

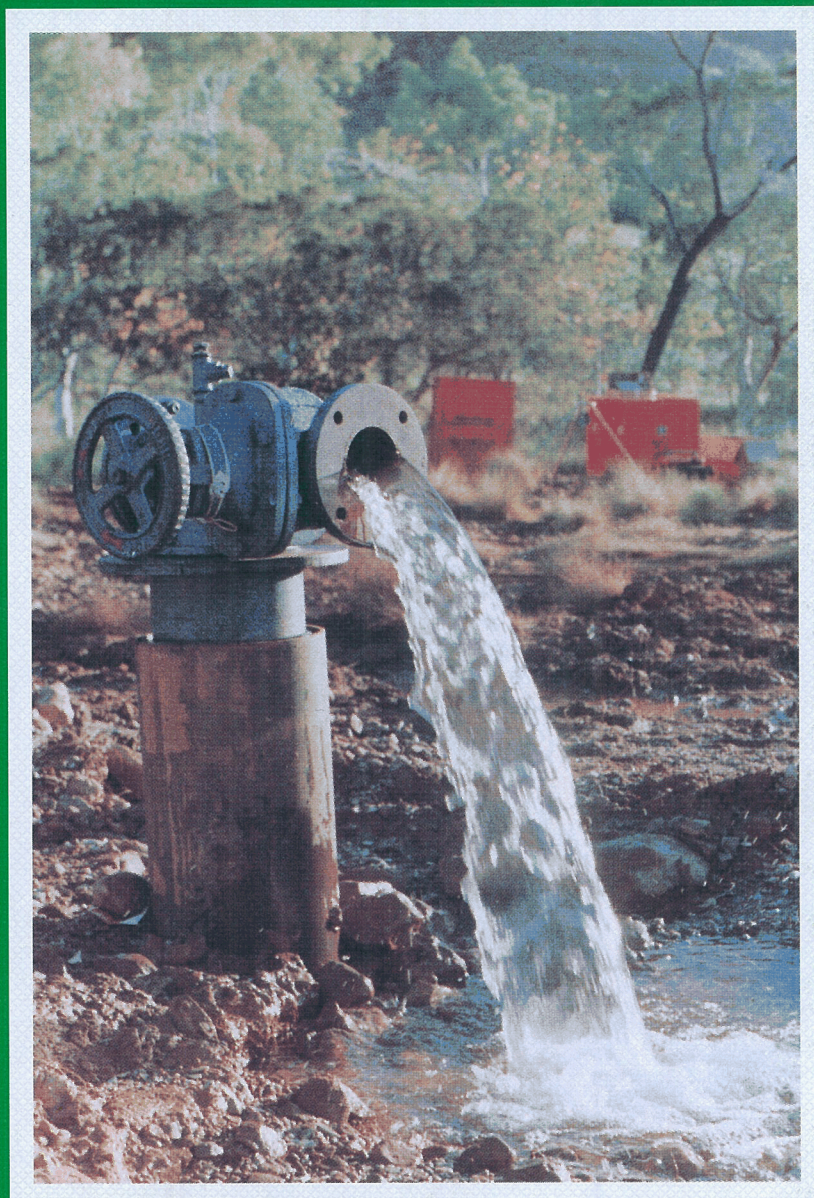
**REPORT  
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# **GROUNDWATER: THE STRATEGIC RESOURCE**

**A geological perspective of groundwater  
occurrence and importance in  
Western Australia**

**by A. D. Allen**



**GEOLOGICAL SURVEY OF WESTERN AUSTRALIA**  
**DEPARTMENT OF MINERALS AND ENERGY**



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Perth 1997

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Artesian bore near the Argyle Diamond Mine, East Kimberley (reproduced with permission of Dr J. R. Passmore, Rockwater Pty Ltd).

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# Groundwater

## The strategic resource

### A geological perspective of groundwater occurrence and importance in Western Australia

by A. D. Allen

### Abstract

The availability of groundwater has been a major determinant in settlement and development in Western Australia because climate, topography, and geological factors limit the ready availability of surface water over about 90% of the State. Yet the strategic role of groundwater and its potential for further development are not generally appreciated. Similarly, the important role of groundwater as an environmental agent and the vulnerability of the groundwater environment to man-made changes are not widely known.

The State's groundwater resources are unevenly distributed but are more widespread than surface water resources. Although they are not readily observable or measurable, geological data, specific drilling projects, and hydrogeological data acquired by the Geological Survey have provided an understanding of the State's groundwater resources and enabled quantitative estimates to be made of the order of magnitude of the renewable and stored groundwater resources to varying levels of confidence. The largest renewable groundwater resources occur in the sedimentary basins, and forty-four actual or potential sources have been identified, from various aquifers, which are capable of yielding 10–390 GL/year of fresh–marginal salinity groundwater. In addition there are likely to be several hundred sources capable of yielding 0.1–10 GL/year in both the sedimentary basins and fractured rock provinces throughout the State. The largest stored groundwater resources also occur in the sedimentary basins, and virtually inexhaustible supplies of brackish–saline groundwater are potentially available. However, there are extensive areas of the State where large and or fresh groundwater resources are absent.

Currently about 45% (450 GL) of all water utilized in Western Australia is from groundwater, mostly in the Perth region. The use of groundwater has caused local impact on wetlands, minor seawater intrusion, and widespread small lowering of pressure in some confined aquifers. In the southwestern part of the State, more widespread effects on groundwater systems have been caused by changes in land use, principally clearing of bushland for agriculture and urbanization. These have changed the water balance and resulted in raised water table levels which have led to widespread land and stream salinization and increased water logging.

There is considerable scope for further development of groundwater resources, particularly in the Perth and Canning Basins. There are also various opportunities for conjunctive use of groundwater and surface water, artificial recharge, and groundwater desalination, which could secure or enhance available water supplies. The major foreseeable problems which may limit the usefulness of some groundwater resources are groundwater contamination from industrial, agricultural and urban activities.

Continued exploratory drilling and hydrogeological mapping are an important State responsibility needed to underpin current and future groundwater management. There is also the need to improve groundwater management by taking a holistic approach to management of groundwater flow systems within the framework of ecologically sustainable development.

**KEYWORDS:** Western Australia, groundwater resources, history, review.

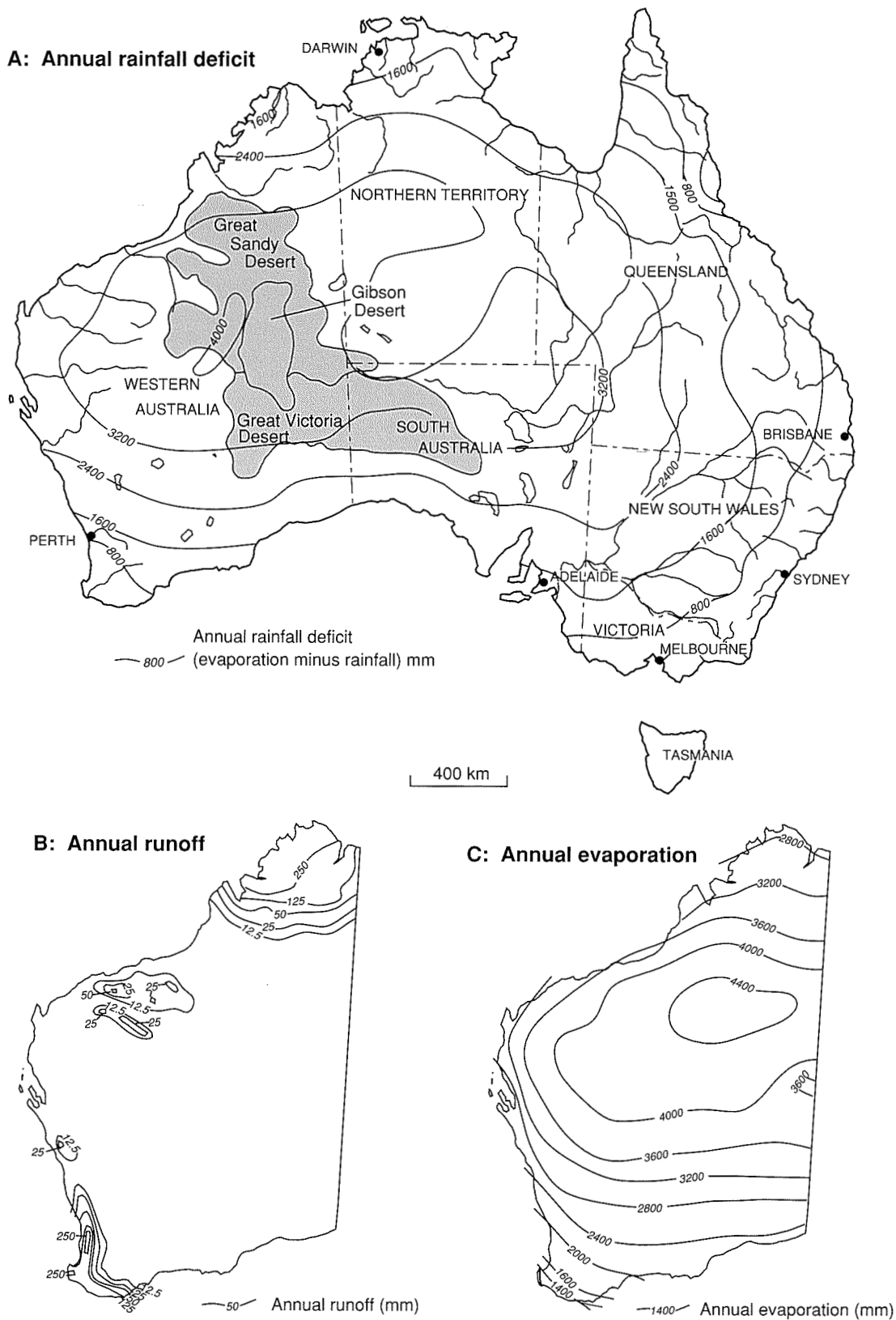


Figure 1. A: Annual rainfall deficit (excess of evaporation over rainfall) in Australia  
 B: Annual evaporation in Western Australia  
 C: Average annual rainfall in Western Australia  
 (A modified after Jacobson et al., 1987; B and C after WAWRC, 1984)

## Introduction

### Background

Western Australia comprises almost one third of Australia, and despite the fact that it is mainly arid to semi-arid (Fig. 1), the presence of abundant natural resources are certain to ensure the ongoing economic growth and development of the State. It is well known that the availability of water underpins this growth and development, and that the availability of water has been the 'abiding challenge' (Hunt, 1980) since the commencement of European settlement in 1829. The Comprehensive Water Supply Scheme, including the Goldfields and Agricultural Water Supply (Perth–Kalgoorlie pipeline) and the Great Southern Towns Water Supply are examples of efforts to service important but water deficient areas of the State. They illustrate the problem in Western Australia, that water resources are not necessarily limited but are unevenly distributed, and the cost of their development, not their availability, is the major constraint.

The availability of water is of major importance in determining the character of Perth (the capital city) and the lifestyle enjoyed by its residents. Recently there have been unfounded public fears that Perth may run out of water. This has ignited widespread debate about the availability of water resources. The idea of transcontinental, parallel water and gas pipelines (Fig. 2) conveying water from the Ord and Fitzroy Rivers in the Kimberley region and gas from the Northwest Shelf to Perth and Adelaide via major mining centres and towns was widely discussed (Bridge, 1991). As a result, the Government established the Kimberley Pipeline Management and Advisory Board in February 1992 to examine the engineering and economic feasibility of these proposals. The Board commissioned various studies which confirmed that, as discussed in the Mining Review (1991), a pipeline (including use of canals) was technically feasible but currently not economic.

One of the studies commissioned was a report by the Geological Survey on the availability of large groundwater resources in the State (Allen et al., 1992). This study synthesized large, incomplete, and not readily available sources of information about groundwater resources in Western Australia. It showed that the availability of groundwater had played a major role in the development of Western Australia, and that there were large, poorly known and undeveloped groundwater sources in many areas of the State.

### Purpose and scope

The purpose of this publication is to raise awareness about the State's groundwater resources. In particular, it sets out to provide a general overview of the current understanding of their occurrence, location, and size; the role they play as an environmental agent; and issues affecting their development and management. The publication

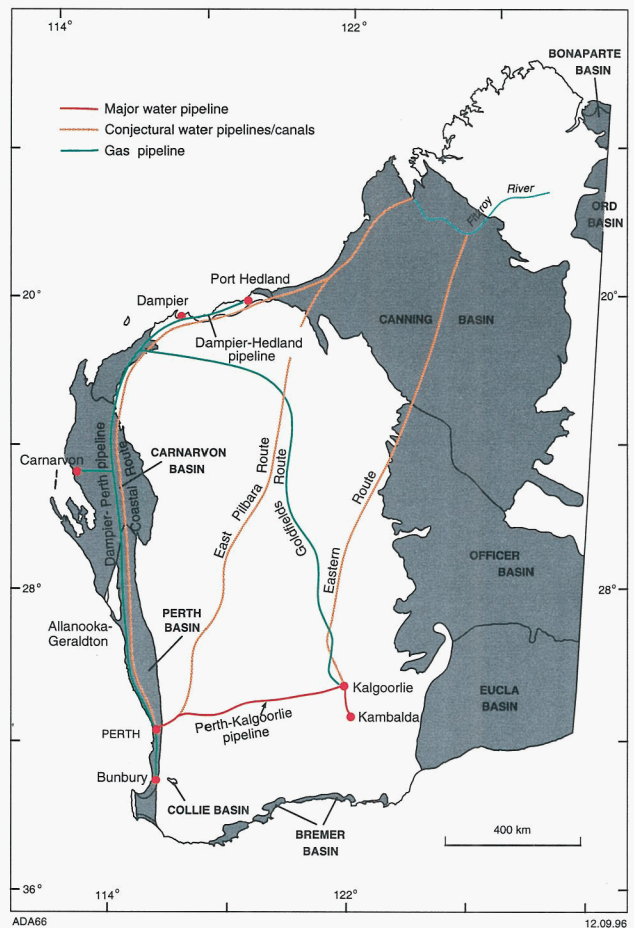


Figure 2. Existing and proposed major water and gas pipeline routes

builds on the report commissioned by the Kimberley Water Resources Development Office for the Kimberley Pipeline Management and Advisory Board. It also embodies other data from numerous scattered and sometimes not readily accessible sources, and attempts to convey, by means of maps and diagrams with supporting text, a general picture of the State's groundwater resources. It is intended for a wide audience not necessarily familiar with groundwater concepts, and the groundwater resources are described from a geological perspective as part of Western Australia's very wide base of earth-sourced natural resources. Therefore, to assist the reader, some important groundwater concepts are explained and a glossary of terms and selected references are provided.

This work should not imply that the groundwater resources in Western Australia are well known, or even adequately known. The rapidly expanding knowledge of the State's geology, together with some groundwater investigations in key areas mainly during the last 30 years, permit a general understanding of the groundwater resources. Because of the size of the State and remoteness of large areas, however, our understanding of the quantity and quality of the groundwater resources is still inadequate.

## Role of the Geological Survey of Western Australia

The State's groundwater resources occur within the complex fabric of rocks (Fig. 3) forming Western Australia (Geological Survey of Western Australia, 1990). In common with mineral and petroleum exploration, geoscientific techniques and concepts together with exploratory drilling are utilized by appropriately trained geoscientists for groundwater exploration and assessment. Also in common with mineral and petroleum resources, groundwater belongs to the State. Unlike minerals and petroleum, however, the private sector has no economic incentive to explore and assess groundwater except for some resource development projects. Consequently, because of the strategic nature of the resource and the long-term effort and funding required in acquiring and archiving data, groundwater assessment in Western Australia is a State responsibility. Until recently, this was undertaken by the Geological Survey, which had the necessary expertise. However, this role and that of advice to Government are now vested in the Water and Rivers Commission.

The Geological Survey of Western Australia was founded in 1888 and is a Division of the Department of Minerals and Energy (Geological Survey, 1988). Since its formation the Geological Survey has been active in defining the State's groundwater resources, firstly in determining the extent of the sedimentary basins and location of artesian groundwater supplies, and during the last 30 years actively exploring and assessing the groundwater resources in key areas of the State (Allen, 1996). This has continued in parallel with an improving knowledge of the State's geology resulting from regional geological mapping by the Geological Survey, and from mineral and petroleum exploration.

The Geological Survey formally assumed responsibility to undertake groundwater related work on behalf of the State in 1957 when ministerial approval was given to establish a specialized Groundwater Group within the Geological Survey (Ellis, 1957). This was reconfirmed after a special enquiry in 1983 prior to merging of elements of the Public Works Department and Metropolitan Water Authority to form the Water Authority of Western Australia. Conditional on this arrangement was the establishment of a system of staff secondment between the Geological Survey and the Water Authority. This has operated successfully and ensured that the Water Authority had access to geoscientific expertise and up-to-date hydro-geological data to underpin management of groundwater resources. The Geological Survey has also provided groundwater information and advice to other Government agencies such as Agriculture Western Australia and Department of Environmental Protection as well as to private industry and the general public.

