10 m/day, the majority being in the lower part of that range; some higher values occur. No particular pattern or preferred distribution is apparent, though such a distinction is difficult to establish with the distribution and amount of data available (about 350 wells with hydraulic conductivity values). Almost all wells are completed in aquifers in the Cadna-owie Formation, Hooray Sandstone (and their equivalents) and the Pilliga Sandstone, and therefore almost all the available transmissivity and hydraulic conductivity values come from these aquifers.

Storage coefficient values of the aquifers tapped could not be determined from the data obtained by the tests carried out without observation wells. An empirical method, using the relationship between aquifer porosity and the storage coefficient was used to derive the latter. In most petroleum exploration wells drilled through the basin sequence, sonic or acoustic logs were run, though these logs (as most other geophysical logs in these wells) do not cover the upper parts of the Cretaceous sequence. Porosities of permeable layers in the Cretaceous-Jurassic sequence were calculated (Keys & McCary, 1971, Schlumberger, 1972), as the lithology was known from the lithological log and from other geophysical logs run in the boreholes and converted into storage coefficient values. For aquifers where no logs were available Lohman's (1972) approximation was used, where $S = 3.3 \times 10^{-6} \times$ thickness of the aquifer (m). Storage coefficient values obtained by either of the two methods result in values averaging about 10^{-5} (range from 10^{-4} to 9×10^{-5}).

Intrinsic permeability, average effective porosity (percentage of bulk volume) and average density (dry bulk and apparent grain) values were determined by the Petroleum Technology Laboratory of BMR from many core samples of the aquifers sequences encountered in petroleum exploration wells and stratigraphic drillholes, as well as outcrop samples. Some results are reported in Petroleum Search Subsidy Acts publications, in Gray (1972), and well completion reports of stratigraphic holes drilled by the Geological Surveys of New South Wales and Queensland. Intrinsic permeability and porosity values range from several tens to several thousands of millidarcys, and from about 10 to 30 percent respectively; they decrease with depth.

The vertical flow from one aquifer to another is restrained by the very low permeability of the confining beds which are assured to be leaky. Hydraulic parameters of the confining beds could not be determined from the available data. An approximate vertical hydraulic conductivity value of the confining beds was calculated (Audibert, 1976). Confining beds in petroleum exploration wells were defined from geophysical logs and subdivided into four rock types according to their dominant lithology. Each rock type was assigned a value (Todd, 1959; Castany, 1967): sandstone—10^{-1} m/day; sandstone, siltstone, shale—10^{-2} m/day; shale, siltstone, sandstone—10^{-3} m/day; shale—10^{-4} m/day. The conductivity values were distributed according to the thickness of each layer, and produced an average value for the total thickness of the confining unit. Average vertical hydraulic conductivity values were obtained from

$$K_{av} = \frac{D}{\frac{d_1}{K_1} + \frac{d_2}{K_2} + \dots \frac{d_n}{K_n}}$$

in which D = total thickness confining unit, d_1 = thickness layer 1, K_1 = vertical hydraulic conductivity of layer 1 (International Institute for Land Reclamation and Improvement, 1972; Bouwer, 1978). The resultant average vertical hydraulic conductivities of confining beds in some parts of the sequence intersected by petroleum exploration wells in the basin range from 10^{-1} to 10^{-4} m/day.

Recharge

Outcrop areas of aquifers, most of which provide the opportunity for recharge to the aquifer units, occur mainly along the eastern margins of the basin (Fig. 12).

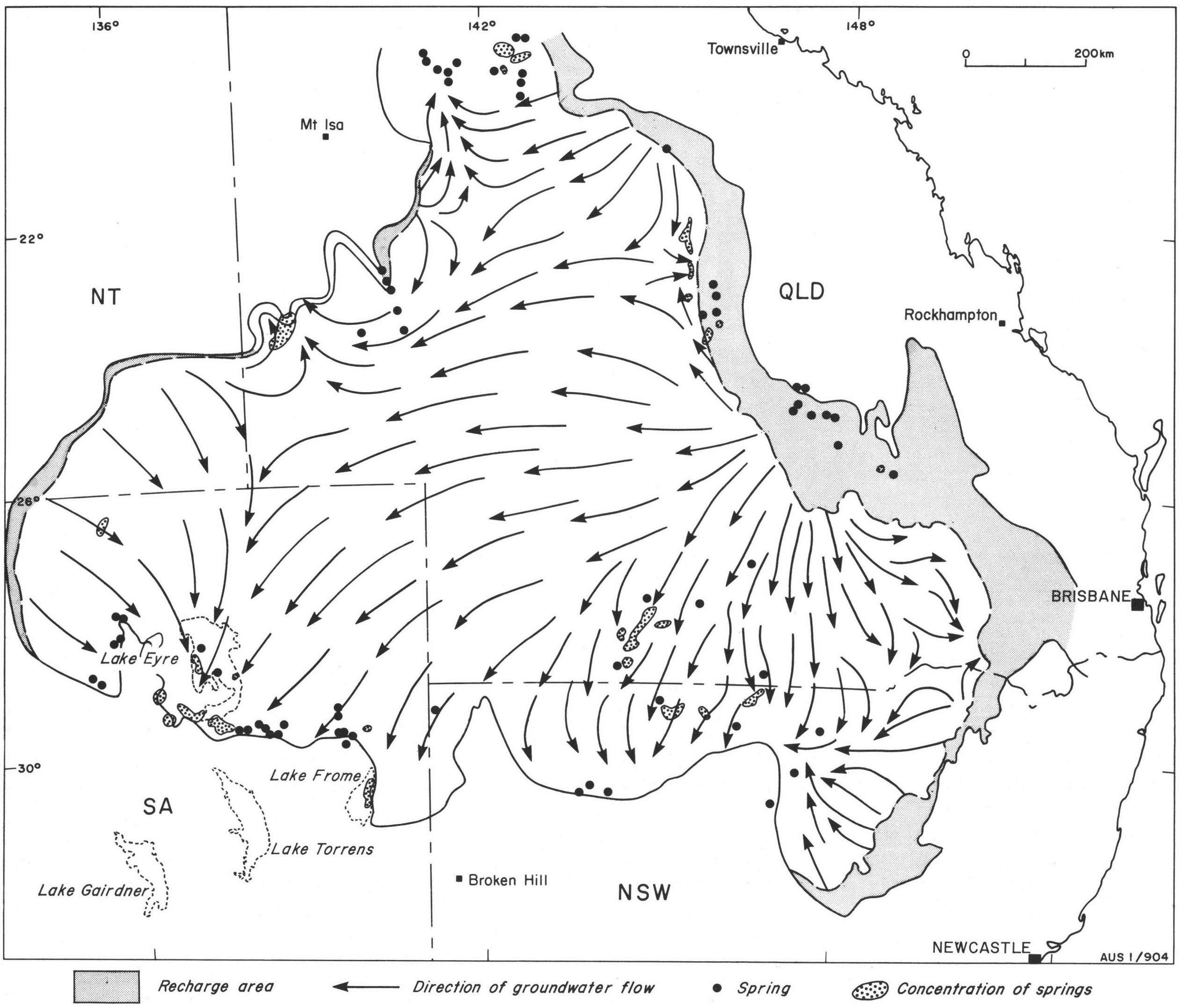

Figure 12. Recharge and natural discharge (springs) areas and directions of regional groundwater flow in the Great Artesian Basin.

