GROUNDWATER IN AUSTRALIA

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ABSTRACT

Australia is an arid continent, with widespread but unevenly distributed groundwater resources. In the arid and semi-arid interior, groundwater is limited and often of poor quality. More than 60 percent of Australia is entirely dependent on groundwater, and in another 20 percent groundwater is the major source. Groundwater withdrawal from 400,000 wells is 2700x10^6 m^3/year, or 14 percent of all water used by Australia's population of 15 million. Irrigation, the largest water user, relies heavily on groundwater, mainly from highly productive and heavily developed surficial aquifers. Deeper aquifers in large sedimentary basins in the interior supply the pastoral industry and towns. Fractured rock aquifers are extensive and locally important. Overdevelopment in several areas has caused supply problems, and land use changes resulted in water-logging and salinization. Increased groundwater development for agriculture, towns and industry is possible, but requires enhanced hydrogeological techniques, assessment and management.

INTRODUCTION

Australia is an arid continent with low rainfall, high evaporation and low runoff (Fig. 1). Water availability has been a major factor in the nature and direction of Australia's development. Groundwater is widespread in Australia, although its quantity and quality vary greatly in different parts of the country. Groundwater is important because it is generally available in many areas where surface water resources are highly variable and unreliable. More than 60 percent of the continent's total area of 7.7x10^8 km^2 is entirely dependent on groundwater, and in another 20 percent groundwater is the major source of water (Fig. 2).

Australia lies between latitudes 10° and 44°S, and is covered by several climatic zones ranging from tropical with summer rainfall in the north to temperate with winter rainfall in the south. Most of the interior has an arid climate, with some areas receiving less than 100 mm median annual rainfall (Fig. 1) and experiencing annual evaporation of more than 4000 mm. The northern, eastern, southeastern and southwestern coastal areas and Tasmania have tropical, subtropical and temperate climates respectively with higher and more reliable rainfall, which result
in water surplus. The rainfall over the continent averages 465 mm and results in a runoff of only 57 mm because of the high evaporation (Brown, 1983). In 75 percent of the continent rainfall does not exceed evaporation in any month of the year. Variations in evaporation are much lower than for rainfall, especially in the arid and semi-arid areas, which cover about two-third of Australia. There, the range of annual rainfall may be several times the mean annual rainfall.

Seasonal distribution of rainfall varies greatly over the continent, which is of low relief, and where topographic effects on rainfall mainly occur near the Great Divide, parallel to the east coast, and in the southwestern and southeastern parts.

Australia's population of 15 million is highly urbanised, with more than two-thirds living in eleven cities along the eastern, southeastern and southwestern coastal areas. The economically very significant pastoral, agricultural and mining industries are all located inland in areas of low, and highly variable, rainfall and unreliable streamflow. Large groundwater basins occur in these areas, and surficial deposits and fractured rock aquifers provide additional sources of groundwater. Sedimentary basins cover about 65 percent of the continent and fractured rock provinces about 35 percent; they are both partly overlain by surficial aquifers, mainly in unconsolidated sediments, which cover 25 percent of the continent. Total groundwater withdrawal from 400,000 waterwells, which are mainly concentrated in the southeastern and southwestern parts of the continent, is $2700 \times 10^6$ m$^3$ per year, or about 14 percent of the total amount of water used in Australia.

A description and assessment of Australia's groundwater resources, based on limited data, is given in Jacobson et al. (1983) which forms part of a 14 volume study of all aspects of Australia's water resources, their potential supplies and expected demands to the year 2000 (Department of Resources and Energy, 1983). Earlier reviews of Australia's groundwater resources include Australian Water Resources Council (AWRC)
Fig. 2. Groundwater use as a percentage of total water use in Australia, based on surface water drainage divisions.

(1975, 1976), Habermehl & Seidel (1979) and O'Driscoll (1979); an updated review based on 1985 data is in preparation, and will include a hydrogeological map of Australia at scale 1:5 000 000.