## Sources of data

### General

Groundwater cannot be directly observed and measured like surface water, and data have to be acquired from

knowledge of the geology, from local bores and wells, or from specific drilling and testing programs. Consequently, when the Geological Survey was established it commenced a system of reporting and map publication which has gradually built up the main databases of the State's geology and groundwater resources. These have been strengthened by data supplied by the Water Authority and its predecessors; acquisition of data from about 100 000 groundwater bores and wells obtained during regional geological mapping and specific water bore surveys; and, since 1964, by specific State- and Commonwealth-funded groundwater assessment programs.

### Groundwater assessment program

In 1962 the Australian Water Resources Council (AWRC) was established by agreement between the Commonwealth and State Governments. The principal objectives of the AWRC were 'the provision of a comprehensive assessment on a continuing basis of Australia's water resources, and the extension of measurement and research so that future planning could be carried out on a sound, scientific basis'. This was followed by a review of the nation's water resources in 1963 (AWRC 1965), which found serious shortcomings in the understanding and assessment of Australia's water resources. Subsequently, in 1964, the National Water Resources Assessment Program commenced with joint Commonwealth and State funding for expansion of the network of stream gauging and meteorological stations, and for exploratory drilling to assess groundwater resources. National leadership was provided by the AWRC which, in addition to directing expenditure for groundwater resources assessment, sponsored education programs and conferences, and commissioned various important publications. It also identified long-term strategic needs and supported various applied research in the area of water resources.

In Western Australia, funding averaging about \$1.5 m/year was provided for groundwater assessment by means of matched grants to the State until 1986 when Commonwealth funding ceased. The State then provided funding until October 1990 when it was suspended in response to budgetary restraints. The program was reinstated in 1993/94 following the election of a new State Government, with funding of \$0.5 m/year for an ongoing program.

The steady funding for groundwater assessment over 30 years, together with acquisition of other hydro-geological data, is gradually revealing the location and size of the State's groundwater resources. The rationale for the assessment program and strategies for funding are set out in publications of the Western Australian Water Resources Council (WAWRC, 1989, 1992). The work undertaken by the Geological Survey was approved by the non-statutory Hydrogeology Subcommittee, comprising representatives of the Water Authority, Agriculture Western Australia, Department of Resources Development, Department of Environmental Protection, and research-based organizations and the mining industry.

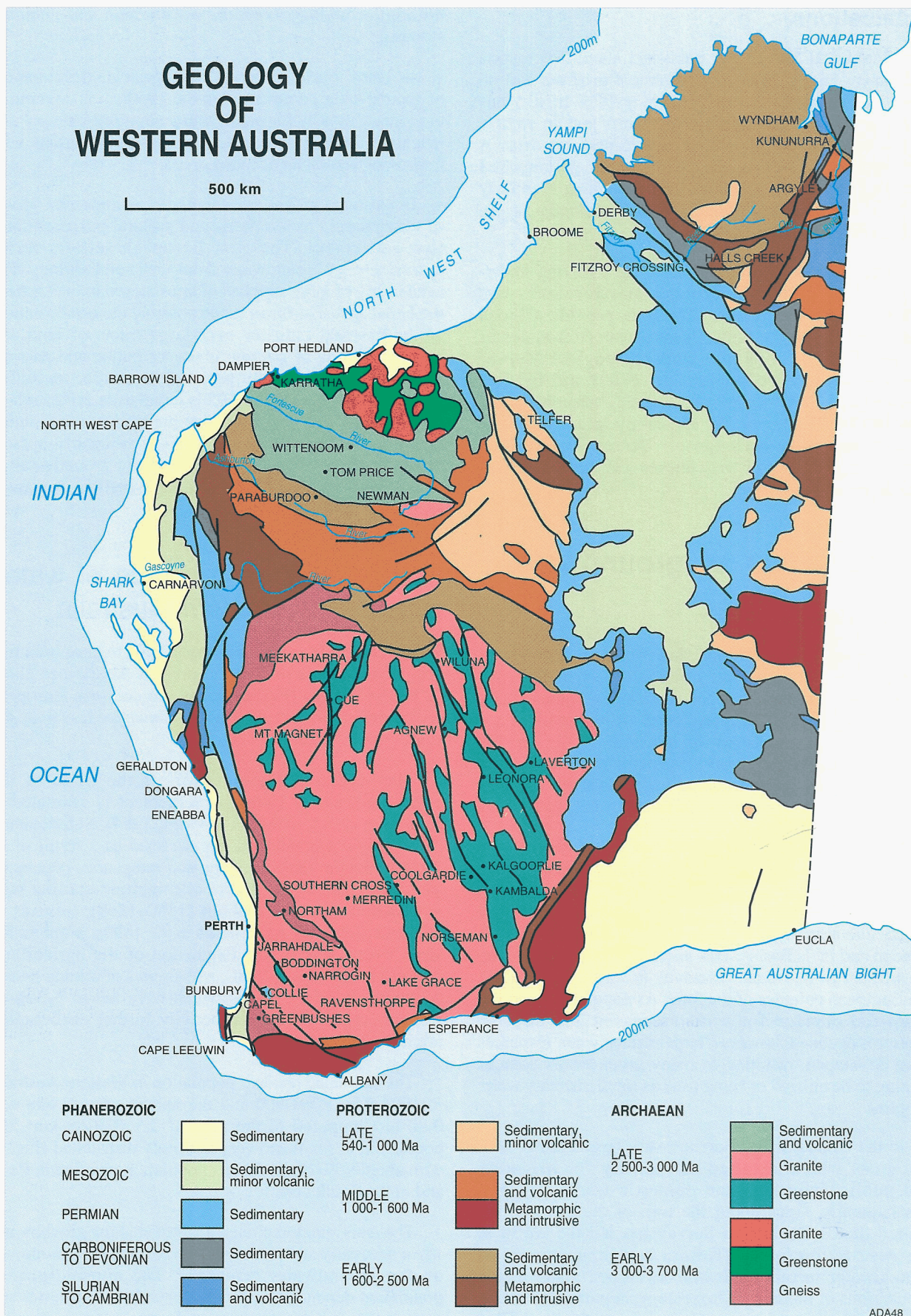


Figure 3. Generalized geology of Western Australia

## Publications

The Geological Survey has published about 500 reports and papers arising from the assessment program and on other groundwater topics (Smith, 1992). It also has available about 3000 unpublished reports and an archive of about 300 confidential consultants' reports. A bibliography of reports and papers about groundwater published by other agencies and individuals, mainly dealing with Perth and southwest Western Australia, is also maintained (Smith, 1993).

This large body of data reflects the evolving understanding of the State's groundwater resources and underpins its management. The data provide a broad understanding of the State's groundwater resources as shown in the 1:2 500 000 Hydrogeological Map of Western Australia (Commander, 1989) and by data provided in the 1985 review of Australia's water resources (AWRC, 1987). Despite the apparently large amount of data, however, knowledge of Western Australia's groundwater resources is very uneven and incomplete (see Groundwater Resources).

## Importance of groundwater

### Historical setting

Groundwater from springs, dug wells, and collector systems has been used for millennia by mankind, for drinking and irrigation and for medicinal and therapeutic purposes (hot springs). It has been an important factor determining the movement of nomadic people and the location of trade routes and settlements, but only within the last 150 years and particularly within the last 50 years has there been large-scale use of groundwater.

In Europe, large-scale exploitation of groundwater for public and industrial water supplies commenced in the 1830s during the Industrial Revolution, when many fundamentals of hydrogeology were established. Large, spectacular artesian flows were obtained from bores in the London and Paris Basins. This inspired world-wide drilling for artesian groundwater, especially in North America and the European colonies of the time. As populations and the industrial demand for water increased and artesian pressures declined, however, large surface water resources were developed, resulting in many groundwater sources ceasing to be utilized or being used as supplementary water supplies.

In the United States there are very large groundwater resources which are used extensively for irrigation and public, industrial and domestic water supplies. Consequently, since about the turn of the century, the United States Geological Survey has led the world in the description, quantification and management of groundwater resources. It has developed many of the foundations of modern hydrogeology, in particular during the last 20 years of computer-based aquifer modelling and investigation and remediation of groundwater contamination. In addition, commercial companies have been in the forefront of major developments in water-bore

drilling technology, borehole construction and pumping systems.

In Third World countries the large-scale development of groundwater commenced in the 1950s. It is continuing to increase rapidly for public water supplies, industry and irrigation to meet demands of growing populations with improving standards of living.

In Australia groundwater has been an important source of water supply for domestic and pastoral purposes since first settlement. The first European settlers relied extensively on groundwater from wells and springs. The availability of large supplies of artesian groundwater from the Great Artesian Basin made possible the establishment of the pastoral industry over large tracts of land and inspired drilling of artesian bores for public and pastoral water supplies in many parts of Australia, including Western Australia. In the 1950s large-scale utilization of groundwater for irrigation commenced and expanded rapidly during the 1960s and 1970s, particularly in New South Wales and Queensland. Currently groundwater is widely used in the arid and semi-arid parts of Australia, especially in Western Australia.

### Groundwater as a source of water supplies in Western Australia

Western Australia is generally considered to have been first occupied by ancestors of the present Aborigines about 40 000 years ago (Hodan, 1989). In contrast, European settlement in Western Australia commenced less than 200 years ago, in 1826.

The Aboriginal population of the State at the commencement of European settlement is estimated to have been about 74 000 (Crawford, 1984). Subsequently the Aboriginal population has declined as a result of its contact with the settlers and the non-indigenous population has grown mainly by bursts of migration starting with importation of convict labour (1850–1868); influxes of migrants during the gold rushes in the 1890s; immigration after World War II; the expansion of the agricultural industry in the 1950s–1960s, and a series of mining booms commencing in the 1960s which have led to increased commercial and industrial activity further encouraging migration into the State.

The estimated resident population in Western Australia in 1994 was 1 701 900 and the annual growth rate was 0.88%. Compared to the area of 2.5 million km<sup>2</sup>, the population is small and very unevenly distributed (Fig. 4) with about 90% of the State's population residing in Perth and in the Southwest.

The Aborigines exploited areas of shallow groundwater when necessary and are not known to have had any impact on the groundwater resources. The non-indigenous population depended on groundwater from the outset and as it increased has used groundwater extensively as a domestic supply and for development of resources, particularly in the pastoral and mining industries. Groundwater has also been used in road, rail and pipeline

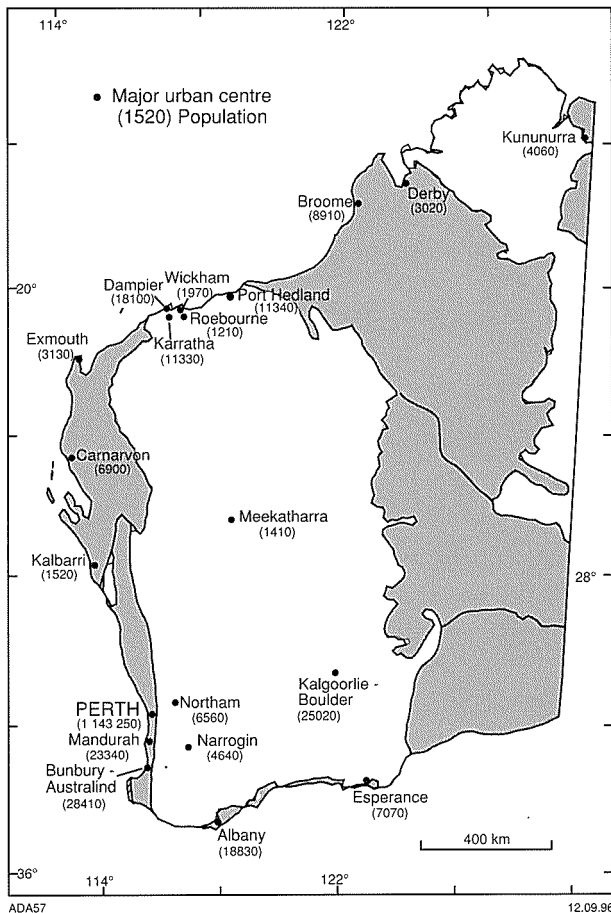


Figure 4. Population of selected major urban centres and localities

construction projects, for industry and as a source of strategic supplies during wartime. Since European settlement, clearing for agriculture, urbanization, industrialization, and local intensive use of groundwater have affected the quantity and quality of groundwater resources in some areas.



Figure 5. An aboriginal well, Rawlinson Range area

## Aboriginal water supplies

In the arid and semi-arid regions of the State, nomadic aboriginal groups relied on the availability of water for their lifestyle. They used ephemeral water supplies (filled from rainfall) in gnammas and rock holes, and more permanent groundwater-maintained supplies from what were referred to as native wells (Fig. 5) and native soaks. Most of these were situated around hills or along drainage lines. These sources of water made possible the nomadic lifestyle of the Aborigines in these regions. Elsewhere in the State, many groundwater-maintained riverine pools, lakes, swamps, springs and soaks were used extensively by tribal groups, as meeting sites and as localities where food could be obtained.

Aboriginal water sites greatly assisted early explorers, pastoralists and prospectors who often described them in considerable detail (e.g. Talbot and Clarke, 1917). Some were later developed for pastoral and mining water supplies and dependence on them only declined when pastoralists established other bores and wells, and when Government drilling programs were undertaken to provide water supplies on tracks to mining centres and for stock routes.

## Perth water supply

For the first 60 years of settlement in Perth, groundwater from springs, dug wells and wetlands was a major source of water supply until the construction of the Victoria Reservoir in 1891 (Hunt, 1980). After the discovery of artesian water in 1895 (Maitland, 1913; Allen, 1979), groundwater from artesian bores provided up to 60% of Perth's water supply until the construction of the Canning Dam in 1940. Subsequently, until about 1970, use of artesian groundwater declined to about 10% of the water supply and was used mainly during times of peak summer demand.

Groundwater was also important in Fremantle for domestic use and also for supply to shipping. Early supplies were obtained from wells and from a system of galleries constructed beneath Fremantle Prison tapping unconfined groundwater (Fig. 6). This was later supplemented by artesian water from two deep bores, also at Fremantle Prison. The system operated until water became available from the Canning Dam.

In 1970 a radical change in Perth's water supply occurred when hitherto undeveloped sources of unconfined groundwater at the southern end of the Gnangara Mound were exploited by the Mirrabooka Groundwater Scheme wellfield. The utilization of unconfined groundwater was accompanied by recognition that there were limitations on the available conventional surface water resources in the Darling Range, and that groundwater might provide Perth's projected water requirements (Hillman, 1971). As a consequence, exploratory drilling programs defining both unconfined and confined groundwater resources were commenced (Allen, 1981a) and various groundwater schemes on the Gnangara and Jandakot Mounds, supplemented with confined groundwater, have been progressively commissioned (Fig. 7).

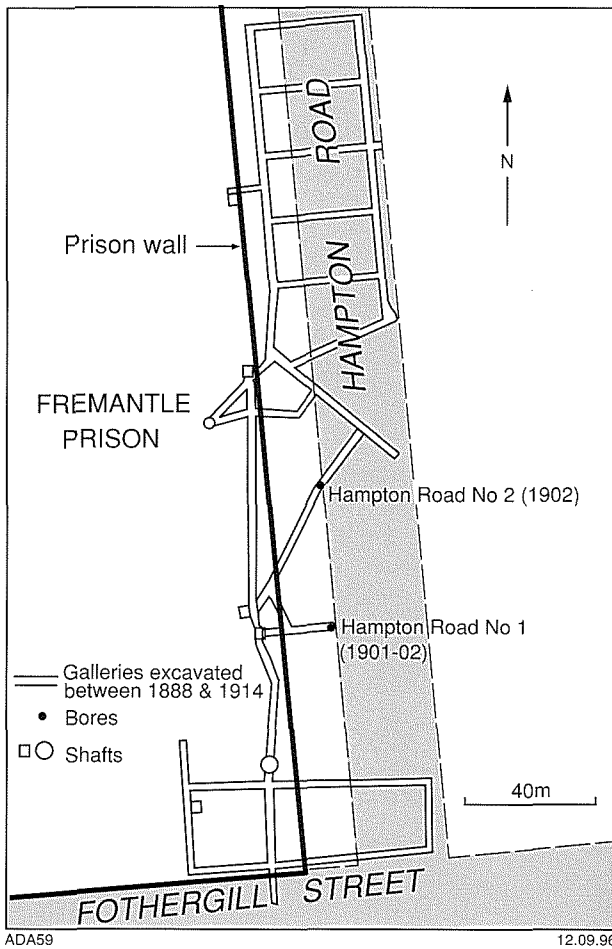


Figure 6. Plan of galleries and bore sites formerly used for Fremantle Water Supply

The importance of groundwater in Perth was emphasized in 1976–77 when surface water supplies reached low levels. Water restrictions were applied and about 50% of Perth’s public water supply was then provided from groundwater sources. In parallel there was a boom in domestic bore construction resulting in one house in five having a bore for garden reticulation. This led to concerns about Perth’s groundwater supplies and resulted in several major reviews and accounts of Perth’s groundwater supplies (Allen, 1976, 1979, 1981; Cargeeg et al., 1987).