Most recharge areas are on the western slope of the Great Dividing Range (though some aquifers in rocks of Triassic age outcrop on the eastern side of the surface watershed), and vary from scarp-bounded plateaus and cuestas to alluvial or rolling country, traversed by creeks and rivers. Some recharge takes place through Cainozoic sandy sediments overlying sandstone units, as in the eastern part of the Surat Basin.

Outcrops of aquifers and subcrops of aquifers in the Jurassic-Cretaceous sequence overlain by sandy sediments along the western margins of the Great Artesian Basin provide the possibility of recharge in those areas (Fig. 12). Randal (1978) also inferred recharge in the northwestern area.

Gradients of the potentiometric surfaces of confined groundwater in the aquifers of the Cretaceous and Jurassic rock sequence indicate the flow of the groundwater, and the occurrence of surface recharge has been interpreted from the distribution of well potentials (Fig. 15). Studies of environmental isotopes from water of wells in areas basinwards of the recharge areas support the assumption of continuing recharge from geological to modern times (Airey & others, 1979; Calf, in prep.). Stable-isotope (D/H and $^{18}O/^{16}O$) results show unequivocally that the artesian water is of meteoric origin. Observed systematic variations in chloride levels of water samples with distance from the recharge area probably reflect variations in the mean annual rainfall and the rate of infiltration of recycled salt throughout the Late Quaternary; the minimum and maximum of the chloride curve correlate with the last glacial and interglacial period respectively (Airey & others, 1979).

Discharge

Discharge from the Great Artesian Basin takes place as natural discharge in the form of concentrated outflow from springs, vertical leakage towards the regional watertable, subsurface outflow into neighbouring basins, and as artificial discharge by means of free artesian flow and pumped abstraction from wells drilled into the aquifers.

Springs occur in groups, mainly in the marginal areas of the basin (Fig. 12); many appear to be fault-controlled, others occur where aquifers abut impervious basement rocks or where only thin confining beds are present.

Discharges from individual springs range up to 85 l/sec; the total discharge of all known springs (*c*350), which form eleven groups, is estimated at about 1500 l/sec. Many are only seepages or are no longer flowing; spring discharges generally have declined since the early development of the wells in the basin. The largest concentrations of springs are in the southern, south-central and southwestern parts of the basin; the area southwest and northwest of Lake Eyre contains the largest and most active springs. Williams (1979) stated that 95 percent of the natural discharge in South Australia occurred from the group of springs at Dalhousie (Williams & Holmes, 1978), northwest of Lake Eyre, near the State border. Springs are commonly characterised by conical mounds of sand and silt-size sediment and carbonate, which range in height and diameter from a few metres to tens of metres (Fig. 13). Some of the larger mounds have waterfilled craters. Springs near Lake Eyre were described by Williams (1974, 1979), and Cobb (1975); some data on mound springs in Lake Frome is given in Draper & Jensen (1976). Springs in eastern areas are described by Ball (1918), Jensen (1926), and Rade (1954b, 1955).

The discharge of some springs is sufficient to maintain small creeks for hundreds of metres or some kilometres in this arid region, in which evaporation and evapotranspiration is very high. Vegetation lines some of these streams and surrounds many of the springs, whereas usually swampy areas and large, bare salt plains are present away from many of the springs.

Few historical records exist on springs in the basin, but diminishing spring discharge in the northwestern area, following well development, is shown by figures in Interstate Conference on Artesian Water (1913), David (1950), Queensland Government (1954), Whitehouse (1954) and Randal (1978).

Some springs in the eastern marginal part of the basin owe their flows to 'overfilling' of aquifers in nearby recharge areas (rejected recharge).

Southwest of Lake Eyre several ancient non-active mound-springs occur more than 40 m above the surface of the surrounding plain. The present, lower landsurface in this area is partly the result of tectonic movement and dissection, but mainly from deflation (Wopfner & Twidale, 1967; Bowler, 1976). Lowering of the spring outlet levels has resulted from the combined action of a series of step-wise stages of lowering of the landsurface by erosion and denudation, and the breakthrough of water at a lower level. The latter caused a reduced flow from higher springs. Clogging of the upper outlet of springs by sediments and (carbonate) cement, and the resulting lower-level breakthrough and discharge of water, has a similar effect.

Vertical leakage from the confined aquifers upwards through the confining beds, which are considered semi-pervious, probably occurs over extensive areas of the basin, and despite the low percolation rate, involves a considerable volume of water. High evaporation rates and a deep phreatic surface (generally several tens of metres below the ground surface), disguise vertical leakage. Areas most likely to be influenced by concentrated leakage from aquifers, as inferred from the potentiometric maps of the aquifers in the Jurassic and Cretaceous sequences, are the western part of the Coonamble Embayment, and parts of the southern and western margins of the Eromanga Basin. Contributions from upward groundwater movement could be obliterated by the surface water inflow in some of these areas (Fig. 3). Intermittent river systems, large swamps and lakes are present in these possible discharge areas. The relative high groundwater table in the Lake Eyre region during long dry periods suggest upwards leakage

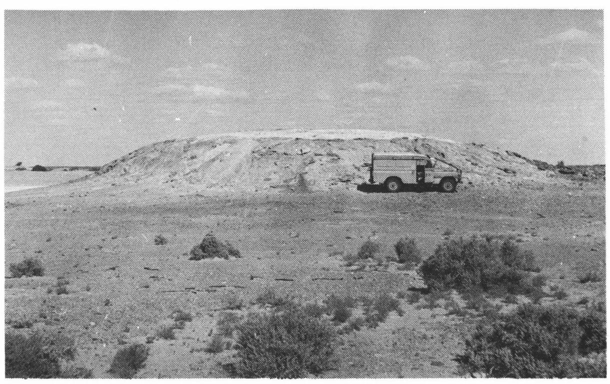

Figure 13. Moundspring in the area near Lake Eyre.

from the underlying confined aquifers in the Cretaceous and Jurassic sequence.