Australia is a federation of States, and under the Australian constitution the responsibility for water matters rests with the States. The Federal or Commonwealth Government has been involved in cooperating with the States in water resources research, planning, development and management in activities relevant to the national interest, and especially as a funding agency to the States, particularly since the inception of the Australian Water Resources Council in 1963. Australia does not have a national water research centre (AWRC, 1982). Groundwater investigations
and some research in the States are carried out by the State geological and water authorities and published in reports (e.g. Geological Survey of Queensland & Irrigation and Water Supply Commission, 1973, Lawrence, 1976, Sheperd, 1978; McEniery, 1980; Western Australian Water Resources Council, 1984; Water Resources Commission of New South Wales, 1984) and numerous papers, some of which have been listed in AWRC (1975) and Lau and Jacobson (1983). Several groundwater conferences organized by AWRC during recent years resulted in a large increase of published papers. References to some earlier bibliographies occur in Habermehl (1980). The periodical publications 'Water research in Australia - current projects 1984' and 'Streamline Update' provide information on present activities and references obtained from the national computerised water data base on published and unpublished documents (Department of Resources and Energy, 1985 a, b).

Groundwater research is carried out by the Bureau of Mineral Resources, Geology and Geophysics (BMR), the Commonwealth Scientific and Industrial Research Organization (CSIRO) and the Australian Atomic Energy Commission (AAEC); several universities have some limited involvement. BMR, a Federal agency, is Australia's main geoscientific research organisation, and has a long history of involvement in research and assessment of groundwater resources, mainly at the national level, and generally in collaboration with State agencies. The BMR Division of Continental Geology's Hydrogeology Research Group objective is to develop an understanding of the hydrodynamics, hydrochemistry, isotope hydrology and palaeohydrology of groundwater in large, regional sedimentary basins and in fractured rocks. CSIRO (mainly the Division of Groundwater Research) is involved in the study of physical, chemical and biological processes affecting the quality and quantity of groundwater, largely in unconfined aquifers; AAEC studies isotope hydrology, usually jointly with other organizations.

Groundwater studies which do not consider groundwater only as a resource include studies which determine the role of groundwater in the formation, migration and entrapment of minerals and hydrocarbons, groundwater and geothermal gradients and heat flow, aspects of engineering geology and groundwater's role in geological processes, including geomorphology, weathering and diagenesis. Some Australian examples are given:

The relationship between groundwater movement and hydrocarbon occurrences in the Eromanga Basin has been dealt with by Habermehl (1985) and Senior and Habermehl (1980). Groundwater geochemistry and mineral deposits are considered by Giblin (1983), and geothermal gradients and heat flow in Australian sedimentary basins by Cull and Conley (1983). Groundwater aspects in engineering geology and environmental geology are included in Knight et al, (1983).

GROUNDWATER RESOURCES

Three main aquifer types have been distinguished in Australia: surficial aquifers, deeper aquifers in sedimentary basins and fractured rock aquifers (Fig. 3).
Surficial Aquifers

Surficial aquifers occur in alluvium, colluvium and dune sands, and generally consist of unconsolidated clastic sediments. Surficial aquifers are also present in calcretes (carbonate deposits associated with drainage systems) and aeolianites (carbonate cemented dune sands). Most surficial aquifers are in Cainozoic sediments and less than 150 m below the surface. Highly productive surficial aquifers with good quality water account for 60 percent of total groundwater abstraction in Australia. Most are alluvial aquifers in river valleys and fan deposits bordering the Great Divide in southeastern Australia and in coastal river valleys, where the groundwater is used for irrigation and urban water supply. Several central Australian alluvial deposits are locally good groundwater sources. Many sediments containing surficial aquifers partly overlie sedimentary basins and are difficult to distinguish as they belong to a continuous sedimentary sequence. High
transmissivities and high yields characterize many of the sand and gravel bed aquifer systems, showing great variations in yield and quality in vertical and lateral directions. Groundwater exploitation has caused significant changes in many of the major surficial aquifers and overdevelopment has occurred in several areas, including the Burdekin Delta, Lockyer, Condamine and Namoi Valleys, North Adelaide Plains and Millstream (Fig. 3). Seasonal and long term climatic fluctuations, such as drought conditions of several years duration which is very common to Australia influence some shallow aquifers.