Perth is built over large, readily exploited groundwater resources. With limited readily accessible surface water resources, it is more dependent on groundwater than any other major city in Australia (AWRC, 1987). In 1991–92, water usage in Perth was about 406 GL (68%) of which 275 GL was from groundwater (Davidson, 1995). Of the groundwater usage, 81 GL (40% of public supply) was used by the Water Authority and the remaining 194 GL mainly for irrigation by local government, the horticultural industry and the general public. There are an estimated 100 000 private bores with access to shallow groundwater supplies. These maintain parks and gardens and underpin the urban environment and reputation of Perth as a garden city during the summer. The groundwater resources are essential for Perth’s public

water supply and their availability from private bores and wells limits demand on the public water supply. Their importance as a source of public and private water supply will increase in the future (Stokes et al., 1995; Davidson, 1995).

### Town water supplies

As Western Australia became settled, rural and coastal towns were established to service the pastoral, pearling, cereal, mining, timber, fishing, and whaling industries. In most of these towns groundwater from shallow wells together with water collected in domestic rainwater tanks provided water supplies. Carnarvon and Geraldton, in particular, were noted for their number of windmills.

Efforts to locate artesian groundwater sources (Fig. 8) for various townsites in the State were undertaken between 1896 and the commencement of World War I (Maitland, 1913). Exploratory bores to a maximum depth of 918 m (Carnarvon) were drilled (Fig. 9). Most of these bores encountered artesian supplies but the water was brackish or saline and was not utilized. During the same period, drilling for shallow, non-artesian groundwater was carried

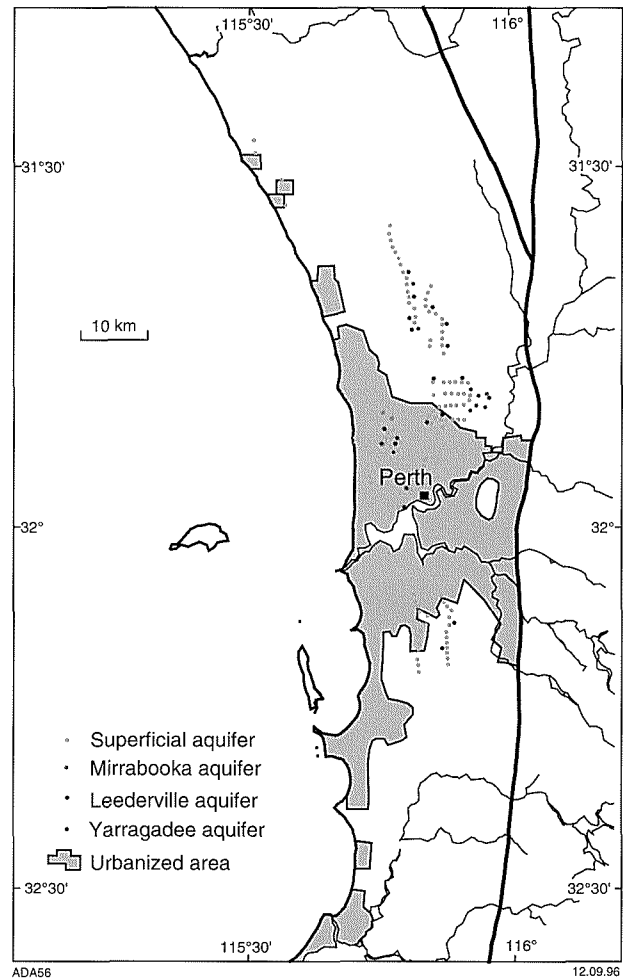


Figure 7. Location of wellfields in unconfined aquifers, and wells in confined aquifers for Perth Water Supply



Figure 8. Drilling an artesian bore near Derby about 1910

out at Mullewa, Mingenew, York, Northam, and other centres with limited success.

In the early 1960s, as a result of increasing population, greater prosperity, and adoption of World Health Organization criteria for water supplies, a general upgrading of town water supplies was commenced by the Public Works Department and has been continued by its successor the Water Authority. Major investigations were carried out for Geraldton, Port Hedland, Carnarvon, Karratha–Dampier–Wickham, and Broome, as well as numerous investigations for small towns and communities. Consultants have also undertaken major investigations for mining town water supplies at Goldsworthy, Tom Price, Newman, Telfer, Leinster, and others. The various towns and communities relying on groundwater-based water supplies are shown in Figure 10, illustrating the importance of such supplies throughout the State.

## Goldfields water supplies

Following the discovery of gold in Coolgardie (1892) and Kalgoorlie (1893), major gold-rushes occurred and thousands of prospectors flocked into the State. From the outset the availability of water was a major problem in remote areas, and in the mining centres for domestic and mining purposes. There are numerous accounts of death from thirst or water-related diseases.

The scarcity of water was particularly acute in Coolgardie and Kalgoorlie (Blatchford, 1899). To meet the demand, brackish and saline groundwater was desalinated using privately operated wood-fired condenser plants (Fig. 11) in what may have been the first large-scale desalination for water supplies, other than for locomotives. The condensers could not meet demand and the water they produced was very costly.

To meet the demands for water there was public pressure to drill for artesian water, possibly because there was local knowledge of significant but saline groundwater in some palaeochannels. The region is not underlain by a sedimentary basin and the likelihood of obtaining artesian groundwater was dismissed by the Geological Survey.

Nevertheless the Government, mainly for political reasons, eventually undertook an unsuccessful attempt to locate artesian groundwater in 1896–97, when a diamond drillhole was drilled to 915 m before being stopped because of technical difficulties. It intersected about 43 m of weathered material overlying ‘granite’ and ‘diorite’ and encountered only a small seepage of saltwater at 36 m. Following this result a proposed deep bore at Kalgoorlie was not drilled and shortly afterwards C.Y. O’Connor commenced planning the construction of Mundaring Weir and a pipeline to Kalgoorlie. The water supply problem was eventually solved in 1903 when the 550 km long Goldfields Water Supply pipeline was completed and water was pumped to Kalgoorlie.

Another significant event occurred in 1902 when the Mining Development Act (1902) was enacted, and a Mines Water Supply Branch was established in the Department of Mines. This operated until 1912 and the Branch was responsible for establishing water supplies from bores, wells and small-scale dams along tracks throughout the various goldfields, for batteries, mines, condenser plants, and stock routes. Records show that over 250 successful bores and wells were constructed. However, apart from statistical data and the location of various Government water reserves, data from most of these have now been lost. This program significantly assisted opening up the Goldfields and development of remote areas of the State.

From about 1912 the gold-mining industry went into a long period of decline, with minor revivals until the abolition of the gold standard in 1971. This and other international events led to a marked increase in the free-market price of gold. At the same time, improved gold extraction technology (carbon-in-pulp, and carbon-in-leach processes) resulted in reworking many formerly uneconomic gold deposits and active exploration for new ones. Consequently there has been a ‘gold-boom’ which has continued to the present. The availability of groundwater, in particular saline and hypersaline groundwater in the Kalgoorlie region, has been a major factor in facilitating the mining activity.

## Other mining water supplies

In addition to providing water supplies for gold mines and mining towns, groundwater has also provided water for dust suppression, mineral processing, cooling and slurring in mining operations and mineral exploration activities. Examples are base metal mining in the Kimberley; tin mining near Marble Bar; iron ore mining in the Pilbara; solar salt works at Lake McLeod and Shark Bay; mineral sands mining at Capel and Eneabba; sea sand mining in Cockburn Sound, and bauxite processing at Pinjarra. Many other current and future mining activities (Fig. 12) are also likely to depend on groundwater.

## Pastoral water supplies

Since first settlement, the pastoral industry has been of major importance and has played a significant role in pioneering remote areas and in the economic development of the State. Sheep are run mainly in the low rainfall areas

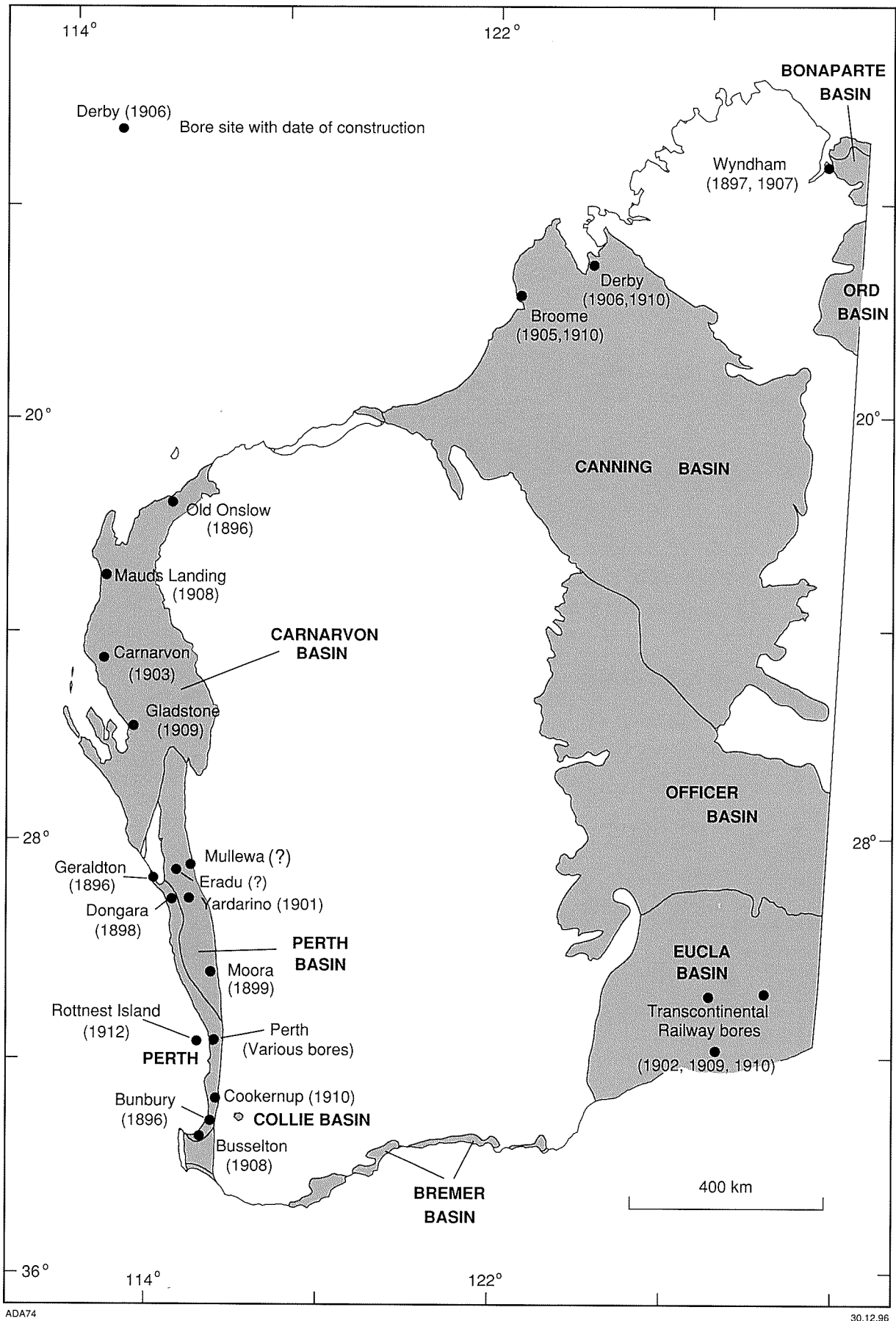
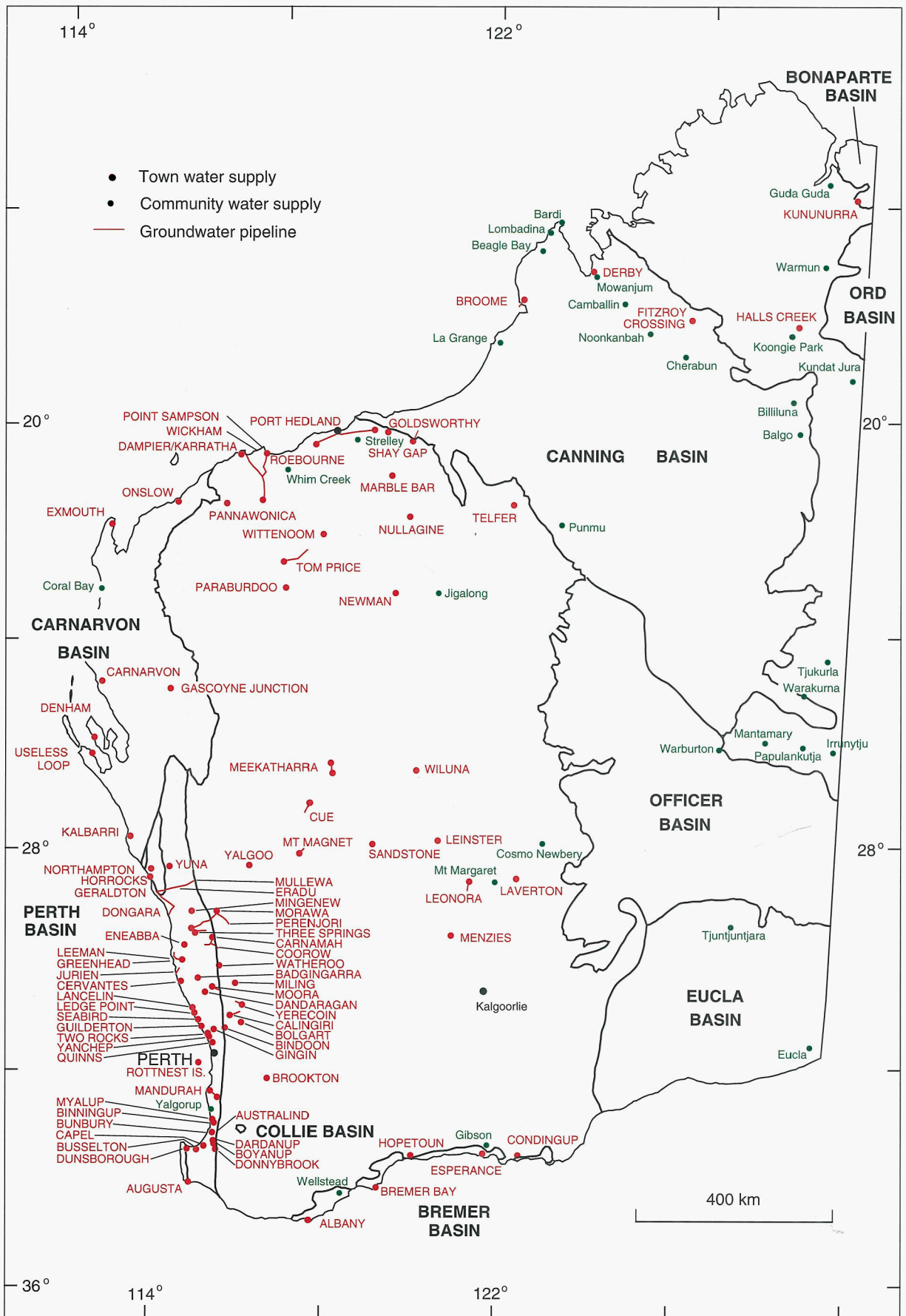


Figure 9. Location of artesian bores drilled from 1896 to 1912



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Figure 10. Towns and communities wholly or partly relying on groundwater-based water supplies



Figure 11. Condensers operating in Coolgardie about 1896

of the Arid, Pilbara, and Agricultural Zones and cattle mainly in the more rugged, sub-tropical, Kimberley Pastoral Zone (Fig. 13).

Both sectors of the industry have experienced various periods of economic expansion and contraction during their history. In the sheep sector availability of groundwater has been a major factor in its viability. Large numbers of bores and wells have made possible access to extensive tracts of grazing land. These have utilized mainly shallow unconfined groundwater, but artesian groundwater has been exploited locally as in the Carnarvon and West Kimberley regions. In the cattle sector the availability of groundwater from relatively large-yielding bores is important, particularly in the drier areas without access to surface water. The availability of groundwater from bores and wells was also very important along stock routes (e.g. Canning Stock Route), prior to improved roads and transport.

### Erosion control and drought relief

In the Kimberley region, riverine pools are used widely for cattle watering. This has led to erosion of river frontages and unequal grazing pressure on the rangelands. From 1950 to 1973 the Government operated the Kimberley Cattle Stations Subsidized Drilling Program to locate bores so that pressure on river frontages would be alleviated. The Geological Survey was responsible for bore siting, and when the scheme ceased about 150 bores had been drilled, of which about 100 had been successful.

Drought is a natural feature of the climate of Western Australia. During the last 30 years several drought relief drilling programs with different funding formulae have been undertaken by the Government to assist the pastoral industry. In 1969–70 a major drought relief drilling program supervised by the Geological Survey was undertaken in the wheatbelt in areas not served by the Comprehensive Scheme. The purpose was to locate acceptable stock water supplies, either on-farm or in locations from which water could be carted. A total of 2639 exploratory bores with an aggregate depth of

67 294 m, with a success rate of about 1 in 10, were drilled (Lord, 1971). Later, in 1980–81, another small-scale drought relief program was undertaken in drought-declared areas of the wheatbelt (Kent and Gnowangerup Shires) when 47 bores with an aggregate depth of 1112 m and success rate of about 1 in 15 were drilled (Martin, 1981).