Geological evidence suggests that subsurface outflow into any of the surrounding or underlying basins is negligible. Though connections exist with the Moreton and Sydney Basins, effective groundwater divides are present, preventing subsurface outflow. Inflow is possible through aquifers in the Hutton Sandstone across the Kumbarilla Ridge. Hydraulic continuity is present across the Euroka Arch, and outflow directed northwards occurs into the southern part of the Carpentaria Basin through the aquifers in the Jurassic-Cretaceous sequence, as shown by potentiometric maps (Fig. 12, 15). Some of this water may eventually emerge through sub-sea springs in the Gulf of Carpentaria.

Most groundwater from the Great Artesian Basin is exploited from flowing artesian waterwells (Figs. 5, 6), which are up to 2000 m deep, but average about 500 m. Flows from individual wells exceeded 10 000 m^3/day (more than 100 l/sec), but the majority have much smaller flows. About 3100 of the original 4700 flowing artesian wells drilled remained flowing during the early 1970s. The accumulated discharge rate of these wells at the time was about 1.5 x 10^6 m^3/day, compared to the maximum flow rate of about 2 x 10^6 m^3/day from about 1500 flowing artesian wells around 1918 (Fig. 6).

Flowing artesian waterwells (Fig. 14) obtain their water from aquifers in the Lower Cretaceous and the Jurassic sequence (mainly the upper aquifers), and the original non-flowing artesian waterwells generally tap the aquifers in the Winton and Mackunda Formations (Figs. 9, 10; Table 1). These non-flowing wells are generally shallow, and several tens to hundreds of metres deep. It is estimated that these generally windmill-operated pumped wells supply on average 10 m^3/day. Most wells drilled to aquifers in the Lower Cretaceous, Jurassic or Triassic sequence encountered Upper Cretaceous aquifers higher in the hole; the latter aquifers are usually cased off, as the water is of poor quality. A proportion of wells drilled into aquifers in the pre-Rolling Downs Group part of the sequence obtain their supplies from more than one aquifer unit (or formation). Most wells produce from perforated or slotted casing intervals opposite aquifers, or from an interval of open hole in the aquifer below the casing. Almost all existing waterwells are lined with metal (steel) casing in the form of a single telescopic string or several strings of different diameter (usual diameter about 300, 250, 200, or 150 mm).

Flow rates and potential data of individual wells, when plotted against time, show curves with high initial flow rates and pressures. Most curves flatten out with time, and ultimately approach asymptotic shapes similar to the curve of accumulated discharge rate in Figure 6 for the period 1918 to about 1960.

The areal distribution of high (initial) flowrates is fairly uniform in the areas of development, and the accumulated discharge taken from specific areas (usually from the highest aquifer in the Lower Cretaceous-Jurassic sequence) relates mainly to the density of wells in the area and the prevailing net pressure—the head or waterlevel elevation above groundlevel to which the free-flowing discharge is directly related. Most of the flowing artesian wells tap aquifers in the Cadna-owie Formation, the Hooray Sandstone and the Pilliga Sandstone. A few wells obtain water from aquifers below the Hooray Sandstone; in such cases they usually tap aquifers in the Hutton and Clematis Sandstones. Only a small number of flowing artesian wells originate from aquifers in the upper part of the Cretaceous sequence.

Groundwater levels

Potentiometric maps showing the conditions during the early years of development and around 1970 for the main aquifers in the Lower Cretaceous-Jurassic sequence—which produce flowing artesian wells—are given in Figure 15a and b respectively. These maps were prepared with the GABHYD simulation model (Seidel, 1980); all available potential data were used and some manual adjustments made.

First waterlevel readings in newly drilled, widely spaced wells during the early years of development represent data for almost undisturbed aquifer conditions, approximating the natural steady-state condition of the groundwater basin.

Measurement of water levels in the Great Artesian Basin commenced with the drilling of the first waterwells, and were repeated until the present on a periodical basis on most flowing artesian wells. Potentiometric surface maps, covering only parts of the basin, are included in Gregory (1906), Pittman (1914), Interstate Conference on Artesian Water (1913, 1914, 1922, 1925, 1929), Ward (1922), Tandy (1939, 1940) and Ogilvie (1954) and Randal (1978). Ward (1946) only showed a map with the general direction of groundwater movement.

Enough pressure data are now available for wells tapping specific aquifers, and ground elevation data of wells, to prepare reliable potentiometric contour maps of large parts of the basin for certain time intervals.

State water authorities systematically measured pressure heads of existing flowing artesian wells, usually by reading pressure gauges as the flowing well was closed and pressure built up. Water levels of original non-flowing artesian wells are usually only measured at the time of completion of the well.

Pressure-head values recorded in the GAB-ADP system during the present study, were recalculated using a standard equivalent of pure water at 15°C, and the potentials determined. Corrections caused significant changes for temperature effects, but because of the low salinity of the groundwater, only a negligible effect for the latter. Most pressure-head values relate to wells tapping aquifers in the Hooray Sandstone and its equivalents (including the Pilliga Sandstone, which is the main aquifer tapped by wells in the southeastern

Figure 14. Flowing artesian waterwell in the Great Artesian Basin (WRC-NSW Reg. No. 4263—Four Posts-2; depth 1174 m, flow 35 l/sec, wellhead temperature 57°C; aquifer Pilliga Sandstone).