Salinity is a major factor in groundwater use and development in Australia, particularly of groundwater from surficial and fractured rocks aquifers. Fresh groundwater, with less than 1000 mg/L total dissolved solids (TDS) occurs in about 10 percent of the surficial aquifers, mainly alluvial fans and coastal river deposits. Brackish water, with 1000 to 14000 mg/L salinity values is found in about 30 percent of the surficial aquifers, and another 30 percent contain saline water of more than 14000 mg/L. The brackish and saline water aquifers occur mainly inland, and include alluvial and aeolian deposits, and weathered mantles overlying older geological units. About 30 percent of the surficial aquifers, particularly in the central and northern half of the continent are insufficiently explored. Some saline surficial aquifers overlie marine sediments, others occur in thick Tertiary weathering profiles. The basic cause of most man induced salinity problems in Australia is however the disturbance of these groundwater systems by land use changes, such as clearing land for agriculture and irrigation. Both practices lead to rises of watertables and land salinisation, and increase stream salinity (Peck et al, 1983).

Significant surficial aquifers include the Burdekin Delta in Queensland, where $260 \times 10^6$ m$^3$ groundwater per year is extracted from aquifers in alluvial and deltaic sediments to irrigate 600 km$^2$ of a sugar cane producing area. Artificial recharge is applied, and the annual recharge of $250 \times 10^6$ m$^3$ is made up of natural recharge of $200 \times 10^6$ m$^3$ and artificial recharge through channels. Limitations on groundwater extraction have been imposed, in addition to the recharge scheme, to combat the groundwater overdraft and to prevent saltwater intrusion (Volker, 1981, Hadgcraft & Volker, 1981). In the Bundaberg region annual groundwater use for sugarcane irrigation has been nearly twice the estimated safe yield of $55 \times 10^6$ m$^3$, and resulted in overdevelopment and saline intrusion. Overdevelopment has also occurred in the alluvial aquifers of the Callide, Lockyer, Condamine and Namoi Valleys, because of demands for irrigation and town water supplies. Abstraction is now controlled, and artificial recharge and conjunctive use of surface water are applied, as natural recharge is only about one-third of the abstraction in most of these areas (Henry & Palmer, 1981). The alluvium of the Namoi Valley is very important for groundwater use and $175 \times 10^6$ m$^3$ is annually extracted mostly for irrigation, including cotton, and town water supplies, apart from exploitation for household and stock supplies. It is one of the most intensely developed groundwater systems in New South Wales, and some wells yield in excess of 200 L/s from alluvium up to
Alluvial deposits in river valleys bordering and crossing the eastern and southern parts of the Murray Basin generally have small and partly developed groundwater resources where they overlie fractured rock provinces, and extensive, high-yielding aquifers in the basin area, particularly in the alluvial fans near the eastern basin margin. These include the Lachlan, Murrumbidgee and Murray Valleys, which are all relatively undeveloped, and offer scope for further groundwater development. In the Murrumbidgee Valley annual groundwater abstraction is $5 \times 10^6$ m$^3$ and recharge $100 \times 10^6$ m$^3$. Substantial yields are also obtainable from alluvial aquifers in the Goulburn, Campaspe and Loddon Valleys along the southern basin margin. Parts of these valleys have been developed for irrigation, and rising watertables and salinisation in areas of natural saline groundwater discharge zones have caused severe problems, necessitating drainage and interception of saline groundwater and amelioration of increasing salinity in the Murray River (Macumber, 1978, Maunsell and Partners, 1979, Peck, et al, 1983).

In some central Australian rivers alluvial deposits and outwash fans contain locally good groundwater resources, but many are poorly explored.

Many of the coastal valleys in the southeastern part of the continent contain small resources and are partially developed; major development of larger resources of alluvial aquifers has occurred in the Hunter, Mitchell and Latrobe Valleys.