In the Kimberley region, two drought relief drilling programs have been undertaken for stock water supplies. The first was in 1985 when 28 bores with an aggregate depth of 1100m and success rate of 1 in 3 was undertaken in the East Kimberley (McGowan, 1986). The second was conducted in the same area in 1990, when a total of 27 bores with an aggregate depth of 1695 m with a success rate of about 1 in 4 were drilled (Laws, 1991c). The successful bores have provided reliable water supplies in tracts of land which formerly could be only partly utilized.

### Irrigation water supplies

The climate of Western Australia ranges from sub-tropical in the north to temperate in the Southwest (Fig. 14) and provides the opportunity for producing many horticultural products that depend on the availability of suitable land and adequate water. Present horticultural production for domestic and overseas markets includes a wide variety of

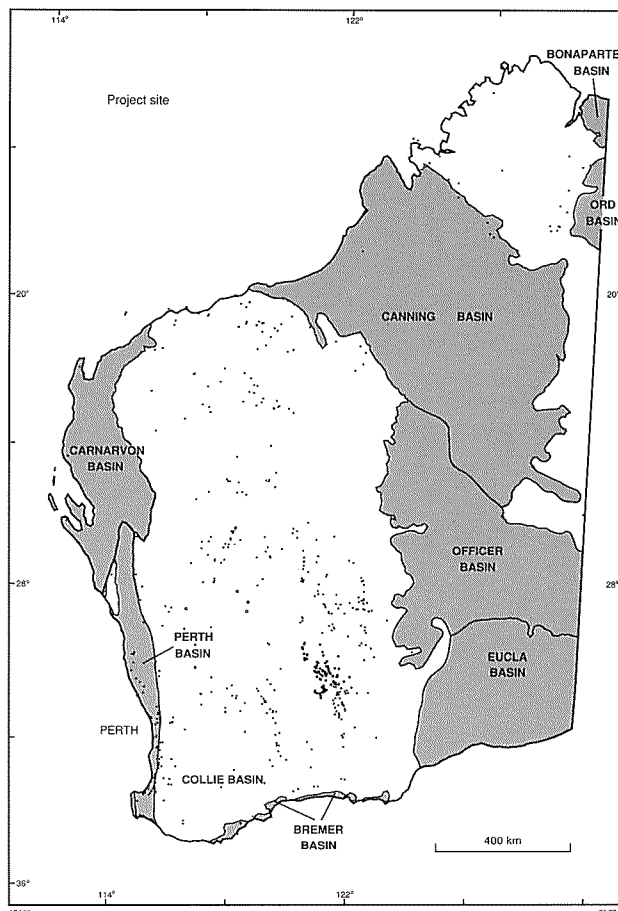


Figure 12. Location of operating and proposed mining projects in Western Australia in 1993

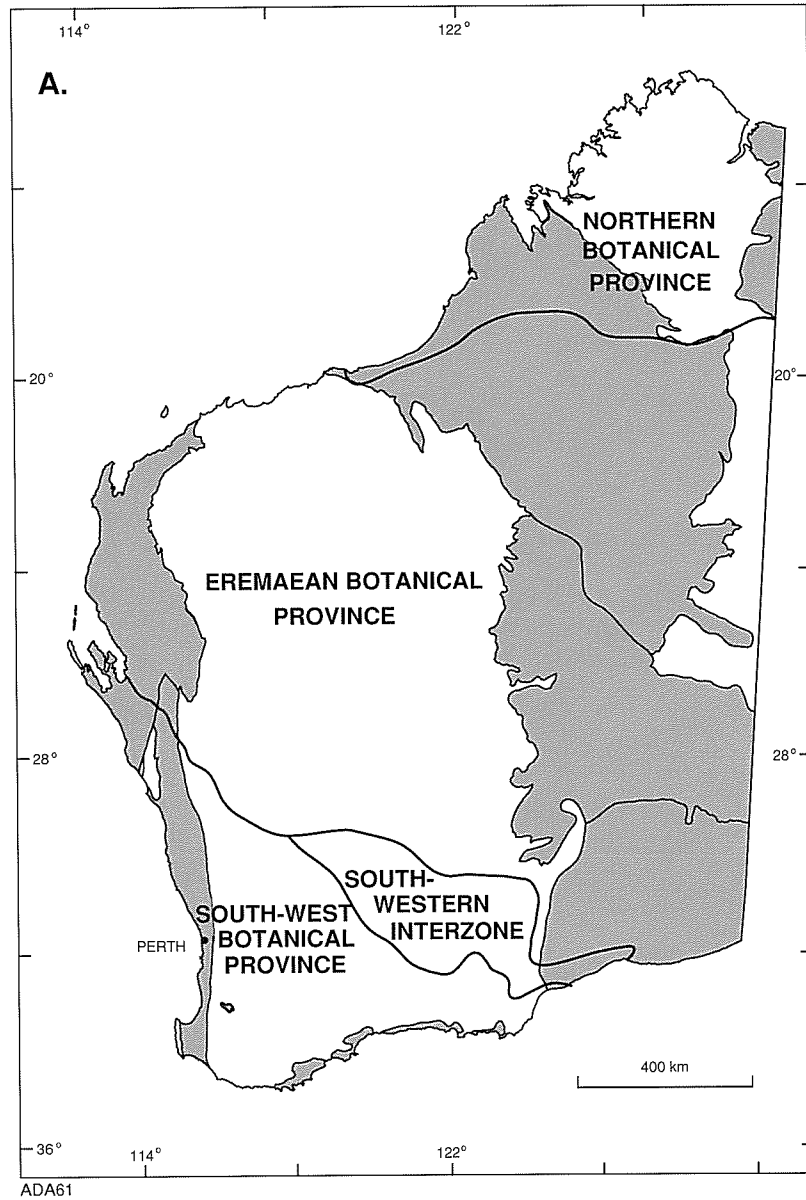
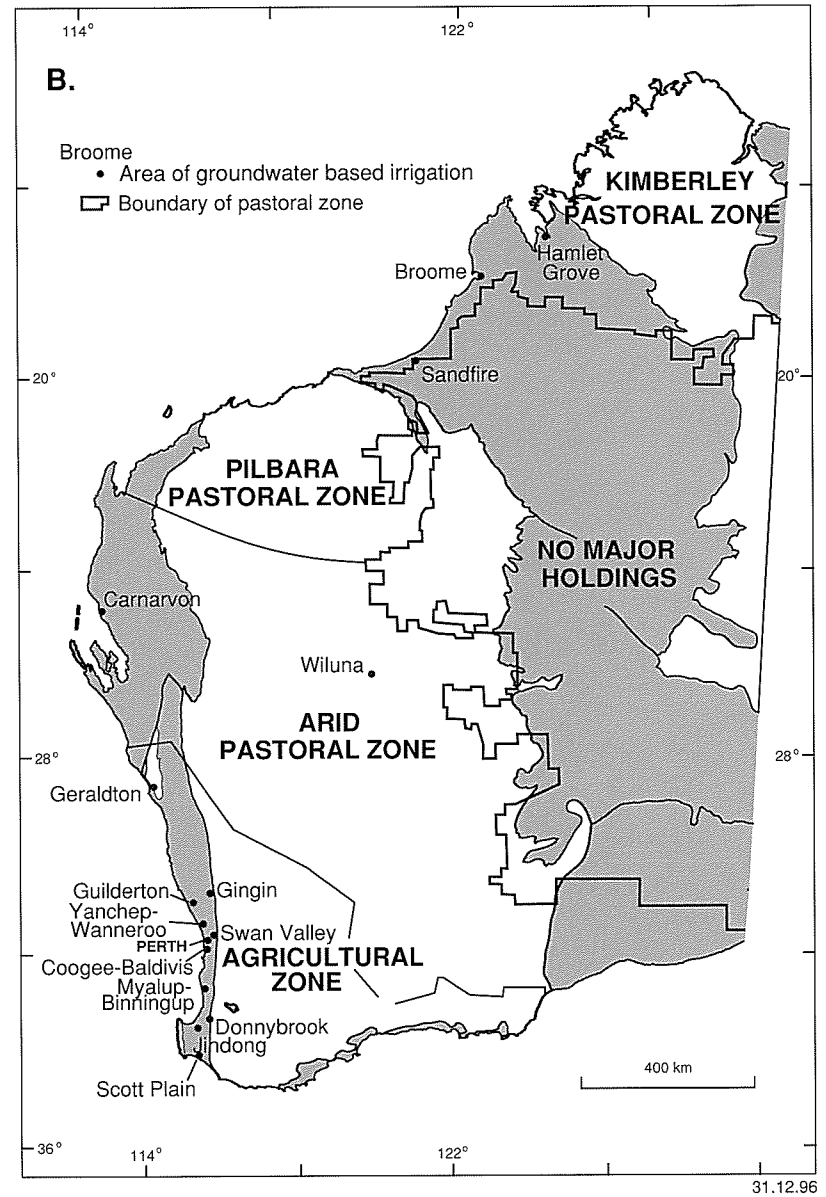


Figure 13. A: Botanical provinces of Western Australia



B: Agricultural and pastoral subdivisions, and areas of groundwater-based irrigation

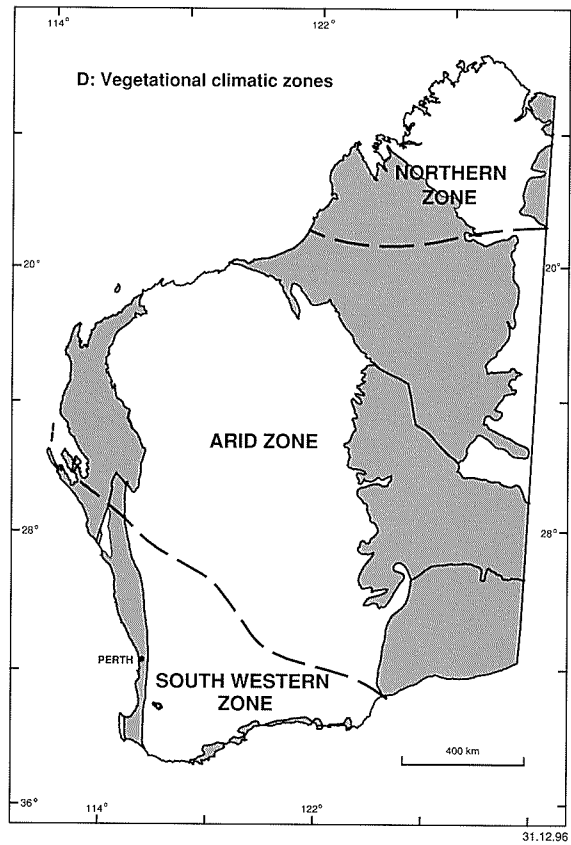
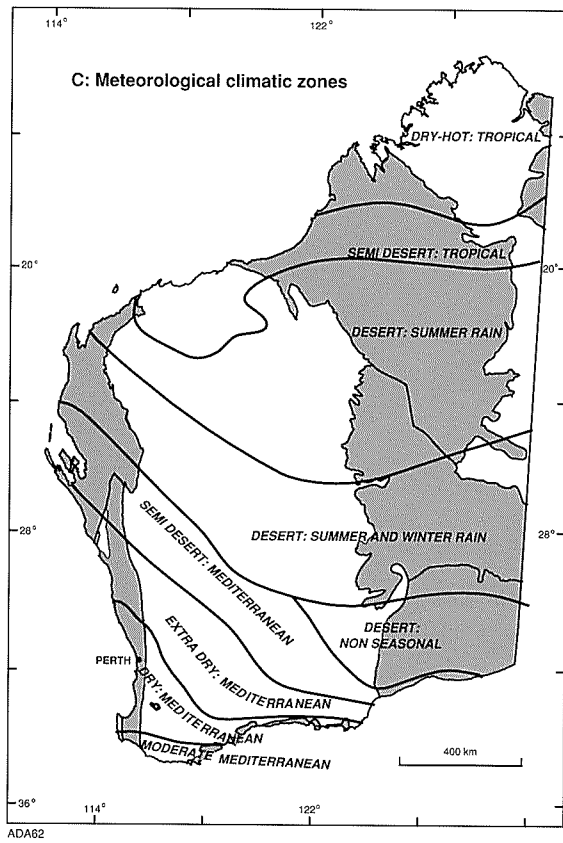
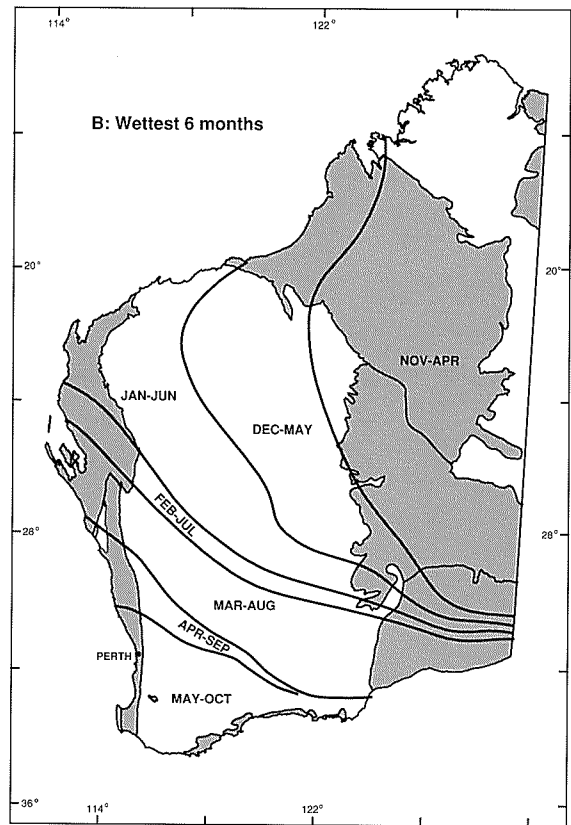
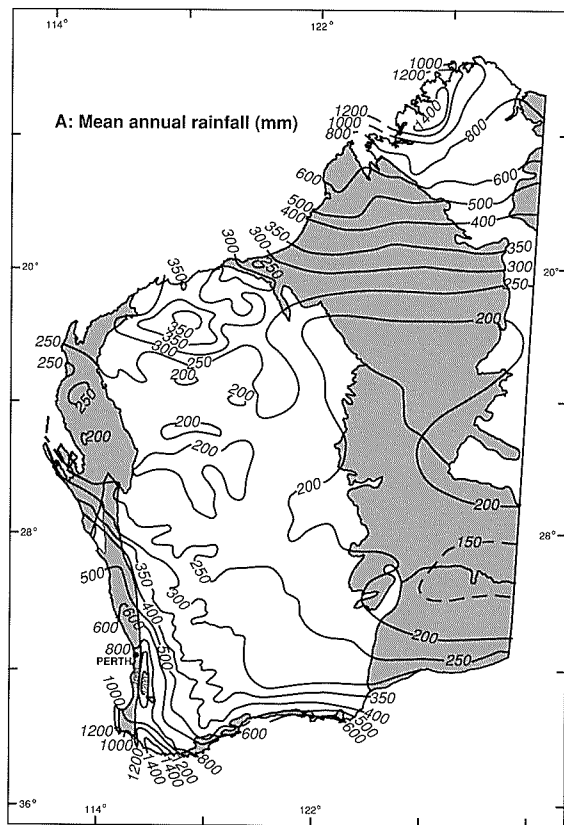


Figure 14. A: Mean annual rainfall  
 B: Wettest six-monthly period of year  
 C: Major climatic zones  
 D: Vegetational climatic zones

vegetables, citrus, tropical fruits, nut crops, grapes, flowers, lucerne, turf, and nursery products.

Currently, most groundwater-based irrigated horticulture depends on self-supplied groundwater sources except at Carnarvon where the Water Authority provides a groundwater-supply to supplement self-supplied groundwater sources. The main large-scale groundwater-based irrigation is practiced in the Perth region and at Carnarvon. Small-scale groundwater-based irrigation is undertaken at various centres from Derby in the north to the south coast and inland at Wiluna (Fig. 13).

Irrigation currently utilizes about 100 GL/year of groundwater (see Current Groundwater Usage). In the future it is expected that, as the population increases and further crops and markets are developed, exploitation of suitable groundwater supplies will increase substantially.

## Engineering and strategic water supplies

The size of Western Australia has necessitated many large-scale infrastructure projects for communication, access to mineral and petroleum resources, and defence undertakings. The availability of groundwater has been a key factor in the construction of many of these projects.

The Trans-Continental Railway (now Trans-Australian Railway) was constructed between 1901 and 1917 and the Geological Survey advised on the availability of groundwater supplies (Maitland, 1915). During construction of the railway, 19 bores ranging to 448 m depth were drilled and later some of these were used for the operation of the railway.

Road construction has utilized large quantities of groundwater. The Eyre Highway, a major road link with eastern Australia, was only a track until World War II since when it has been progressively upgraded and finally was sealed to the South Australian border in 1975. Various water bores (Sofoulis, 1962) were utilized and made possible the road construction works. Similarly, since 1980 the Main Roads Department has had an active program of road and highway construction and upgrading throughout Western Australia. The Geological Survey has located numerous bores for this program and helped save millions of dollars in water cartage costs.