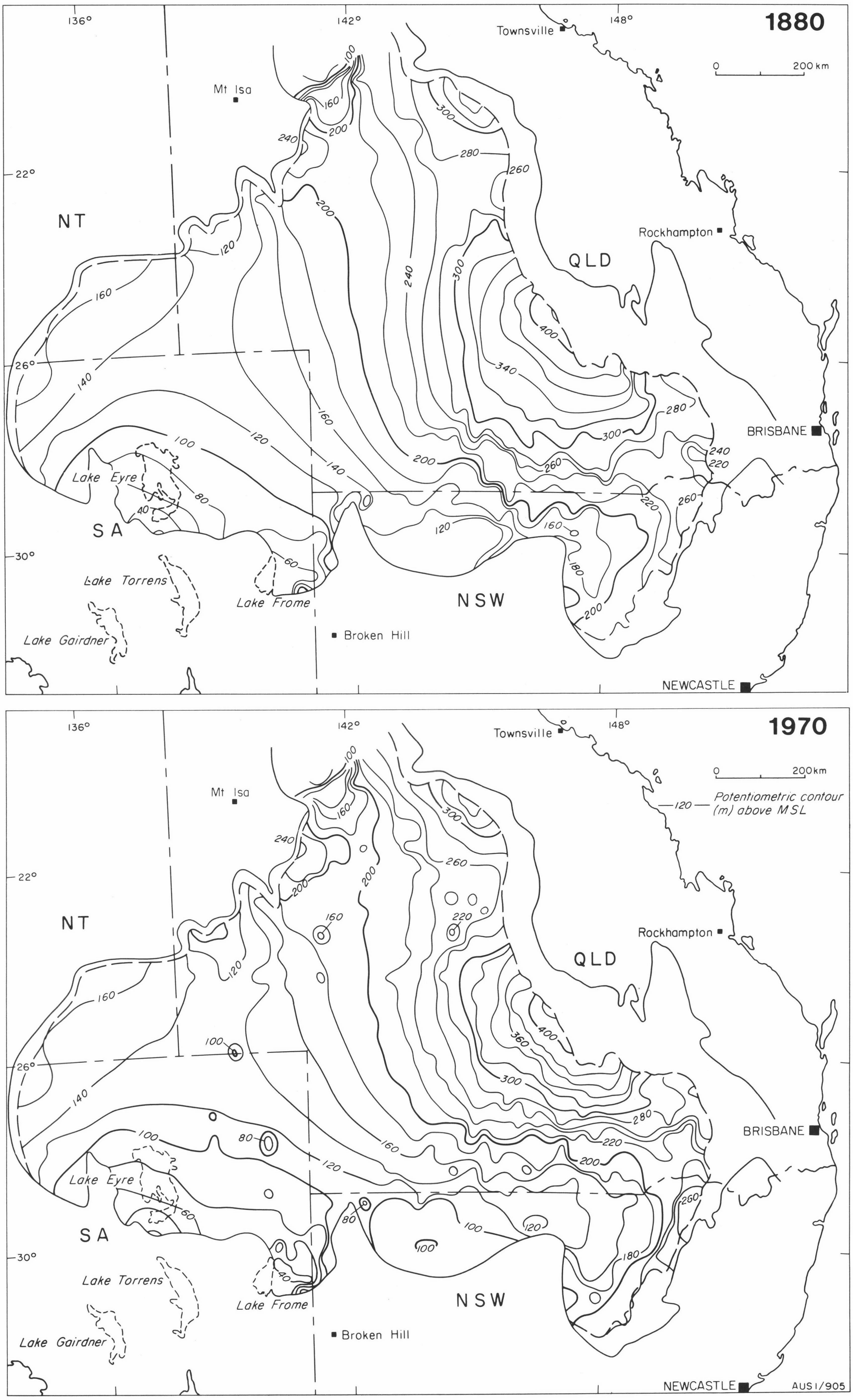

Figure 15. Potentiometric maps of the main aquifers in the Lower Cretaceous-Jurassic sequence during 1880 and 1970, modified from GABHYD simulation model results, using all available potential data. Datum is mean sea level, and potentials relate to pure water at 15°C.

part of the basin) and few data are available for other aquifers.

Waterlevels recorded during drilling of wells include those encountered in the upper confining beds of the sequence, which are regarded as the upper boundary of the saturated zone, and as such the regional watertable (Fig. 16). It is the uppermost expression of the (leaky) artesian system of the Jurassic and Cretaceous aquifers (Fig. 9). The generalised contour map of the regional watertable has a marked resemblance to the topographic contour map; this proven affinity between the regional watertable and the topography in areas with dense data coverage has been used to extrapolate contours to those parts of the regional watertable map, where few data points are available. Local confined and unconfined aquifers, usually as perched aquifers in Cainozoic sediments overlying the Great Artesian Basin sequence, have been ignored.

The change in waterlevels as a result of development is shown in Figure 7. The concentration of development in some of the marginal areas (Fig. 5) led to considerable changes in the patterns of isopotential contours (Fig. 15). Hydraulic gradients of aquifers in the Lower Cretaceous and Jurassic sequence (Fig. 15) changed in some areas from 1:2150 to 1:1750, and from 1:2300 to 1:1600. Hydraulic gradients of aquifers in the upper part of the Cretaceous sequence are about 1:1800. Changes to potentials of the aquifers in the upper part of the Cretaceous are much smaller during the period of development because of the small rate of withdrawals. Furthermore, a relatively large part of these Cretaceous aquifers is unconfined; in these areas, relatively few changes are expected in the regional watertable which represent the waterlevel of this aquifer.

Groundwater movement

Regional groundwater movement in the basin, as determined from the potentiometric surface maps of the aquifers in the Jurassic and Cretaceous sequences (Fig. 15), is shown in Figure 12.

Convergence of flow and steepening of the hydraulic gradient coincides with the occurrence of springs near the Eulo Ridge, and the lowering of transmissivities reflects thinning of aquifers. Similar preferential drainage patterns are also present in the southeastern part of the basin. Along the northwest margin of the basin an area of outflow is bordered by two areas of inflow.

In some areas faults locally displace or disconnect aquifers, and obstruct part or all of the groundwater flow in the main Early Cretaceous and Jurassic aquifers, which is normally directed to these structures. Little is known about the hydraulic character of these faults, which could act as impermeable barriers or as preferential permeable zones.