Coastal sand dunes provide significant groundwater sources in parts of Queensland, New South Wales (particularly for the town of Newcastle) and Tasmania. Dune sands of the Swan Coastal Plain, overlying the deeper confined aquifers in the Perth Basin supply 40 percent of the Perth metropolitan water. Total withdrawal from the surficial aquifers is $200 \times 10^6$ m$^3$, most of it from uncontrolled private wells used for garden watering, irrigation of market gardens and industrial use. These unconfined, highly permeable, aquifers are highly susceptible to pollution. Septic tanks are used in about half of Perth and the increased recharge in urban areas caused by the disposal of roof run-off on the housing blocks all contribute to groundwater contamination (Whelan, et al, 1981, Allen, 1981, Brown, et al, 1983).

The Millstream calcrete aquifer (Fig. 3) is an important groundwater source, and an example of carbonate related aquifers which occur in many coastal and inland streams and palaeodrainages in Western Australia (Commander, 1983). Coastal aeolianites are other important aquifers and have been exploited in Western Australia and in South Australia, where they provide 75 percent of the water supply of the Eyre Peninsula.

Sedimentary Basin Aquifers

Several major sedimentary groundwater basins underlie large parts of the arid and semi-arid zones of Australia, and constitute significant groundwater resources which enabled development of these regions of sparse and unreliable surface water resources. Sedimentary basins cover 65 percent of the
continent and 30 percent of groundwater in Australia is abstracted from aquifers in these Palaeozoic, Mesozoic and Cainozoic sedimentary sequences. Total thickness of these basins range up to several thousand metres, and the aquifers generally consist of clastic sediments with intergranular porosity, though several basins comprise carbonate rocks which contain aquifers with solution cavities, joints and fractures. Sedimentary basin aquifers are usually tens or hundreds of metres thick, hydraulically continuous over large areas, confined and form multi-layered aquifer systems separated by semi-pervious layers. Hydraulic characteristics and quality differ widely, but groundwater quality of the deeper aquifers is commonly better than surficial or near-surface aquifers. Groundwater movement in many of these basins is slow and their long and deep flow paths result in very old, and warm to hot water. Most aquifers produce good yields and exhibit large storage, facilitating large scale development. Many sedimentary basins are poorly explored for groundwater, although limited regional geological and geophysical investigations, and petroleum exploration activities have established good geological frameworks for several of them. Better known and well studied groundwater basins include the Great Artesian Basin, and the Murray, Perth, Georgina, Wiso, Daly and Otway Basins.

The Great Artesian Basin is a confined groundwater basin comprising a multi-layered aquifer system, with aquifers occurring in quartzose sandstones of continental origin and confining beds of siltstone, mudstone and marine argillaceous sediments of Middle Triassic to Late Cretaceous age (Habermehl, 1980, 1983). The Great Artesian Basin occupies $1.7 \times 10^6$ km$^2$, or about one-fifth of Australia, and underlies arid and semi-arid regions. Discovery of the basin's groundwater resources around 1880, partly as a result of the first application of scientific research to Australian water resources problems, enabled settlement and the establishment of an economically important pastoral industry. Pastoral, domestic and town water supplies are largely dependent on artesian groundwater, and groundwater from the aquifers in the Lower Cretaceous – Jurassic sequence is of good quality, with generally about 500 to 1500 mg/L TDS, dominated by sodium bicarbonate. The high water temperature, up to 100°C, is a minor inconvenience, and necessitates cooling. It is chemically incompatible with the soils in most areas and therefore generally unsuitable for irrigation. Future additional usage of the artesian groundwater will be for the Olympic Dam mining project and town located about 150 km outside the basin, and will be a major new development (Kinnhill Stearns Roger, 1982).

The basin is up to 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, large scale groundwater movement (Fig. 4) is towards the southern, southwestern and western margins, where natural discharge occurs from many springs, generally in the form of moundsprings (Habermehl, 1980, 1983). Regional groundwater movement was determined by a basin-wide hydrogeological study and the computer based simulation of the basin's hydrodynamics.
Fig. 4. Hydraulic isochrones calculated from the 1880 potentiometric surface in the Great Artesian Basin, Australia. Flowing artesian waterwells sampled for environmental isotopes are shown; letters refer to divisions based on carbon isotopes (Calf and Habermehl, 1984).