Large quantities of groundwater were used in the construction of the 1400 km natural gas pipeline from Dampier to Perth, completed in 1984. During construction, the pipeline required hydraulic testing, and groundwater from 11 borefields (located by consultants) was used to test various sections of the pipeline and for construction of access roads. New gas pipelines from Dampier to Port Hedland and to the Goldfields presently under construction also utilize groundwater supplies.

During World War II, between 1942 and 1944, the Royal Australian Engineers drilled various bores for army camps and airfields in Western Australia. Bores were drilled at Dandaragan, Exmouth, Fremantle, Garden Island, Gingin, Mingenew, Moora, Morawa, Muchea, Pinjarra,

Pithara, Point Peron, Port Hedland, Rockingham, Toodyay, and Walebing. More recently, groundwater supplies were used extensively for the construction of the North West Cape Communications Facility, and for construction of the Curtin Airbase near Derby. The Geological Survey has provided data on availability and quality of groundwater to the army for defence planning in northern Western Australia.

## Groundwater as an environmental agent

In a generally arid region such as Western Australia, groundwater plays an important role in stream flow, maintenance of wetlands, and location of a number of important ecosystems relying on groundwater discharge, or access to shallow groundwater.

Most Western Australian rivers and their tributaries are intermittent and streamflow is often maintained for variable periods by groundwater discharge (baseflow). This occurs when the watertable rises and intersects the stream bed and the resulting groundwater discharge maintains stream flow. Examples occur mainly in the areas of higher rainfall, particularly where major rivers cross the Swan Coastal Plain as in the Perth metropolitan area (Allen, 1981a) and on the Kimberley Plateau (Allen, 1966). In the more arid parts of the State, groundwater commonly provides flow along reaches of some rivers (e.g. Millstream), and frequently maintains local pools.

Saline lakes are widespread in the interior of the State, and freshwater and brackish lakes occur extensively on the Swan Coastal Plain and near the western half of the south coast, particularly in the Esperance region. Many of these, such as Lake Yindarlgooda in the Eastern Goldfields (Commander et al., 1991b); Lake Toolibin in the Southwest Agricultural Zone (Stokes and Martin, 1986); Lake McLeod near Carnarvon (Logan, 1987); Lake Gregory on Sturt Creek (Allen, 1990), and the many hundreds of lakes and wetlands on the Swan Coastal Plain (Semeniuk, 1987) directly affect groundwater flow systems.

Some native vegetation is dependent on access to shallow groundwater, generally along drainage lines and in areas of shallow groundwater, or cavernous limestone. Examples are river gums on river banks; dense stands of Melaleuca upstream of Rocky Pool on the Gascoyne River (Allen, 1972); fig trees with sub-aerial root systems in caves on Cape Range (Allen, 1993); various areas of relict vegetation in the Pilbara (e.g. Millstream), and vine thickets on the Kimberley Plateau.

Important ecosystems have developed in and around seasonal and perennial groundwater-maintained wetlands. These occur mainly in areas of groundwater discharge, or where the watertable intercepts the ground surface. The most widespread are the numerous lakes and swamps on the Swan Coastal Plain (near Perth) in which the biota have been studied in some detail (e.g. Davies and Rolls, 1987). Notable ecosystems dependent on groundwater discharge are communities of stromatolites at Lake Clifton

(Moore et al., 1984) and other localities. Some coastal ecosystems dominated by mangroves (Semeniuk, 1993) and seagrass meadows are dependent on discharging groundwater for small quantities of nutrients which may determine their location and extent.

## Occurrence of groundwater

### Hydrological cycle

Water occurs in a global dynamic system, and via the atmosphere and the ocean circulates around the entire globe. The part of the circulation system involving exchange of water between the ocean and the land is known as the hydrological cycle (Fig. 15).

The main source of energy for the hydrological cycle is radiant energy from the sun. This causes evaporation from the ocean which in response to various geographical, physical and topographical factors is precipitated unevenly on the land surface as rain, snow or dew. Most precipitation is returned rapidly to the atmosphere by evapotranspiration or to the sea by runoff. However, a small proportion is temporarily stored in snowfields, glaciers and deep lakes, or infiltrates as groundwater below the land surface, before eventually discharging and rejoining the hydrological cycle.

Almost one third of the earth's surface consists of land masses. Consequently, depending on the nature of the rocks, there is opportunity for temporary storage of very large quantities of water within porous and fractured rocks. Globally this is only about half a per cent of all water on the planet, but is the third most abundant source of water (Fig. 15).

### General principles

Most groundwater originates from direct rainfall infiltration or indirectly by infiltration of rainfall-runoff along drainage lines. Direct infiltration may occur where rocks are exposed at the surface, but more generally it takes place through overlying soils after available water exceeds that held by attractive forces within the soil profile. Similarly in drainage lines, infiltration may occur directly into exposed rock, or via alluvial sediments which may retard or facilitate infiltration depending on the geological conditions. Consequently, because of the wide variety of topographical, geological, soil, and landuse conditions, infiltration is spatially uneven and may occur at preferred sites or over wide areas. Infiltration is further affected by rainfall duration and intensity and by preceding soil moisture conditions. It may occur continuously, seasonally, or as episodic events, sometimes many years apart.

Depending on conditions, the infiltrating water slowly or rapidly percolates down to the watertable — the level below which all voids in the rock material are filled with water (Fig. 16). Having reached the watertable the water may be depleted by deep-rooted vegetation (transpiration) or by evaporation where suitable watertable and soil

conditions occur. The net amount of infiltration (recharge) that eventually remains as groundwater commonly ranges from 1% to as much as 50% of average annual rainfall.

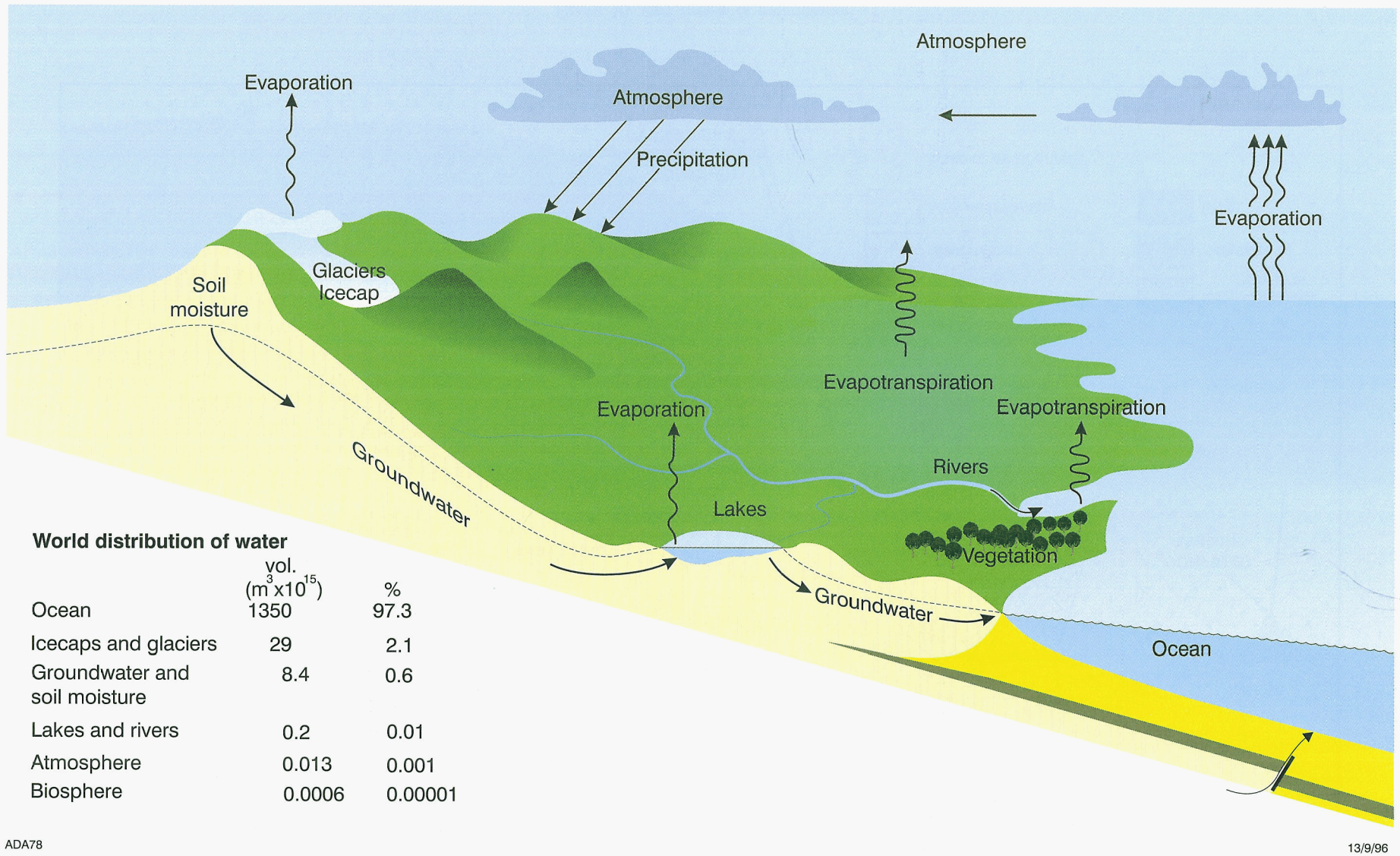
The watertable lies generally sub-parallel to the broad features of the landscape. In areas underlain by fractured rocks (Fig. 16), groundwater recharge from rainfall (meteoric water) usually occurs to a depth of about 100 m below the watertable, below which most fractures are closed, except along some major faults where fractures may extend to greater depths. In contrast in the sedimentary basins (Fig. 16) which contain porous and permeable rocks, meteoric groundwater may occur to depths of 2 km or more. Below this, and depending on the thickness and sequence of strata and their structure, is groundwater emplaced during the geological history of the basin (fossil groundwater), or groundwater entrapped during deposition of the sediments (connate water).

The meteoric groundwater moves under gravity through the void spaces in the fractured rocks and pores in the sedimentary rocks, except in some limestone and volcanic rocks where rare underground streams may occur. In the fractured rocks the groundwater usually moves in distinct sheet-like topography-driven flow systems sub-parallel to the topography, and constrained within the major surface drainage catchments. Similarly, in the sedimentary basins, the unconfined groundwater also occurs in topography-driven flow systems, but beneath these there may be a series of superimposed, interconnected flow systems following complex paths controlled by the sequence and structure of the sedimentary rocks. The fossil and connate groundwater is virtually stagnant and moves in response to lithostatic pressure, geothermal differentials, tectonic events, tidal effects, or in response to hydrocarbon extraction.

In both the fractured rocks and sedimentary basins, groundwater occurring immediately below the watertable is at atmospheric pressure, whereas groundwater at depth beneath layers of clay or strata of low permeability may be under greater pressure. In these situations the groundwater is referred to as unconfined and confined groundwater respectively, and the aquifers in which the groundwater occurs as unconfined or confined aquifers. The meteoric groundwater in unconfined aquifers is generally in hydraulic continuity with underlying confined aquifers in discrete recharge areas and moves in flow systems which vary in complexity depending on the sequence of strata and geological structure (Fig. 16).

The rate of groundwater movement is generally faster in unconfined than in confined systems. Groundwater movement is typically 10–100 metres/year in unconfined flow systems; <1–10 metres/year in confined flow systems and is virtually stagnant in the deep-seated systems (fossil and connate groundwater). Consequently the groundwater in unconfined flow systems may range from days to several thousand years in age, whereas in the confined and deep-seated flow systems it may be thousands to millions of years in age.

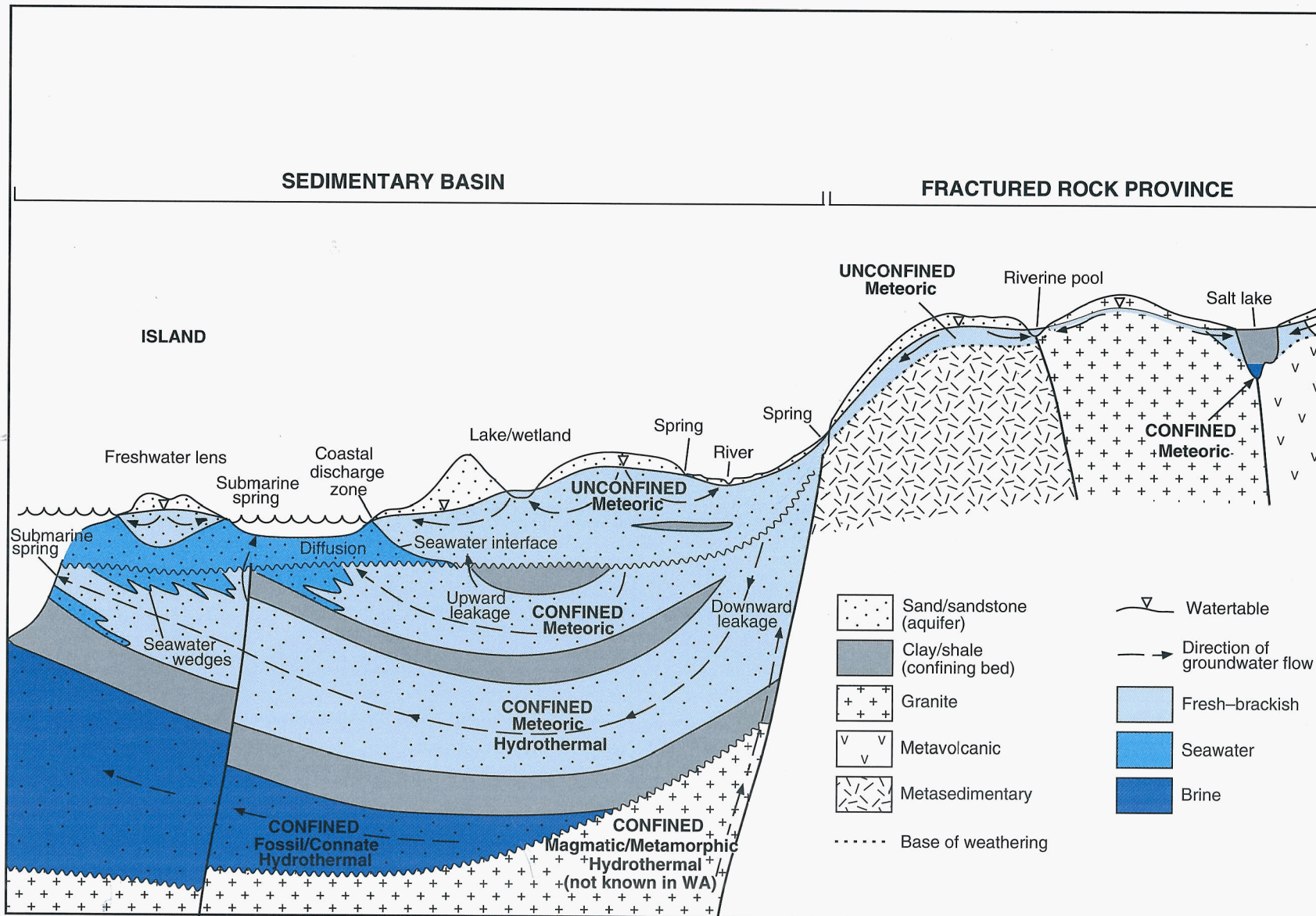
Discharge from groundwater flow systems can occur in various ways. In unconfined flow systems, groundwater generally discharges as discrete springs or seeps into the



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Figure 15. Hydrological cycle



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Figure 16. Occurrence of groundwater

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beds of drainages and wetlands; from seepage zones over a wedge of seawater along the coast; by evapotranspiration of vegetation; and by downward leakage into confined aquifers. The confined flow systems may discharge via upward leakage into overlying unconfined flow systems, via local fault-controlled surface or subsea springs, or subsea springs at the edge of the continental shelf. The deep-seated flow systems may discharge by diffusion into overlying flow systems, or during diagenesis, faulting or volcanism, when they may be sources of geothermal water.

Groundwater can vary extremely widely in the concentration and composition of the dissolved substances that it contains. In meteoric groundwater, the salt content (salinity) of groundwater results from small concentrations of salts in rainfall that are concentrated by evapotranspiration and modified by water-air-soil reactions in the root zone of vegetation, and by solution of rock forming minerals assisted by temperature, and pressure during the slow course of groundwater flow. The composition may be further altered by biological activity during infiltration to the watertable and within groundwater flow systems. The wide variety of rocks and rock-forming minerals that might be encountered during groundwater flow, especially in fractured rocks, may result in a wide variation in the dissolved and colloidal materials in groundwater. The most common constituents of groundwater are sodium, calcium, magnesium, potassium, chloride, sulfate, carbonate, nitrate, and silica. In addition, groundwater may contain a wide variety of trace elements, organic substances, and dissolved gases such as carbon dioxide, nitrogen, oxygen, hydrogen sulfide, methane, and radon. Fossil and connate groundwaters are usually sodium chloride dominated brines resulting from modification of meteoric water or entrapped seawater.

The salinity of groundwater in confined aquifers is generally greater, and the constituents more variable, than in unconfined aquifers. This results mainly from the slower rates of groundwater movement and longer residence time of groundwater in the confined aquifers. In these conditions the salinity of groundwater may be increased and its composition modified by rock-water reactions increased by geothermal heating and pressure, and mixing with groundwater leakage from confining beds or with other flow systems. A notable exception to this could be low-salinity groundwater in some confined flow systems as a result of past, higher recharge during more humid climatic conditions.