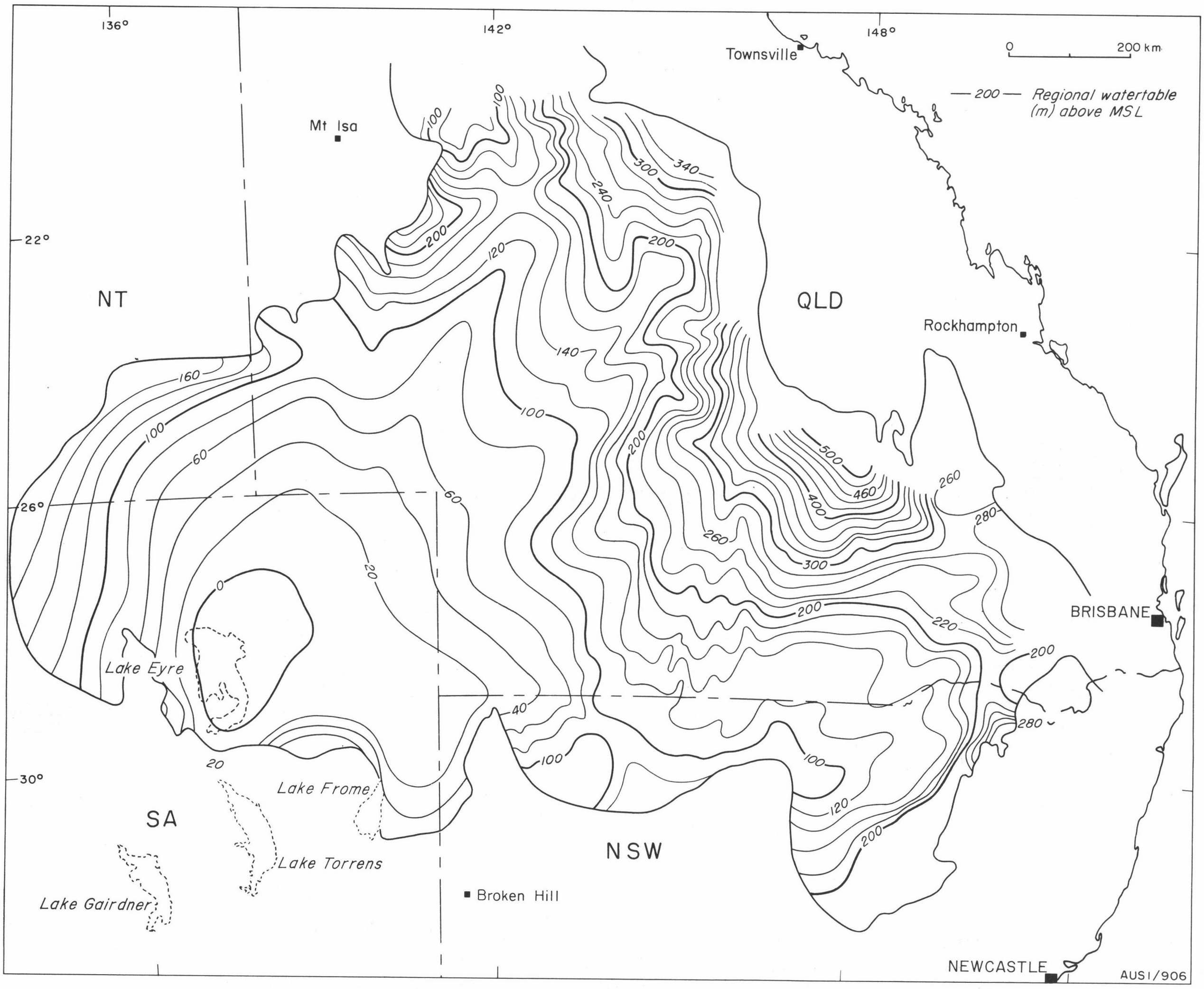

Figure 16. Regional watertable in the Great Artesian Basin.

Where they act as barriers, flow directions will have changed, and salinity of semi-stagnant water could increase. Hydrocarbons, from either the marginally mature or mature Eromanga Basin sequence or the underlying Cooper, Galilee or Adavale Basins, and transported by the groundwater flow, could accumulate and be trapped near such faults in stagnant or semi-stagnant zones (Senior & Habermehl, 1980). Upward migration of warm artesian water through permeable zones near the Canaway Fault, is indicated by the geothermal gradient (Polak & Horsfall, 1979; Senior & Habermehl, 1980).

Estimate of the average groundwater velocity can be made with the equation $\bar{v} = \frac{Ki}{p}$ where $\bar{v}$ = average velocity, K = (horizontal) hydraulic conductivity; i = hydraulic gradient, p = porosity (decimal fraction). Groundwater movement in the main aquifer in the Lower Cretaceous-Jurassic sequence in the eastern marginal areas of the basin have average velocities ranging from about 1 to 5 m/year. These values for the rate of flow of artesian groundwater severely restricts the application of ^{14}C dating (Airey & others, 1979). Residence time determinations with this naturally occurring isotope are limited to relative short distances from the recharge areas of the aquifers, as ^{14}C has a half-life time of 5730 years and the method can be used only for water with ages up to about 30 000 to 40 000 years. Application of ^{36}Cl, which has a half-life time of about 308 000 years would be more suitable for the dating of very old groundwater (Elmore & others, 1979), such as in the Great Artesian Basin, i.e., where it has moved over considerable distances.

Groundwater chemistry

Groundwater in the most widely exploited aquifers in the Lower Cretaceous and Jurassic sequence is generally of good quality, containing usually about 500 to 1000 mg/1 total dissolved solids, mainly sodium bicarbonate with some chloride and minor sulphate. A higher chloride and sulphate content is present in the most western parts of the basin (Fig. 17). The salinity values tend to increase near discharge areas. Some results of chemical analyses carried out from 1968 to 1978 by the Government Chemical Laboratories of Queensland, and the Chemical Laboratories of Department of Mines, New South Wales; Department of Mines, South Australia; Water Resources Branch, Northern Territory Administration; and Australian Atomic Energy Commission, on groundwater samples from the main aquifers in the Lower Cretaceous-Jurassic sequence in different parts of the basin are