(Habermehl, 1980, Seidel 1980). Groundwater flow patterns and the continuing recharge from geological to modern times have been confirmed by environmental isotope and hydrochemical studies (Airey et al, 1983, Calf & Habermehl, 1984, Habermehl, 1983). Chlorine-36 and carbon-14 isochrones are in good agreement with ages obtained from hydrodynamic data, and show residence times from 10 000 years near the eastern marginal recharge areas to 1.4x10^6 years near the Queensland-South Australia border. Use of 36 Cl as a novel technique in groundwater dating has extended the limit for dating beyond that of 14 C (Airey et al, 1983, Bentley et al, in prep.). Another novel technique applied in the Great Artesian Basin has been the evaluation of I as a tracer in groundwater (Fabryka-Martin, 1985). Groundwater in the Lower Cretaceous-Jurassic confined aquifers in the eastern and central
parts of the basin is dominated by Na-HCO₃-Cl type chemistry. In the southwestern part the groundwater is characterised by Na-Cl-SO₄ (Fig. 5). Hydrochemical differences relate to the sources and directions of groundwater flow patterns (Habermehl, 1983).

Flowing artesian waterwells, with depths up to 2000 m number 136° 140° 144° 152° 156°, with individual flows exceeding 100 L/s. The maximum flow from 1500 wells was 2×10⁶ m³/day in 1918. Non-flowing artesian wells number 20,000 and supply on average 10 m³/day. Potentiometric surfaces of the aquifers are still above ground level in most areas of the basin, but development has caused considerable drawdowns, with regional differences of more than 100 m between 1880 and 1970 (Habermehl, 1980). Rapid changes occurred during the first half of the century, but conditions stabilised during the last 30 years and future (restricted) groundwater abstraction will produce only minor changes in discharges and pressures according to model predictions (Habermehl, 1980, Seidel, 1980, Habermehl & Seidel, 1979). Much larger development is possible, and more efficient

Fig. 5. Major ion hydrochemistry of selected flowing artesian waterwells in the Great Artesian Basin.

4700, though only 3000 wells remain flowing, and their accumulated flow is 1.5×10⁶ m³/day; individual flows exceed 100 L/s. The maximum flow from 1500 wells was 2×10⁶ m³/day in 1918. Non-flowing artesian wells number 20,000 and supply on average 10 m³/day. Potentiometric surfaces of the aquifers are still above ground level in most areas of the basin, but development has caused considerable drawdowns, with regional differences of more than 100 m between 1880 and 1970 (Habermehl, 1980). Rapid changes occurred during the first half of the century, but conditions stabilised during the last 30 years and future (restricted) groundwater abstraction will produce only minor changes in discharges and pressures according to model predictions (Habermehl, 1980, Seidel, 1980, Habermehl & Seidel, 1979). Much larger development is possible, and more efficient
use could also be made of the basin's groundwater as much of it is wasted by free flows. The well-heads and the distribution systems, consisting of tens of kilometres long open earth channels, should be upgraded. The basin transgresses State boundaries, which complicates the planning and management of its development, as no joint or single coordinating authority exists.

The Murray Basin extends over 300 000 km$^2$ and consist of fluviolacustrine, aeolian and shallow-marine sediments (Brown, 1985). The Tertiary succession is up to 600 m thick, and the three depositional sequences contain major regional aquifers and several partial aquifers (Fig. 6). Groundwater is extensively exploited for stock and irrigation purposes, and increasingly for town water supplies. Yields differ widely, and water quality ranges from fresh to highly saline. Recharge is from river valleys and alluvial fans draining the higher adjacent areas surrounding the basin, particularly in the east and south. Regional groundwater movement is towards the central-western part of the basin, and discharge is partly intercepted and drained by the River Murray, which drains most of southeast Australia. The surface water resources of this river are highly developed, mainly for irrigation, and provide a significant source of water for Adelaide and large parts of South Australia (Brown et al, 1983, Peck et al, 1983). Large scale clearing of native vegetation has increased recharge and dryland salinisation. Irrigation has produced large groundwater mounds beneath

![Fig. 6. Schematic cross-section (W-E) of the Murray Basin.](image-url)
irrigation areas and caused waterlogging and salinity problems.