## Types of aquifers

The amount of groundwater available in a particular area depends on the geology that controls the water-yielding characteristics of the underlying rock types. This depends on the interconnected void spaces in the rock (effective porosity) and the ease with which water will move through the rock (hydraulic conductivity). Those rock-types that yield economic supplies of groundwater are termed aquifers.

In Western Australia aquifers are classified into three major types:

**Table 1. Qualitative differences between unconfined and confined aquifers in Western Australia (modified after Allen et al., 1992)**

Feature	Unconfined aquifer	Confined aquifer
Area	Usually localized	Extensive
Thickness	Usually thin	Thin-very thick
Lithology	Variable	Uniform-variable
Age	Usually Quaternary	Tertiary-Cambrian
Recharge	Large	Small
Storage	Small	Large - very large
Groundwater movement	Slow	Very slow
Groundwater age	Young	Old-very old
Salinity	Low-variable	Variable-high
Water level in bores	At watertable	Above confining bed; may flow
Pumping effects	Local dewatering	Widespread depressurization
Effect on wetlands	Large	Small-none
Susceptibility to contamination	Readily affected	Not readily affected
Seasonal effects	Large	Small
Seawater intrusion	Significant concern	Minor concern
Subsidence	Possible	Unlikely

- *surficial aquifers* e.g. sand, gravel, and limestone, occurring in alluvial, eolian, lacustrine and coastal plain deposits overlying sedimentary basins and fractured rock provinces
- *sedimentary aquifers* e.g. sandstone, limestone, and conglomerate in sedimentary basins
- *fractured rock aquifers* e.g. fractures in granite, gneiss, metavolcanic and metasedimentary rocks, dykes, quartz veins, and the weathering profiles in fractured rock provinces.

Independent of the type of aquifer, a further practical distinction is whether it is unconfined or confined, which determines the way it responds to pumping and how it should be managed. In particular, pumping from an unconfined aquifer usually produces localized dewatering and diversion of groundwater flow whereas pumping from a confined aquifer may produce lowering of pressure over a wide area and may significantly divert the direction of groundwater flow. Some qualitative differences between unconfined and confined aquifers which may affect their development and management are given in Table 1.

## Groundwater regime in Western Australia

The continent of Australia is part of a large crustal plate slowly drifting northwards. Western Australia forms the western third of the continent and comprises cratons of ancient volcanogenic, clastic and chemical sediments intruded by large bodies of granite, on which have been superimposed basins of variously deformed and metamorphosed volcanic and sedimentary rocks. These have in turn been overlain by younger basins of sedimentary rocks and surficial sediments. It is within this complex and highly variable fabric of rocks (Fig. 3) that Western Australia's groundwater resources occur: in the

fractures of the cratons and old sedimentary basins, and particularly within the porous sedimentary rocks of the younger basins and surficial sediments.

The geological history of Western Australia during the last 50 million years has been marked by a lack of any major mountain building or volcanic events. There has been broad flexing of the land surface causing stagnation and aggradation of drainage systems in the interior of the State; local sagging around the coastal margins causing rejuvenation of some drainage systems in the Southwest and Pilbara; and drowning around the Kimberley coast as the continent has moved northwards. There has also been expansion and contraction of the coastal margins in response to global, geologically and climatically induced changes in sea level. During this time, erosion has proceeded slowly, deep weathering has occurred, and a relatively flat but diverse landscape has developed (Fig. 17). Large climatic changes have also been experienced since Australia separated from Antarctica and drifted northwards through about 20° of latitude, opening the Southern Ocean, and in response to the Pleistocene glaciation and other phenomena.

The main controlling influences on the present climate are the geographic position of Western Australia within the global atmospheric circulatory system, the lack of mountain ranges, and exposure to the Indian and Southern Oceans. In winter, reliable rainfall is received over southwest Western Australia, while in the remainder of the State generally dry conditions prevail (Fig. 14). In summer the reverse occurs, and in the extreme north monsoonal conditions bring rainfall to wide areas, mainly in the Kimberley region, with generally dry conditions elsewhere. Superimposed on this general pattern is the irregular occurrence of cyclones during summer which may bring intense rainfall over large areas, mainly in the north and central parts of the State; and thunderstorms which may affect local areas.

The highest, most reliable rainfall falls in the north and southwest of the State (Fig. 14). The total, statewide, average annual rainfall input is estimated to be 775 000 GL and of this about 94% is lost by evapotranspiration while the remainder is lost by runoff or as recharge to groundwater (Table 2).

Runoff to the ocean occurs from about 45% of the State (Fig. 18). In the remainder there is only poorly coordinated internal drainage from which any runoff is lost by evapotranspiration. The amount of discharge to the ocean depends on seasonal conditions. In the southwest, discharge occurs during winter and ceases in summer whereas in the north runoff occurs during summer and persists for a variable period depending on seasonal conditions. In the intervening region, which has some of the State's largest rivers (Fig. 17), runoff is intermittent and may occur as major floods with runoff persisting for several months.

Like surface runoff, the amount of recharge to groundwater varies widely throughout the State depending on the amount and intensity of rainfall, and on the topography and geology. In the north and southwest of the State recharge is seasonal, whereas for the remainder it is

**Table 2. Estimated average annual water budget for Western Australia**

	Water in (GL)	Water out (GL)	Water out (%)
Rainfall (a)	775 500	—	—
Runoff to ocean (b)	—	40 540	5.2
Recharge to groundwater (b)	—	6 150	0.8
Evapotranspiration (c)	—	728 810	94
	775 500	775 500	100

NOTES:

- (a) Estimated from Bureau of Meteorology map of average annual rainfall up to 1979  
 (b) From WAWRC Publication No. 1/84  
 (c) By difference

episodic, occurring directly from intense rainfall following thunderstorms or cyclonic activity, or from runoff. The rainfall that infiltrates the land surface percolates down to a continent-wide water table to become groundwater. It then flows slowly under gravity through the fractures and pores in the rocks in near-surface, catchment-controlled flow systems, or in strata-controlled flow systems at depth in the sedimentary basins. As the groundwater moves in the flow systems, some is utilized by vegetation; a proportion is discharged via rivers, wetlands and springs; and the remainder is discharged into the sea. The amount of annual groundwater discharge around the coastline varies, depending on whether sedimentary basins or fractured rock provinces form the coastline (Fig. 19). In the sections of coastline bounded by fractured rocks, small quantities of groundwater are discharged in the coastal zone. In areas backed by sedimentary basins, considerably larger volumes of groundwater are discharged in the coastal zone from shallow (unconfined) aquifers and on the continental shelf and continental slope from the deep confined aquifers by diffusion or from subsea springs.

In Western Australia a considerable amount of salt falls in rainfall, and in dryfall associated with wind (Hingston and Gailitis, 1976). The accession of salt varies geographically, the largest saltfall occurring in the Southwest of the State from strong wind and rain originating in the Indian and Southern Oceans (Fig. 20). The salt is concentrated by evapotranspiration and discharged in surface runoff, or retained in the unconfined groundwater systems. Consequently the resultant regional variation in groundwater salinity of the unconfined aquifers (Fig. 21) reflects saltfall, the nature of the drainage system (Fig. 17) and the effectiveness of the groundwater flow systems. Thus, fractured rock areas in the Kimberley and Southwest with similar annual rainfall have considerably different regional groundwater salinity. There is less salt in the Kimberley, mainly resulting from lower salt accession in rainfall, a more effective drainage system, and geological factors such as deep weathering in the Southwest.

Superimposed on the physical, geological and climatic systems is the vegetation regime (Fig. 13) which has developed partly in response to climatic factors. This may remove large volumes of groundwater by evapotranspiration of rainfall infiltration in the unsaturated zone (soil

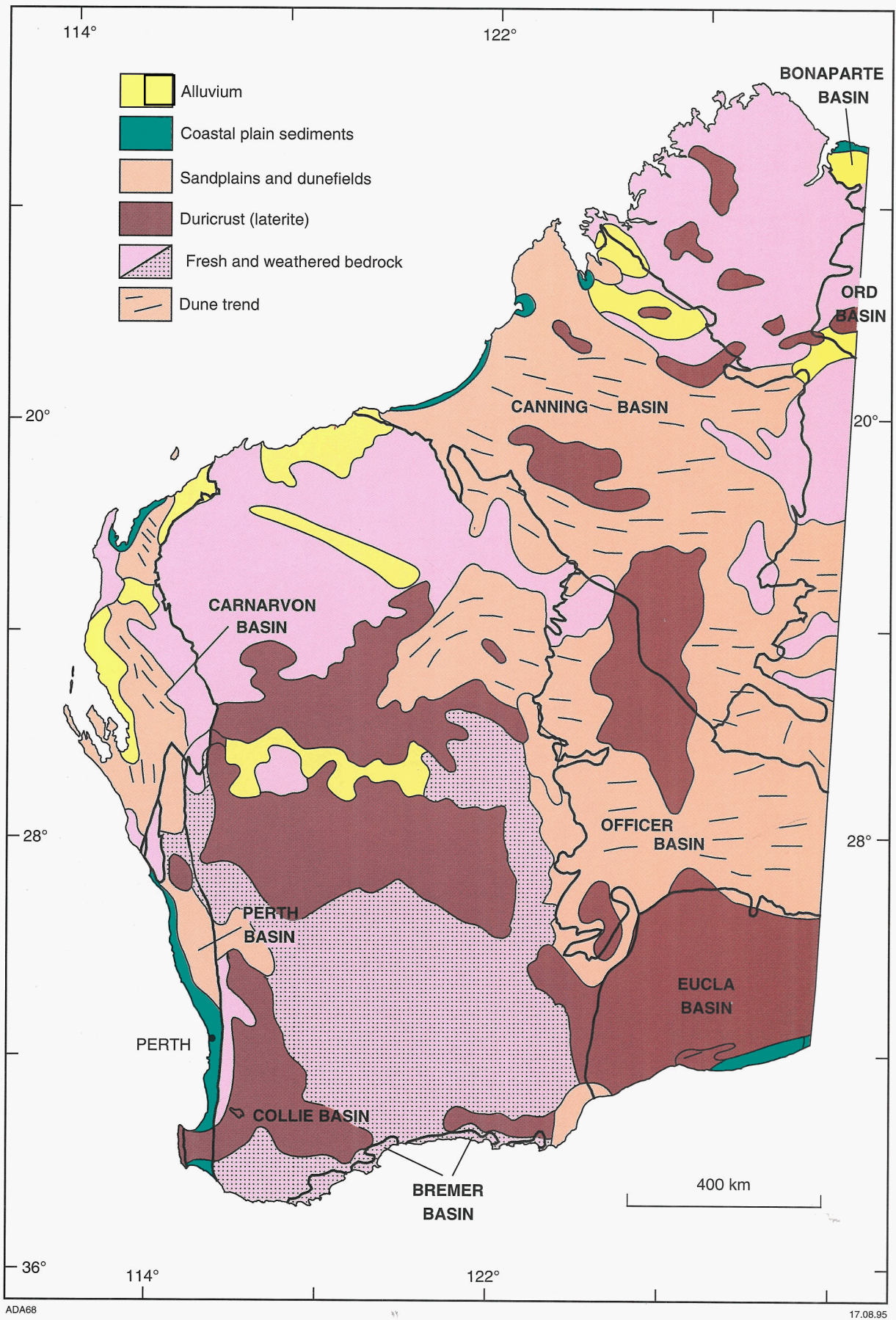
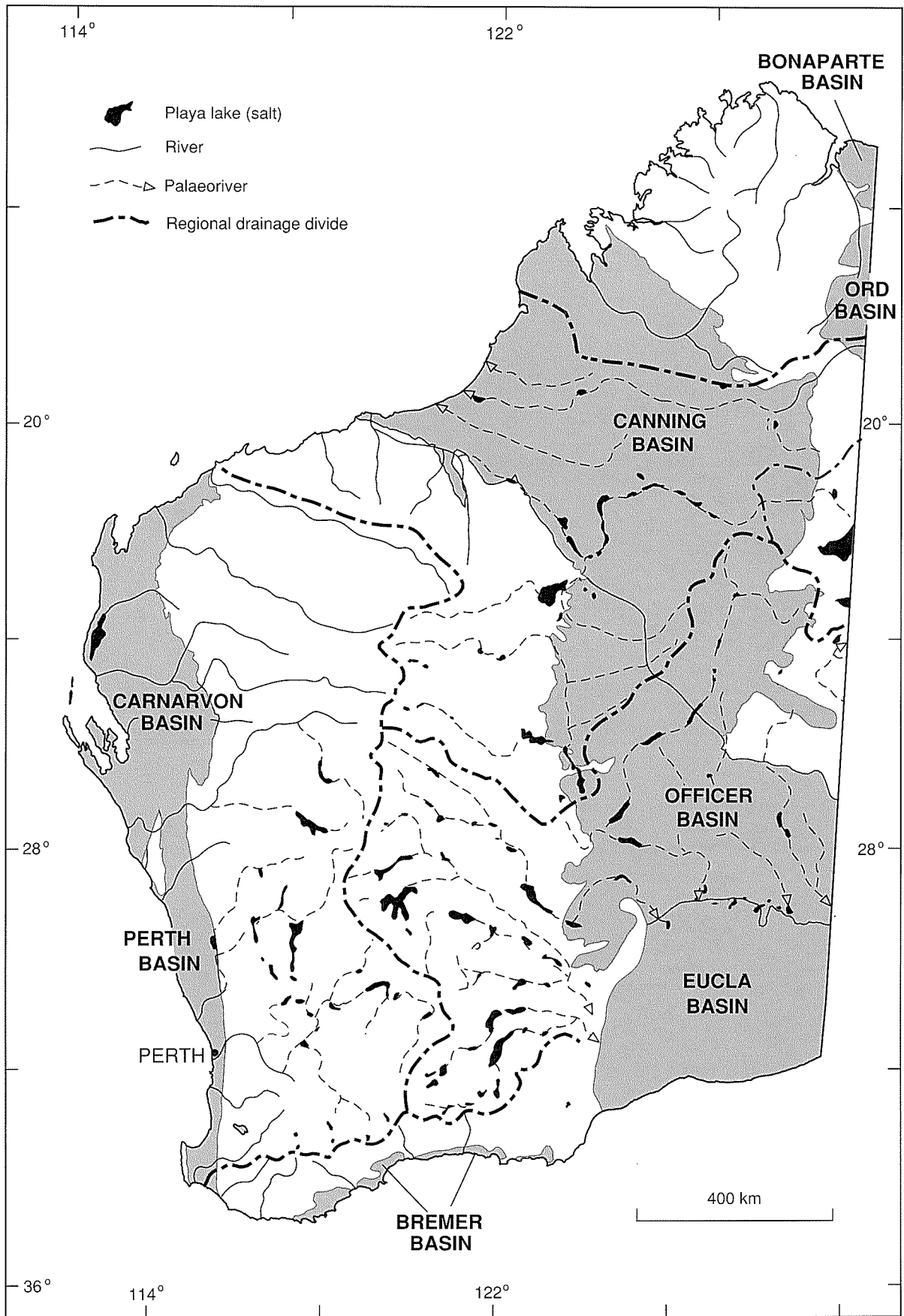


Figure 17. Distribution of relatively fresh bedrock, duricrust, alluvium, and eolian deposits in Western Australia



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Figure 18. Drainage system showing regional drainage divides, major seagoing rivers, palaeorivers, and playa lakes

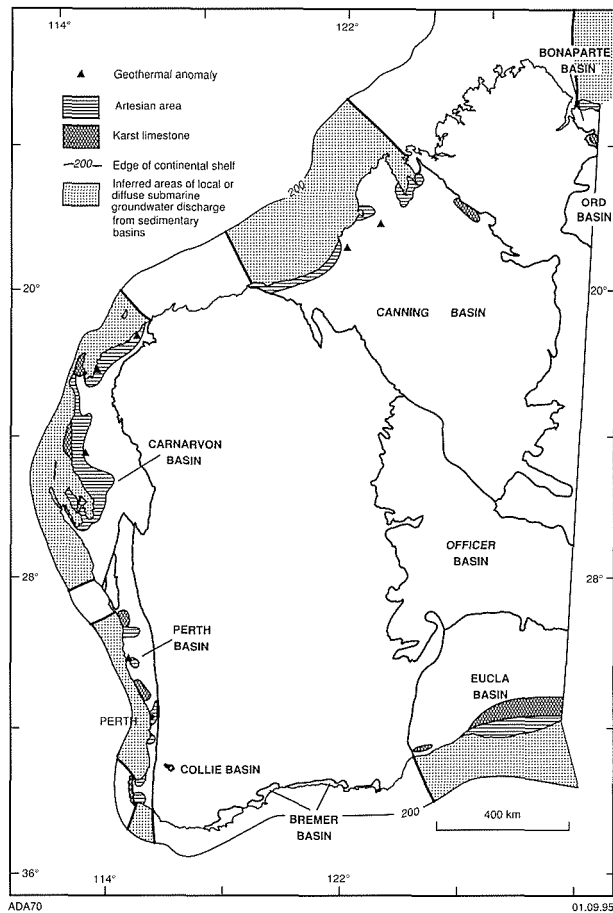


Figure 19. Location of major groundwater discharge areas, artesian areas, karstic aquifers, and geothermal anomalies

moisture) and of groundwater from the water table, and it is likely that vegetation rather than evaporation is the most important factor determining groundwater recharge and salinity in groundwater systems.