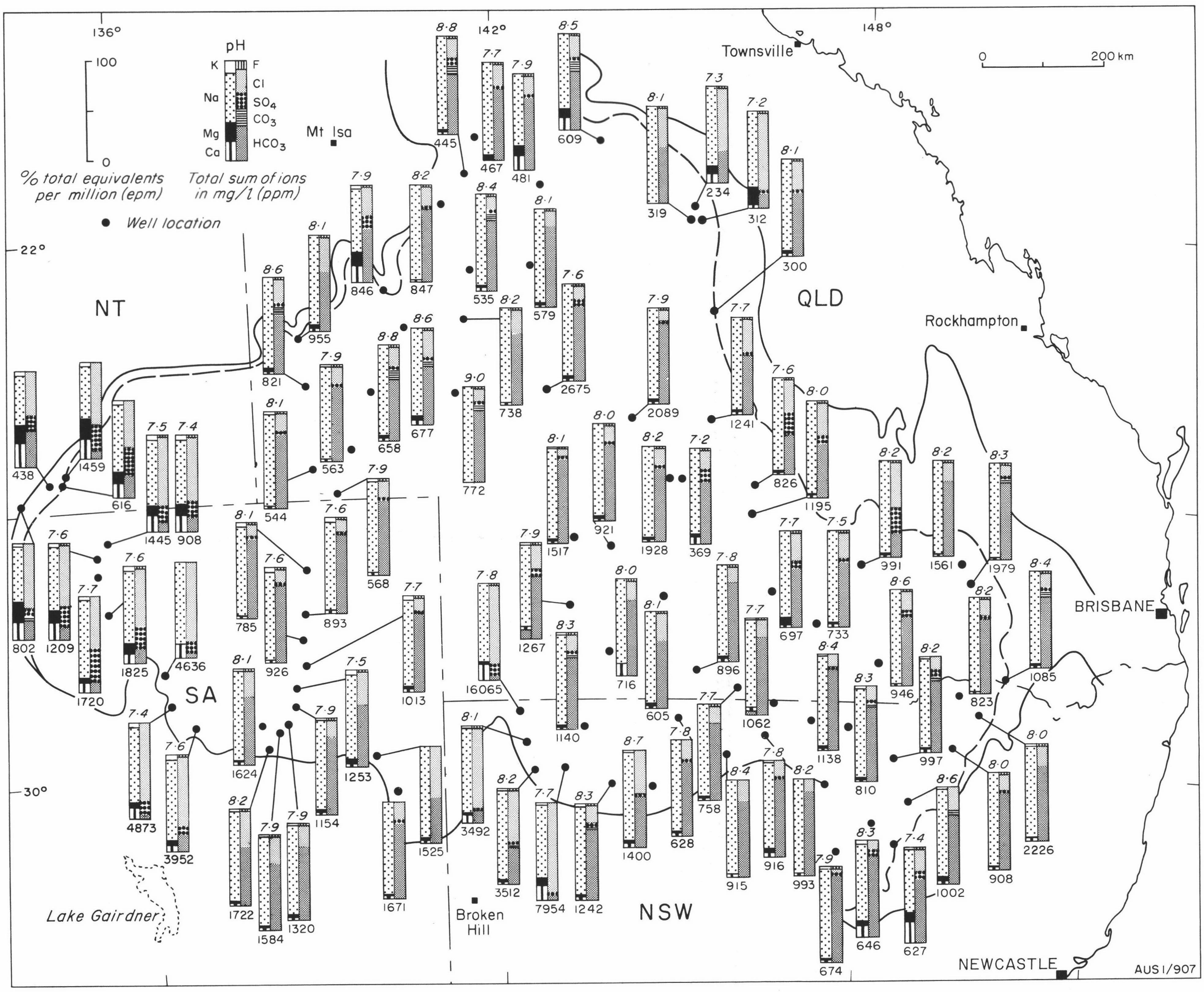

Figure 17. Chemical compositions of groundwater from selected flowing artesian wells tapping aquifers in the Lower Cretaceous-Jurassic sequence.

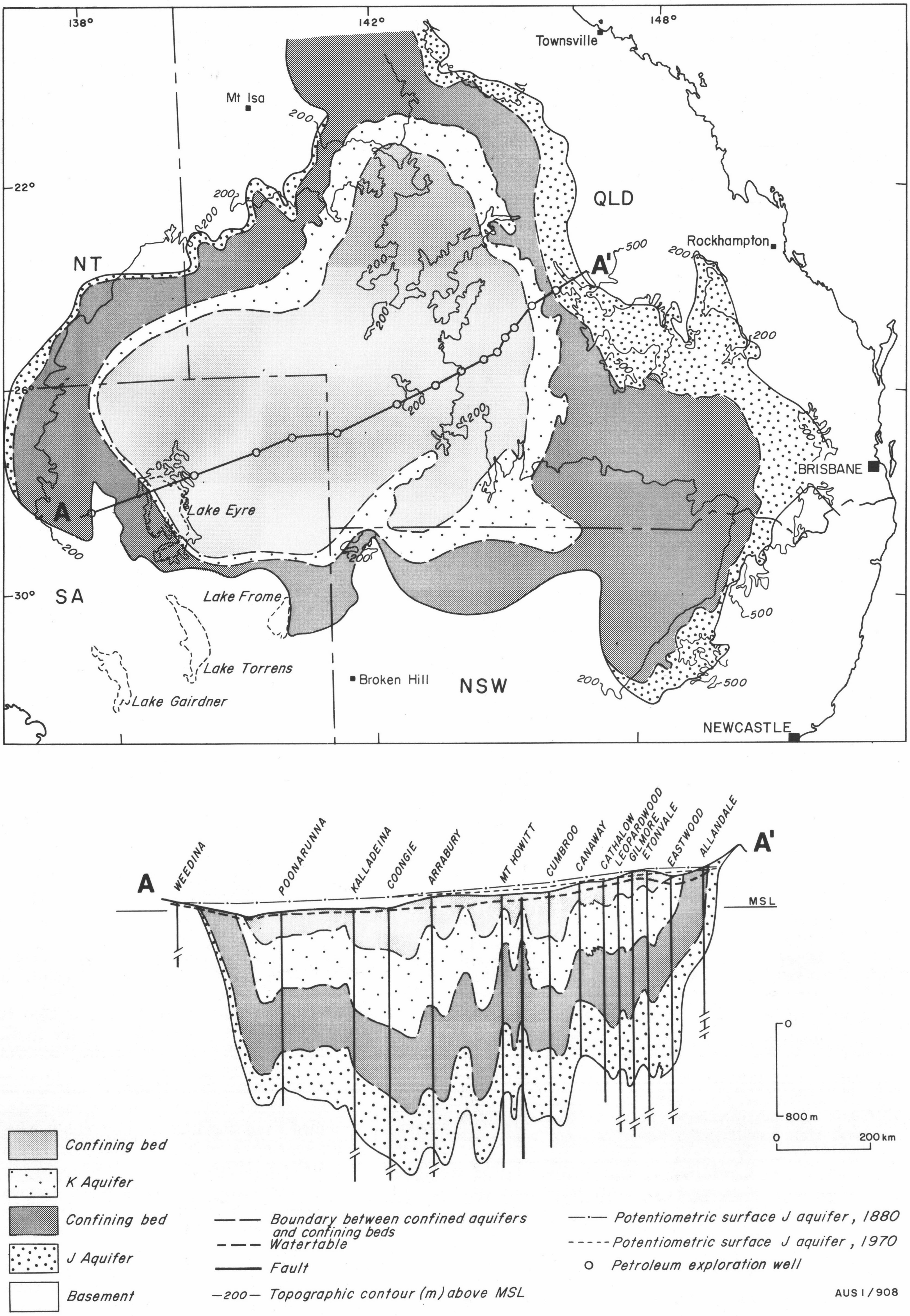

Figure 18. Lateral extent of simplified hydrogeological (model) units and cross-section.

shown in Figure 17. Other examples of groundwater chemistry occur in Australian Water Resources Council (1975) and Randal (1978).