Williamson (1982) concluded from a preliminary three
dimensional steady state model that natural recharge has a
significant influence on the regional groundwater. Allison et
al, (1985) shows that land use changes in some areas has
increased recharge by more than two orders of magnitude, and that
saline groundwater inflow to the River Murray will increase.

The Renmark Group aquifer in continental sediments yields
good quality groundwater, but is not extensively developed
because of its depth (Sheperd, 1978). Good quality water in the
Murray Group aquifer consisting of marine calcarenites is
intensively exploited in the central and western part of the
basin, mainly for town, industrial, irrigation and stock supplies
(Lawrence, 1975, 1976). Proposed large scale central pivot
irrigation use has caused concern and initiated a joint State
study for the management of the aquifer which underlies 30 000
km² near the South Australia – Victoria border.

The uppermost, near surface Pliocene Sand aquifer is partly
confined, and its fluvial sands are exploited in the basin's
southern and eastern margins. High yielding wells, producing
more than 300 L/s of low salinity water from depths of 120 m,
occur in the eastern area and are used for irrigation and town
In parts of the eastern half of the basin the aquifer is confined
and highly saline, and in the northern and western parts marine,
estuarine and fluvial sands are mainly unconfined and highly
saline. Many of the Tertiary sediments are concealed under
Quaternary aeolian dunefields in the western parts of this arid
and semi-arid region, and highly saline groundwater discharges in
lake complexes and salinas (Macumber, 1980).

The Perth Basin contains Permian to Quaternary sediments and
is 13000 m thick. Multi-layered fresh groundwater aquifers
occur, but the main aquifers are unconfined surficial formations.
Confined aquifers in Cretaceous and Jurassic sandstones, with
fresh and brackish water have been poorly developed because of
their depths. Groundwater movement is generally directed
westwards, originating from the restricted recharge areas west of
the Darling Fault. The basin has a substantial groundwater
resource potential, and further development is possible without
affecting the saltwater interface (Allen, 1981).

The Georgina Basin contains aquifers in dolomites and
limestones ranging in age from Middle Cambrian to Early
Ordovician. A regional confined aquifer system has developed
with storage and groundwater movement as in porous aquifers
despite the fractured rock nature of the carbonate aquifers
(Randal, 1978). Annual withdrawal from the Georgina Basin totals
8x10⁶ m³ for pastoral, domestic and small town supplies. This
withdrawal is a small part of the reserves which amount to
3000x10⁶ m³ within economical drilling depth, the latter being
100 m below the potentiometric surface which occurs at 30-80 m
below the surface. Low transmissivities prevent high withdrawal
rates. Groundwater quality ranges from good to saline.

The Daly Basin contains Palaeozoic carbonate aquifers, and
adequate yields for good quality groundwater are obtained for
pastoral and town water supply use.
The Otway Basin is a narrow coastal basin with Mesozoic and Cainozoic sediments which reach a depth of 6000 m. Several aquifer systems occur within the sequence of this basin which has a high number of wells, totalling more than 50 000. Good quality water is obtained for townwater supplies from some aquifers, and other, limestone aquifers provide good quality water for irrigation, stock and domestic purposes, though nitrate pollution from factory wastes has taken place (Forth, 1981).

The St. Vincent Basin includes the North Adelaide Plains sub-basin which is overdrawn, mainly because of the demand for market gardens. Extraction is now strictly controlled.

Many sedimentary basins contain aquifers with good resource potential, others are less prospective. Several are poorly explored and warrant further groundwater investigation (Jacobson et al, 1983, Brown et al, 1983).