### Location of major aquifers

The rocks forming the fabric of Western Australia provide a plumbing system in which groundwater resources can occur (Lau et al., 1987). They are very diverse (Fig. 3), but their distribution and age are now relatively well known, although some problematic areas remain and the level of knowledge may vary considerably between different areas.

The location of the major aquifer types is shown in Figure 21, and their respective areas given in Table 3. From the figure it can be seen that fractured rock aquifers underlie most of the important mining, agriculture and pastoral areas, and that the sedimentary aquifers are mainly in arid parts of the State with the exception of the Perth Basin and parts of the Canning and Bonaparte Basins. In contrast, surficial aquifers are widespread and are superimposed on both the fractured rock provinces and sedimentary basins.

## Groundwater occurrence in surficial aquifers

Surficial aquifers extend over both the sedimentary basins and fractured rock provinces. They include mainly unconsolidated Late Cainozoic alluvial, lacustrine, eolian, and shallow-water marine coastal plain deposits. They are also taken to include Eocene alluvial and shallow-water marine deposits occurring in palaeodrainage systems which vein the State, particularly in the Yilgarn and Pilbara (Fig. 21).

Surficial sediments are widespread but usually form aquifers only along drainage lines and on the coastal plains where they are relatively thick. Elsewhere they generally form a thin veneer that does not contain groundwater. In many areas they may contain local perched groundwater and can facilitate recharge into underlying fractured rock or sedimentary aquifers. Large surficial aquifers occur in the palaeodrainage systems (Commander et al., 1991b); on the Swan Coastal Plain in the Perth Basin (Commander et al., 1991a), and in alluvial and deltaic deposits, particularly on the Ord, Fitzroy, De Grey, Yule, Fortescue, Robe, and Gascoyne Rivers.

The surficial aquifers, with the exception of some aquifers in palaeodrainages on the Yilgarn Craton, generally contain unconfined groundwater. Locally they maintain extensive wetlands such as at Millstream on the Fortescue River, and on the coastal plain near Perth. In sedimentary basins such as the Perth and Canning Basins the surficial aquifers provide significant recharge to underlying confined aquifers. Where they border the coast (e.g. near Perth) large volumes of groundwater are discharged over a seawater wedge into the sea (Fig. 16). The salinity of the groundwater in the surficial aquifers is generally fresh to brackish except in the palaeodrainage systems where some groundwater which has been recycled through salt lake systems may reach 300 000 mg/L TDS – almost ten times saltier than seawater.

Historically, the surficial aquifers have been the most readily accessible sources of groundwater for early settlers, prospectors, the pastoral industry and coastal settlements. Groundwater from surficial aquifers in Perth (Gnangara and Jandakot Mounds), Kununurra, Port Hedland, Newman, Carnarvon, Esperance, and many minor towns and communities and elsewhere are used for public water supplies. They are also utilized as sources of groundwater for irrigated agriculture, particularly at Carnarvon and in the Perth region; and as the major source of water for the mining industry, particularly in the Kalgoorlie region. Individual bores may yield up to 5000 m<sup>3</sup>/d.

## Groundwater occurrence in sedimentary aquifers

In Western Australia there are nine sedimentary basins of Phanerozoic age (Fig. 21), underlying 40% of the State, which contain sedimentary aquifers (Allen, 1991; Allen et al., 1992). Four of these basins (Bonaparte, Ord, Officer and Eucla) extend into adjoining States where to varying

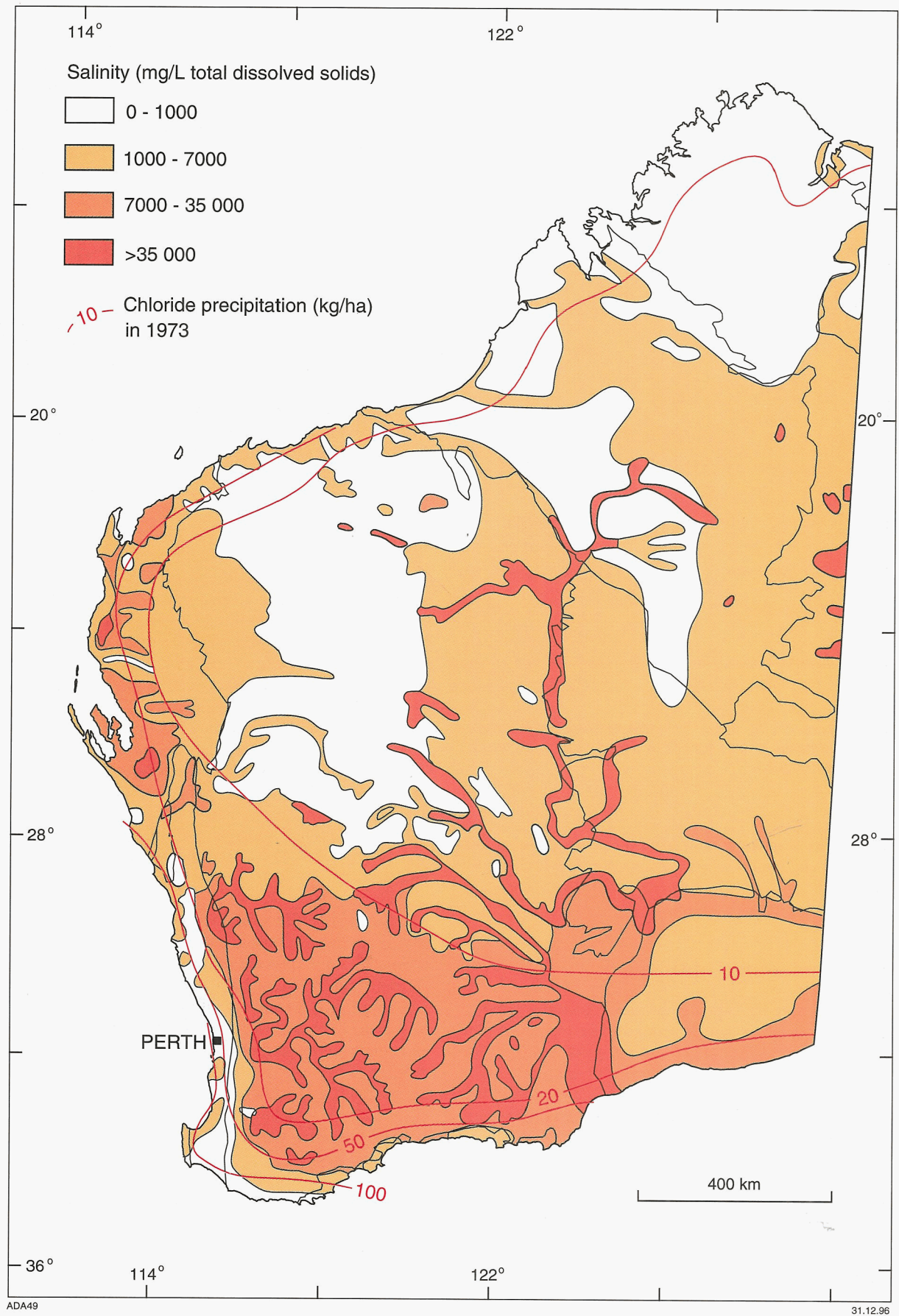


Figure 20. Groundwater salinity at the watertable and chloride precipitation in Western Australia

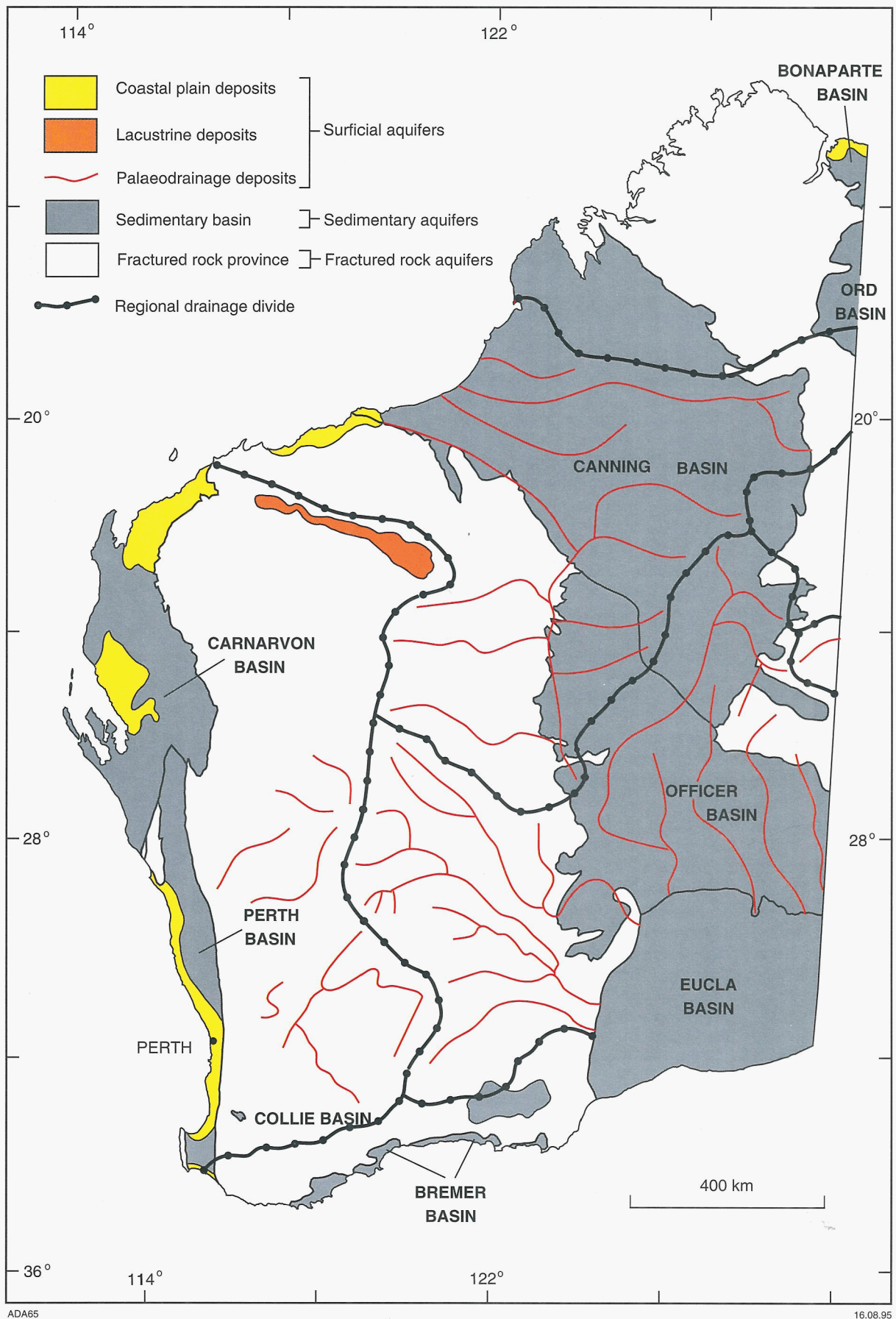


Figure 21. General location of surficial, sedimentary and fractured rock aquifers in Western Australia

**Table 3. Approximate areas underlain by surficial, sedimentary, and fractured rock aquifers**

Aquifer	Area (million km <sup>2</sup> )	% WA	Area not including surficial aquifers (million km <sup>2</sup> )	% WA
Surficial	0.3	12	—	—
Sedimentary	0.9	36	1.0	40
Fractured rock	1.3	52	1.5	60
<b>Totals</b>	<b>2.5</b>	<b>100</b>	<b>2.5</b>	<b>100</b>

degrees they are also exploited for their groundwater resources.

The sedimentary basins contain varied sequences of sedimentary and volcanic rocks, reflecting the geological history of the basins, and contain sequences ranging in thickness from 200 m in the Bremer Basin to 18 000 m in the Canning Basin. Some similarities occur between sequences of the same age in the different basins. Thus the Cambrian–Carboniferous sediments are mainly volcanics, carbonates, sandstones, and shales; the Permian–Cretaceous sediments are predominantly sandstones, shale and coal measures, and the Cretaceous–Tertiary sediments are mainly carbonates, shales and sandstones. The names of the major aquifers identified in the sedimentary basins are shown in Figure 22, but it should be noted that numerous minor aquifers also occur.

In Western Australia the principal aquifers are formations of sandstone; interbedded sequences of sandstone, shale and siltstone; and limestone. Some of these aquifers extend over very large areas. For example, the Yarragadee Formation extends over 40 000 km<sup>2</sup> in the Perth Basin, the Birdrong Sandstone extends over 77 000 km<sup>2</sup> in the Carnarvon Basin, the Broome Sandstone extends over 80 000 km<sup>2</sup> in the Canning Basin, and Tertiary limestone aquifers extend over 110 000 km<sup>2</sup> in the Eucla Basin. The last is also notable for the widespread development of karstic cave systems containing lakes and slow-moving underground streams. The major aquifers range substantially in thickness from about 30 m (Birdrong Sandstone) to 2500 m (Yarragadee Formation).

A regional water table occurs throughout the sedimentary basins irrespective of the nature of the uppermost sedimentary rocks in the basin. Below this, all formations (aquifers and confining beds) are filled by groundwater. Unconfined aquifers occur when the uppermost geological formations are porous and permeable (e.g. Broome Sandstone) and confined aquifers occur at depth. In practice most formations below the watertable can yield small quantities of groundwater but large supplies are obtainable only from the major aquifers.

Groundwater salinity varies considerably between basins depending on factors such as geographic location, topography and prevailing climatic conditions. It may also vary widely in the same basin areally, with depth in individual aquifers, and between different aquifers. In general the freshest groundwater occurs in the unconfined aquifers, but in Perth some of the freshest

groundwater is from the Yarragadee Formation (Allen, 1981a) and has been carbon-14 dated as being greater than 37 000 years in age (Thorpe and Davidson, 1991). A wide variation in the composition of groundwater, as distinct from salinity (total salt content), may occur as a result of water–rock interactions within the aquifers resulting from the presence of a wide range of geological materials. They may also contain various trace elements, heavy metals, and dissolved gases and may vary widely in temperature.

In the early part of the century, artesian groundwater from the sedimentary aquifers was widely sought as it minimized the need for pumping, and some spectacular artesian flows were encountered, principally in the Perth and Carnarvon Basins. In the Carnarvon Basin, some pastoral bores still flow uncontrolled but in other areas, principally around Perth, pressures have declined and the bores have become sub-artesian, or headworks controlling the flows have been fitted to the bores. Irrespective of the local occurrence of artesian groundwater, the sedimentary aquifers, because of their thickness and extent, contain the largest volumes of groundwater and are capable of providing the largest supplies, with individual bore yields up to 10 000 m<sup>3</sup>/d.

### Groundwater occurrence in fractured rock aquifers

Precambrian fractured rocks underlie 60% of Western Australia. They do not have primary porosity (excepting some Proterozoic Sandstones), but have secondary fracture porosity resulting from geological deformation and weathering. They comprise, by area, about 40% granitoid and gneissic rocks, 40% indurated sedimentary rocks, 10% basic volcanics, 5% acid volcanics and minor intrusive rocks, and 5% schists (Allen and Davidson, 1982). Some sequences of volcanic rocks that occur in the Phanerozoic sedimentary basins are also strictly fractured rocks but for convenience are considered as confining beds, or as minor aquifers interbedded with sedimentary aquifers.

Within the fractured rocks a very wide variety of rock-types occurs. The nature and degree of their fracturing depend on the competence of the rock and its geological history, particularly how it has responded to tectonic, metamorphic, intrusive, erosional and weathering events. The most intense fracturing usually occurs along faults and shear zones, with other fracturing resulting from joint sets, slaty cleavage, schistosity, hexagonal jointing, opening of bedding plane partings, exfoliation and movement of rock masses under gravity.

The term aquifer, as used for surficial and sedimentary aquifers, is not particularly appropriate for fractured rocks except for some extensive rock units such as some flat-lying extensive basalts, dolerites and quartzites (e.g. Hart Dolerite in the Kimberley), tabular aquifers formed by near vertical rocks such as folded quartzites, or large quartz veins and pegmatites in which usable supplies of groundwater can be located readily. In other fractured rocks, although groundwater is usually encountered, the

GEOLOGICAL PERIOD/ AGE (My)		PERTH	CARNARVON	CANNING	BONAPARTE	ORD	OFFICER	EUCLA	BREMER	COLLIE
CAINOZOIC	QUATERNARY 2	Superficial Fms	Alluvium	Alluvium	Alluvium		Alluvium			
	TERTIARY 65							Abrakurri Ls	Werrilup Fm	
MESOZOIC	CRETACEOUS 144	Leederville Fm	Birdrong Ss	Broome Ss				Loongana Ss		
	JURASSIC 213	Yarragdee Fm		Wallai Ss						
	TRIASSIC 253	Cockleshell Gully Fm		Erskine Ss						
		Lesueur Ss		Millyit Ss						
PALAEOZOIC	PERMIAN 256		Mallens Ss							Collie Coal Meas
	CARBONIFEROUS 360		Moogooloo Ss	Poole Ss	Keep Inlet Fm			Paterson Fm		
				Grant Gp						
	DEVONIAN 408				Weaber Gp			Wanna Fm		
	SILURIAN 438				Cockatoo Gp	Glass Hill Ss		Lennis Ss		
ORDOVICIAN 505										
CAMBRIAN 590					Hart Ss	Eagle Hawk Ss				
						Antrim Plateau Vol				

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Figure 22. Chart showing principal aquifers in the sedimentary basins

location of economic supplies depends on site-specific fractures or fracture systems and the storage that they command. For example a groundwater supply may be obtained from a granite where there are suitable fractures, but elsewhere supplies may not be obtainable. Thus the aquifer is the interconnected fracture system that may also extend into contiguous rock-types. For convenience, the rock-types in which water bearing fractures are encountered are often referred to as aquifers (e.g. granite aquifers).