Aquifers lower in the Jurassic sequence generally contain water of better quality than the aquifers higher in the Lower Cretaceous-Jurassic part of the sequence, though the proportion of chemical constituents is similar. Poor quality water of much higher salinity than the main, lower aquifers, occurs in aquifers in the Winton and Mackunda Formations. From detailed analyses the State water authorities usually indicate the suitability of the water in each well for drinking, domestic, stock and irrigation purposes.

The water quality generally prohibits use for irrigation, because of high sodium content and high residual alkalinity. The quantity of groundwater required for large irrigation projects would probably represent a further restriction. The chemistry of the groundwater indicates a high to very high sodium hazard, and a medium to high salinity hazard.

Hydrochemical indications of groundwater flow directions were provided by Jack (1923), who determined the southwest and southeast directed flow near Lake Eyre from a potentiometric map, and discovered that westward-moving water, originating from the eastern margin, is characterised by carbonate ions, and eastward-moving water from the western recharge areas, by sulphate (the latter causing rapid corrosion of well casings—Stanley, 1971). The eastward-moving water was shown to have a much higher salinity and a higher chloride content than the good-quality westward-moving water.

Several areas in the northeastern and southeastern parts of the basin contain water that corrodes well casings, mainly because of dissolved carbon dioxide.

In the southeastern part of the basin, results by Andrews (1976) show that some hydrochemical trends are consistent with flow patterns determined from potentiometric maps. Hydrochemical and environmental isotope studies confirm the groundwater movement basinwards of the recharge areas near the eastern margins (Airey & others, 1979; Calf, in prep.).

Groundwater temperatures

The temperatures of water in wells tapping aquifers in the Early Cretaceous and Jurassic generally range from about 30° to 50°C, but in many areas of the basin temperatures at the wellhead are as much as 100°C. Spring temperatures range from about 20° to 40°C.

Geothermal gradients in the Great Artesian Basin range from 15.4°C/km to 102.6°C/km, with a mean of 48°C/km (Polak & Horsfall, 1979). Seventy-five percent of these values exceed the world average of 33°C/km. Temperature data (Polak & Horsfall, 1979; Senior & Habermehl, 1980) were obtained from continuous temperature logs run in flowing and non-flowing artesian wells during BMR's wireline logging program in the Basin from 1960 to 1975, and from petroleum exploration wells (Senior & Habermehl, 1980). Geothermal gradients in the basin are also given in Thomas (1960), Heyl & Thomas (1964), and Hind & Helby (1969).

High gradients occur where shallow basement rocks are present, adjacent to some major faults, and near some discharge areas.

Modelling the groundwater system

A model to simulate the hydrodynamics of the Great Artesian Basin has been developed (Seidel, 1980); this digital computer model (GABHYD), based on finite difference approximation, replaced an earlier version (GABSIM; Ungemach, 1975). After calibration (Seidel, 1978a) it has been applied to predict the hydraulic behaviour of the groundwater basin following management interventions (Seidel, 1980; Habermehl & Seidel, 1979). The results are satisfactory for broad, regional assessment purposes, planning and management decisions, and preparation of recommendations for future exploitation in the basin.

Input data and model prototype

To model the multi-layered real system, a simplified aquifer model was proposed (Fig. 9), which consists of a confined aquifer (K or Cretaceous aquifer, corresponding to the aquifers in the Winton and Mackunda Formations), and a lower aquifer (J or Jurassic aquifer, corresponding to the aquifers in the Lower Cretaceous-Jurassic part of the sedimentary sequence; in parts of the eastern areas the J aquifer includes Triassic aquifers). The aquifers in a simplistic conception of the complex groundwater system, are overlain by confining beds which correspond to the confining beds in the Cretaceous sequence above the aquifers in the Winton Formation, and the confining beds (the main confining unit in the Great Artesian Basin) between aquifers in the Mackunda and Cadna-owie Formations (Fig. 10). The components of this simplified model or prototype, are represented in Figures 9 and 18, and form the link between the real-life system and the digital computer simulation model, which consist of a set of mathematical equations.

Grouping of aquifers in the Jurassic aquifer was necessary because of the complexity of the many aquifers and the paucity of hydraulic data from individual aquifer groups. Most waterwells tap aquifers in the Cadna-owie Formation, and the Hooray and Pilliga Sandstones and their equivalents, resulting in a disproportionate amount of hydraulic data for these aquifers, and a paucity of data for other aquifers. Although pressures are higher in the deeper aquifers in the sequence, the differences are relatively small. Hydraulic heads from individual aquifers in the Cretaceous-Jurassic part of the sequence in neighbouring wells, and heads measured from different aquifers in individual wells, do not show significant differences, and justify the model simplification.

The geometry of the aquifer model or prototype is shown in Figure 18. The boundaries of the units broadly correspond with the boundaries of the lithostratigraphic units which made up the original hydrogeological units. An exception to this is the boundary of the model Cretaceous aquifer, which was mainly determined from the occurrence of non-flowing artesian wells tapping the Winton and Mackunda Formations (Audibert, 1976).

Hydraulic characteristics of the prototype include simplifications based on assumptions derived from the hydrogeological analysis. Flow in the model aquifers is considered to be in the plane of the aquifers only, and the vertical components of flow within the aquifers are neglected. In the confining beds the horizontal flow component is neglected and only the vertical component is taken into account. These assumptions allow the application of Hantush's leaky artesian aquifer scheme (Hantush, 1960; Bredehoeft & Pinder, 1970). Hydraulically the acquifer model is thus characterised by two confined aquifers, consisting of two-dimensional layers with lateral aquifer flow, connected by vertical upwards leakage, and upwards directed vertical leakage from the upper aquifer to a constant based boundary, the regional watertable or upper limit of the vertical leakage. Lateral boundaries are of the prescribed head type and of the impermeable type. Recharge is through prescribed head boundaries, natural discharge through lateral boundaries or vertical leakage. Artificial discharge is through free-flowing artesian wells or through pumped wells and applied in the mathematical model as a function of the hydraulic head.

Transmissivity values of the prototype aquifers were obtained by combining the effective permeable thickness (which is the total thickness of the sequence less the thickness of confining beds between aquifers) and the (horizontal) hydraulic conductivity values; the hydraulic conductivity values are mainly restricted to aquifers in the Cadna-owie Formation and Hooray and Pilliga Sandstones, and are irregularly distributed over the basin, but these values were assumed to reflect the general characteristics of the prototype Jurassic aquifer. No values for the Cretaceous aquifers are available, and the hydraulic conductivity for the prototype Cretaceous aquifer was assumed to be 10 m/day.