Fractured Rock Aquifers

Fractured rocks occupy about half of the continent and directly underlie about one-third of Australia. Fractured rock aquifers include igneous, metamorphic and significantly deformed sedimentary rocks that provide groundwater from cracks, fractures, joints, solution cavities and zones of weathering. Climate and topography are important controls affecting the yield and quality of groundwater from fractured rock aquifers. Yield and quality are commonly poor, but in many arid, mountainous and denuded areas, where the presence of usable water is critical, these generally unconfined aquifers may provide the principal supply. One-third of Australia's waterwells are in fractured rock aquifers which supply $310 \times 10^6$ m$^3$/year or 10 percent of total groundwater abstraction, mainly for stock and domestic use. Yields from individual wells are usually small, and techniques have been developed to improve yields (Williamson & Woolley, 1980). Large areas rely heavily on fractured rock aquifers (Fig. 3). Groundwater from these aquifers is used for agriculture and small town supplies in the northeastern and southeastern coastal regions; mineral water from wells and developed springs related to Tertiary volcanic and Palaeozoic sedimentary rocks have been exploited in the Victorian Highlands (Malone, 1982). Two-thirds of the wells in fractured rock aquifers occur in the eastern and southern parts of the continent, and they usually provide small yields of good quality water, particularly in the higher, mountainous parts. Most other wells occur in the southwestern part of Australia. Groundwater quality there is generally poor, which is unfortunate as the fractured rock aquifers underlie an economically important wheat growing area with a widely dispersed, but relatively dense population (Allen and Davidson, 1982). Elsewhere in the arid and semi-arid parts of the continent groundwater from fractured rocks provide reliable supplies for stock, domestic and town water supplies and some mining areas. Fractured rock aquifers have been developed to provide water up to 5000 mg/L for desalinisation to augment the surface water supply of a small mining town in northern South Australia (Waterhouse and Read, 1982).

Large resources of good quality groundwater exist in the fractured rocks in the northern part of Australia.
Fractured rocks provide scope for further development, especially low yields for domestic, pastoral and small town requirements. Studies of fractured rock aquifers and the determination of aquifer parameters is difficult, and has been neglected, partly because it requires special methods of exploration and investigation, different from studies of aquifers with intergranular permeability.

EVALUATION OF GROUNDWATER RESOURCES

The total possible annual yield of Australia's fresh groundwater resources has been estimated at \(7.2 \times 10^6\) m\(^3\); current annual use of groundwater is \(2.7 \times 10^6\) m\(^3\) (Jacobson et al, 1983; Brown et al, 1983) (Figs. 7 and 8). In addition, substantial resources of brackish and saline groundwater are present in Australia. The unevenly distributed runoff provide existing surface water supplies at the rate of \(1.8 \times 10^6\) m\(^3\)/year from a potential surface water yield of \(1.18 \times 10^6\) m\(^3\)/year, Brown, 1983; Brown et al, 1983).

Groundwater use is relatively high in the southeastern, eastern and southwestern marginal parts of the continent and 90 percent of the total groundwater use is from private wells. Groundwater abstraction is highest in irrigation areas, mainly from surficial aquifers. Irrigation (\(1.6 \times 10^6\) hectares, almost half of it for pasture) is the largest user of water in Australia at 74 percent of total use, and 12 percent of the irrigation water is groundwater, almost all derived from private wells. Urban and industrial use account for 18 percent (domestic 10 percent and commercial-industrial 8 percent) of total use, with 6 percent of the total use coming from public groundwater wells and 9 percent from private wells. Garden water use comprises up to 50 percent of the mean annual residential use in Australian cities. Rural use is 8 percent of total water use, one-third coming from groundwater, and 80 percent being obtained from private wells (AWRC, 1981).