Storage coefficient values for the latter aquifer were not available, and it was assumed that the specific storage coefficient is 3.3 x 10^{-6} per metre of aquifer thickness. Determination of storage coefficient values for the prototype Jurassic aquifer and of vertical hydraulic conductivity values for confining beds have already been described.

Potentials and free-flowing well discharges were obtained from measured data in the GAB-ADP system.

All prototype parameters (geometry of the aquifer model, hydraulic characteristics of the aquifer units and confining beds), variables (hydraulic heads and free-flowing discharges), and boundary conditions (prescribed heads and impermeable boundaries) were quantified. For this purpose, a regular square grid with gridlines spaced 25 km, parallel to the X and Y axes of the mathematical model, was applied. The prototype is covered by 67 x 58 gridlines. Because a gridpoint covers 25 x 25 km^2, several original data points (wells) could be covered by a grid square, necessitating averaging; in other areas no data points are available. Initially maps were prepared showing parameters for areas rather than gridpoints.

Further details on the data preparation, GABHYD model calibration and application are given in Seidel (1980).

Assessment of the groundwater resource and its utilisation

Predicting the effects of future exploitation

The digital computer simulation model GABHYD produces quantitative information (potentials and well discharges) about the real hydrogeological system at greatly reduced time scales derived from calculations on a simplified version of the groundwater basin. Predictions of effects of exploitation for regions or small parts of the basin can be determined. Many management options, generally applicable to the free-flow situation, but also for pumped discharges, and variable space and time requirements, can be specified for the model (Seidel, 1978b, 1980). Despite the approximation and simplification inherent in the prototype and model, necessary because of the complexity of the natural system, and the limitations in available data, it appears that the model results are sufficiently complete and precise to allow interpretation and application of regional effects.

Future exploitation patterns resulting from different demands in the Great Artesian Basin, and the location, timing, size and duration of such changes, are difficult to predict. Usage by the principal landusers for grazing purposes and domestic and town water supply will probably not change significantly, and consist of relative small discharges. Even greatly improved economic conditions which could induce the construction of more watering points are probably less important than the carrying capacity of the arid grazing lands. Furthermore, it would probably cost less to construct shallow wells and earthtanks rather than deep flowing artesian wells for pastoral purposes, which would be a continuation of the present trend in economics and State government policy.

Large-scale development for other than the present users, for example mining or industrial applications, would generally occur as medium to long-term (25 years or longer) high discharges, to be obtained from relatively small areas. The model can estimate changes to the potentiometric surface, extent of the drawdown, and the change in discharge of free-flowing artesian wells for such developments (Habermehl & Seidel, 1979; Seidel, 1980). Physical consequences of such large-scale basin development can be predicted by the model; thus allowing for forecasting, planning or alternative recommendations to deal with the effects of lowering of groundwater levels and reduction in discharges from wells in certain areas caused by development in those and other parts of the basin.

Throughout the historical development of the Great Artesian Basin potentials and discharges of wells tapping the basin's aquifer continued to fall, until a new steady-state condition was reached when total recharge and discharge again reached equilibrium. This equilibrium condition developed during the last decade; provided that no further new development takes place in the basin, little change is expected to occur to the recharge and discharge on a basin-wide scale (Habermehl & Seidel, 1979; Seidel, 1980).

Planning and regulation of groundwater use

The large set of data available, and the simulation model, allow for large-scale, regional planning, and could simplify the monitoring of the groundwater basin. Simulation of local, small-scale development and individual well control is not possible with this model, but could be achieved by applying a similar model to a smaller area, using established boundary conditions from the basin-wide model.

Continued or increased development of the Great Artesian Basin by drilling more flowing and non-flowing artesian waterwells, or abstracting more water from existing wells by pumping, will further lower the potentiometric surface, which will in time result in diminishing flows and cause more wells to cease flowing. Detailed planning and management is required for large-scale developments, which could produce significant hydraulic effects and even cause possible changes in water quality in specific areas.

Conservation of groundwater can be achieved by eliminating wastage of free-flowing artesian water by restricting the flow from wells, if only on a seasonal basis. More efficient distribution systems, the changing from earth drains to plastic piping, reconditioning or pressure-cementing of leaking and corroded well casings, and the regulation of uncontrolled flowing wells could all contribute to a more rational water use. These measures, which are generally expensive, are being carried out in most States, with favourable results. The smaller amounts of water required allow a forced reduction in discharge from flowing wells, which results in an increase of the pressure in the aquifer in that area and so improves duration of flows from the well and neighbouring wells. The present policy in most of the basin area, not to carry out expensive conservation measures in order to preserve flowing wells—but to aim at a withdrawal rate commensurate with natural recharge—is acceptable, provided efficient use is made of the water abstracted.

The ultimate in groundwater conservation would occur if the potentiometric surface were lowered to groundlevel in the whole of the basin area. In such a hypothetical situation no more flowing artesian wells would exist; all groundwater would have to be lifted by mechanical means, necessitating strict economical considerations of water use. Withdrawal rates would be very much less, wastage minimal, and drawdown much reduced. However, with the present or any increased future production rate such a condition is unlikely to occur in most areas of the basin. The extent of the flowing artesian conditions and the size of the regional net pressure show that large areas of the basin will have free-flowing artesian conditions available for very long time periods, provided no change to many large-scale heavy developments occurs.

Development of the basin since about 1880 has mainly yielded water from elastic storage, and caused lowering of the hydraulic head—only a small percentage of the withdrawal was obtained from aquifer throughflow. As development progressed, a change in recharge occurred, and a new equilibrium was established between recharge and discharge. This equilibrium condition prevents mining of the aquifers, which would only occur if abstraction of groundwater exceeded the recharge rate of the basin.

Model results and historical data show that in the early part of the period from 1880 to 1970 the artificial discharge increased, but, as the effects of elastic storage of the groundwater reservoir became less later, it diminished. The discharge from springs decreased during the period, as did the vertical upwards leakage. However, as a result of the pressure decline and steepening of the hydraulic gradient, the recharge to the aquifers of the basin increased significantly, from about 26 to 35 m^3/sec (Habermehl & Seidel, 1979; Seidel, 1980). Rainfall data and the areal extent of aquifer outcrops suggest that the discharge from the wells (565 x 10^6 m^3/year in 1970), which presently takes up about 50 percent of the model computed recharge to the basin, equals about 1 percent of the average amount of water available for recharge.

Withdrawal from the basin by free-flowing and pumped artesian waterwells is small compared to the groundwater reserves; hydraulic characteristics indicate that long-term development is feasible with only minor lowering of the potentiometric surface. Mining of the reserves by using up the net pressure and lowering the waterlevels to within economical pumping depths would provide very large amounts of groundwater.

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