Early development in Australia relied heavily on groundwater, and until two decades ago groundwater was used predominantly in the interior for pastoral, domestic and town water supplies, which involved widely distributed, small yield withdrawals. In recent years increased development, particularly large scale irrigation caused local heavy demand, which has created problems of overdevelopment in at least ten irrigation areas (Jacobson et al, 1983; Brown et al, 1983). Increased demand requires increased control, and restrictions on abstractions, and could also call for the application of conjunctive use of surface water and groundwater, and artificial recharge. Improved efficiency in water use, especially for irrigation, could already lead to a considerable reduction in demand, and alleviate pressures in highly developed areas. A review of available resources, demand, problems and constraints, and planned and potential development is given in Brown et al, (1983). In many areas quantity is the limiting factor and though in many areas present demands can be met, future demands require additional supplies. Quality (Fig. 9) is usually a major concern throughout Australia, either because of salinity (Hart, 1974; Peck, et al, 1983; Garman et al, 1983) or because of particular ions, such as fluoride, or
naturally occurring nitrate (Lawrence, 1983). Induced problems of lowering of watertables, waterlogging and salinisation usually occur on a regional scale; nitrogen contamination from waste disposal is a regional problem in southeastern South Australia. Groundwater pollution problems occur at a local scale in most urban environments, and specifically in some of the larger cities such as Sydney, Melbourne, Adelaide, Perth and Canberra (Lawrence & Hughes, 1983; Jacobson, 1983).

The greatest potential for additional groundwater development is in the northern part of the continent, and to a limited extent in the southeastern part (Fig. 8). Further development is possible in many parts of Australia where groundwater is already exploited for use in irrigation, urban, pastoral and mining
Possible annual yield for each drainage basin was derived from available recharge plus yield from groundwater storage if mined at 1% per year. Fresh groundwater is less than 1000 milligrams per litre total dissolved solids.

**Fig. 8. Possible annual yield of fresh groundwater in Australia.**

activities (Brown et al., 1983; Jacobson et al., 1983). Many of the exploited aquifers are already highly committed and require detailed investigations to facilitate further efficient development to accommodate projected increased demand caused by economic and population growth. A comprehensive understanding of the aquifer systems including information on aquifer properties, recharge, discharge and groundwater quality, is essential to manage the limited groundwater resources and to meet existing and further demands. The rate of groundwater investigations increased after the formation of the Australian Water Resources Council, and the provision of Commonwealth funding to accelerate the assessment of the nation's water resources since 1964. Hydrogeological, geophysical,
hydrochemical and isotope hydrology studies have been carried out in more or less detail on some aquifers, but groundwater resources data are still inadequate for long-term planning purposes in three-quarters of the continent, and large parts remain essentially unexplored. Deficiencies exist in some areas of data collection and storage, and though most States have computerized data systems, data analysis and dissemination require upgrading. Increased efforts are needed to explore, assess and manage the nation's groundwater resources, and in research related to the fields of hydrogeology, aquifer system analysis and hydrochemistry. Adequate data are required to achieve predictions of aquifer behaviour by modelling so safe or sustained withdrawal can be determined and forecasts made on man induced problems. Several areas have been closely studied, monitored and modelled (e.g. Kalf & Woolley, 1977, Volker 1979, Henry & Palmer, 1980, Seidel, 1980, Forth, 1981, Williamson, 1982) and management controls have been applied or are potentially available. Legislation to effect these controls has generally been available since the early years of this century,
as it originated in several States from the early development of the Great Artesian Basin, where controls were required to combat wastage from artesian wells (Clark, 1979, 1980). Following the legislation which controlled the construction and use of wells, most States gradually moved to the licensing of extraction of water, and drillers, and during the last decade into the regulation of groundwater quality. Groundwater legislation in the Australian States has been primarily concerned with the extension of certain administrative controls to areas where hydrogeological problems have arisen or are anticipated.

CONCLUSIONS

Groundwater in Australia is unevenly distributed in quantity and its quality is a significant constraint in many areas. Groundwater is an important resource for irrigation, urban, industrial, pastoral and mining developments, and has been highly committed in several locations. Further development of groundwater resources to satisfy urban, agricultural, pastoral and mining demands, which are all numerous and on which Australia's economy is highly dependent, can be achieved even in developed areas, provided up-to-date technological and management techniques are applied.

Increased research related to the exploration, assessment and management of groundwater resources in Australia is a necessity if further usage and development is to be carried out wisely; further research is also required to estimate the effects of human activity, including land use changes on groundwater quality.

ACKNOWLEDGEMENTS

This paper is published with the permission of the Director, Bureau of Mineral Resources, Geology and Geophysics, Canberra.

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