In southwest Western Australia a very large area has been subject to deep weathering and lateritization (Fig. 17). In this process the upper 30 m of the fractured rocks have been variably weathered, resulting in a layered

weathering profile grading from a complex lateritic duricrust at the surface downward through clay and partially weathered rock to fresh rock. The differential weathering and leaching of the fractured rocks has been caused by groundwater and has resulted in formation of layers of variable permeability, some of which are local aquifers. The deep weathering controls recharge, groundwater storage and salinity, and differentiates the region from other fractured rock provinces in the State (e.g. Pilbara or Kimberley) where deep weathering is of limited extent.

The salinity of groundwater in the fractured rock provinces varies markedly from the southern to the northern part of the State, irrespective of annual rainfall

(Fig. 14). In the south this can be attributed partly to the higher salt accession from rainfall (Fig. 20), soil development, and vegetative cover. However, the main reasons why groundwater is less saline in the north are believed to be the general absence of deep weathering, the high degree of rock exposure, and the greater topographic relief and better integrated drainage. These factors combine to facilitate flushing of the groundwater into the drainage systems, thus limiting the residence time of groundwater within the fractured rocks and the time available to concentrate salt from rainfall and rock weathering.

Rock types of widely different origin and composition can form fractured rock aquifers. Consequently in Western Australia groundwater with unusual or unacceptable concentrations of sulfate, magnesium, lead, arsenic, boron, fluoride, aluminium, radon uranium, and other constituents have been recorded. Also, high levels of nitrate resulting from biological activity, sometimes exceeding recommended limits, are common in groundwater in some coastal areas and in the arid interior.

Groundwater from fractured rock aquifers provides small but significant sources of groundwater which have made possible the development of large arid to semi-arid parts of the State for pastoral purposes. It is also a significant source of water supply for mining and for community and domestic water supplies.

The location of successful bore-sites frequently depends on site-specific conditions requiring accurate bore-site location by experienced geoscientists or by using geophysics. The success rate can also be improved by appropriate drilling techniques such as down-hole-hammer, and, dependent on the rock type, drilling to the base of fracturing. It has been commonly observed that bores close to each other may yield significantly different quantities depending on the fractures encountered. Hydraulic fracturing may enhance bore-yields but has not been widely practiced.

Estimating the renewable resources and long-term yield from fractured rocks is notoriously difficult. Bores may suddenly decrease in yield or vary in salinity (Allen and Davidson, 1982). The open nature of the fracture systems may enable ready access of contaminants, consequently particular care has to be taken in managing water sources if they are being used for domestic purposes. Individual bore or well yields are generally less than 100 m<sup>3</sup>/d but can range up to 2600 m<sup>3</sup>/day. The majority of bores are used for pastoral purposes and generally yield about 5 m<sup>3</sup>/d.

## Groundwater resources

### Estimation of groundwater resources

Surface water resources are readily observable and can be measured directly whereas groundwater resources are unseen and can only be measured indirectly. Furthermore,

unlike surface water, several aquifers may be superimposed on each other and the groundwater they contain may vary widely in salinity both areally and with depth. Consequently, groundwater resources are defined by specially designed drilling and testing programs to collect data from which can be made reliable estimates of the size and quality of groundwater resources, their rate of replenishment, and relationship with other aquifers and the environment.

The size of Western Australia has necessitated the prioritization of groundwater assessment projects, the focus being mainly in areas of current or likely demand for groundwater resources. This work, together with the developing understanding of the State's geology, has provided a qualitative understanding of the groundwater resources throughout most of Western Australia, and quantitative assessment in important areas.

Three levels of groundwater assessment are carried out in Western Australia (WAWRC, 1989). These are:

- safe-yield assessment
- broad-scale assessment
- reconnaissance assessment.

In general, safe-yield assessment is undertaken for important water supply projects and usually includes drilling, pumping tests and modelling; broad scale assessment usually comprises less intensive drilling and testing over relatively large areas; and reconnaissance assessment is undertaken on a regional scale and is based on existing bore data together with geological and climatic information. The areas of the State where the different levels of assessment have been undertaken are shown in Figure 23.

In the various previous assessments, the groundwater resources are usually described as renewable resources (GL/year) and stored resources (GL). This allows an appreciation of the volume of groundwater that can be obtained on a 'sustainable' or 'mining' basis, if needed. Ideally the estimated resources should be provided for each major groundwater flow system. This would equate approximately to the groundwater resources within catchments on the fractured rock provinces, and for each aquifer within the sedimentary basins. However, in this account, because of incomplete data the renewable and stored resources (Table 4) are estimated for the areas of the recognized sedimentary basins and fractured rock provinces (Fig. 24) adopted for the Australian Water Resources Council 1985 review of Australia's water resources.

### Renewable groundwater resources

The renewable (sustainable) groundwater resources are those that are replenished each year from rainfall. They may vary considerably between years as a result of seasonal and spatial variation in rainfall. Nevertheless, assuming that climate is not changing, and that landuse

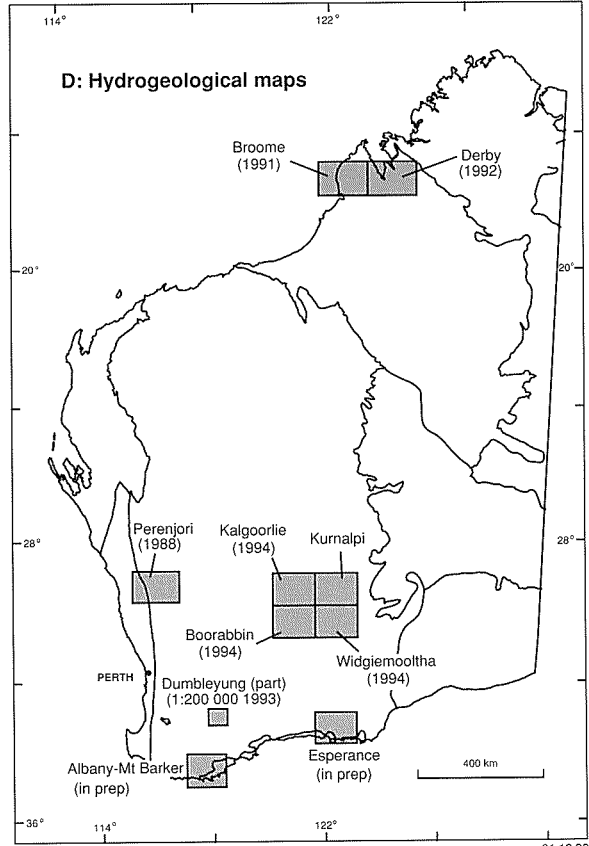
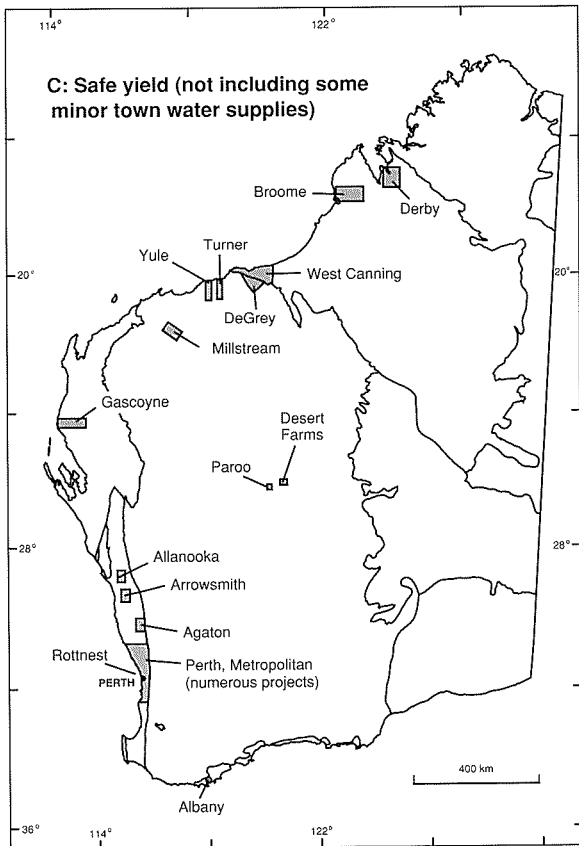
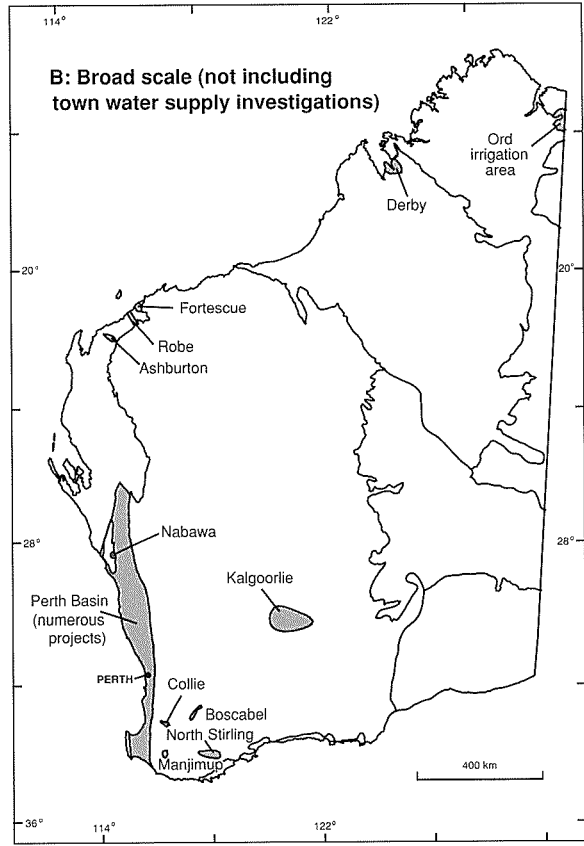
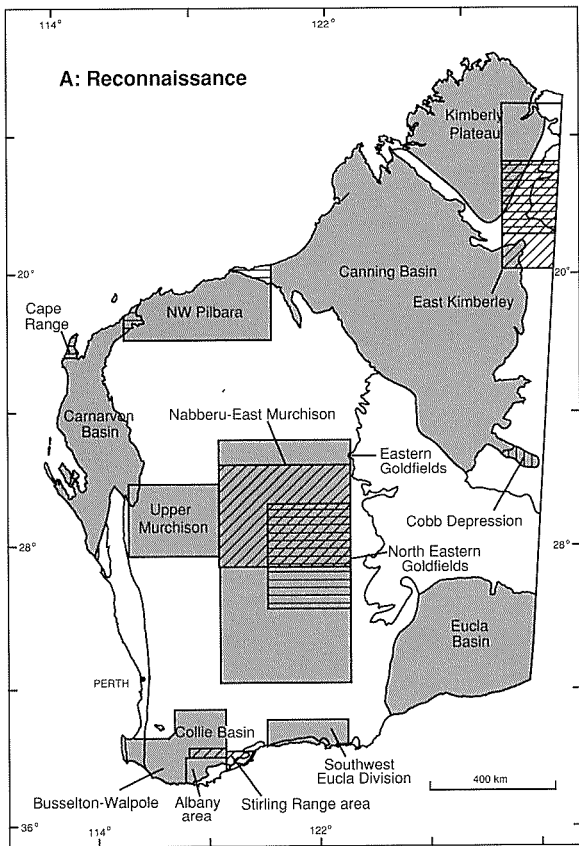


Figure 23. Location of A, reconnaissance, B, broad scale, C, safe yield projects, and D, hydrogeological maps undertaken by the Geological Survey

**Table 4. Estimated renewable and stored groundwater resources, number of bores, and groundwater usage in Western Australia (modified after AWRC 1987)**

AWRC No.	Basin/Province	Area (km <sup>2</sup> )	Renewable fresh-marginal resources (GL/y)	Stored fresh-saline resources (GL)	Estimated No. of bores	Abstraction fresh-saline 1983-84 (GL)
26S	Perth	45 000	1 382	(a) 1 875 000	93 800	284.2
32S	Carnarvon	115 000	161	(a) 1 150 000	2 365	12
41S	Canning	415 000	847	(a) 12 450 000	983	5.3
44S	Bonaparte (c)	8 000	(c) 62	(a) 225 000	204	1.8
58S	Amadeus (c,g)	21 350	4	(e) 6 400	5	—
56S	Officer (c)	260 000	14	(a) 7 800 000	460	0.1
22S	Eucla (c)	170 000	16	(a) 510 000	339	0.1
24S	Bremer	13 000	25	(a) 29 000	1 516	2.6
27S	Collie	250	25	(a) 7 000	250	20.4
23F	Albany-Fraser (b)	55 800	25	(e) 16 750	1 220	2.2
25F	Leeuwin	1 250	(d) 15	(e) 380	650	0.6
28F	Yilgarn-Southwest	183 000	241	(e) 54 900	25 140	3.6
29F	Yilgarn-Goldfields	147 000	24	(e) 44 100	1 300	2.2
30F	Yilgarn-Murchison	278 000	45	(e) 83 400	7 070	4.6
31F	Northampton	3 250	8	(e) 980	760	0.4
33F	Capricorn (b)	131 000	34	(e) 39 300	1 800	(h) 3.2
34F	Marymia	5 250	4	(e) 1 500	20	—
35F	Bangemall (b)	71 500	22	(e) 21 450	670	(h) 1.2
36F	Calyie-McFadden (b)	48 000	29	(e) 14 400	70	—
37F	Sylvania	5 000	2	(e) 1 500	40	—
38F	Hamersley	98 500	145	(e) 29 550	1 150	28.3
39F	Pilbara	48 800	122	(e) 14 640	2 565	7.6
40F	Paterson	33 800	4	(e) 10 140	50	—
42F	Kimberley	140 000	494	(e) 42 000	112	0.2
43F	Halls Creek	51 500	160	(e) 15 450	312	0.4
45F	Ord-Victoria (b,c,g)	22 800	(c) 3	(e) 6 840	25	—
61F	Tanami (c)	21 700	(d) 6	(e) 6 510	60	—
59F	Arunta (c)	9 450	2	(e) 2 835	0	—
57F	Musgrave (c)	31 800	(d) 9	(e) 9 540	50	—
	<b>Total</b>	<b>(f) 2 435 000</b>	<b>3 930</b>	<b>24 468 565</b>	<b>142 977</b>	<b>381.3</b>

## NOTES:

- (a) From Allen (1991).  
 (b) Subdivisions and names need revision on basis of new geological data  
 (c) Data for WA  
 (d) Rounded  
 (e) Estimated in this report assuming 30 m of 0.01 specific yield  
 (f) Actual area of WA 2,525,000  
 (g) Considered a fractured rock province in WA  
 (h) Estimated abstraction this report

remains the same, there is an intuitive expectation that over the long term, variations in recharge are smoothed out and that there is some average amount of recharge to the watertable and by leakage into confined aquifers, related to average rainfall.

In practice, in the interior two thirds of Western Australia, which is arid to semi-arid, rainfall duration and intensity are highly variable. Consequently, groundwater recharge is episodic, occurring after intense rainfall events which may happen several times in a year, or many years apart. In the remainder of the State where there is more reliable winter or summer rainfall there is seasonal groundwater recharge which varies in quantity depending on the preceding year(s) rainfall and seasonal conditions. Groundwater recharge may also be highly localized over soil types such as sands, and particularly along drainage lines which concentrate rainfall runoff. The latter may be

the most significant sites for recharge in the arid and semi-arid areas.

In areas where safe yield and broad-scale assessment (Fig. 23) have been undertaken, the estimated renewable groundwater resources are derived as groundwater throughflow for individual aquifers and usually are based on reliable hydrogeological data that integrate seasonal and spatial variations in recharge. However, reliable estimates such as these are available for only a few areas. Consequently, comparable and consistent statewide estimates of the renewable groundwater resources have been estimated for the different basins and provinces as a percentage of average annual rainfall using formulae established for estimating Australia's groundwater resources (AWRC, 1987). These estimates are shown in Figure 25 and listed in Table 4. They show that the largest renewable groundwater resources occur in

the areas of highest rainfall and that those of the sedimentary basins far exceed those of the fractured rock provinces.

To put the size of the State's fresh-marginal groundwater resources in context, they are shown compared with the State's surface water resources and water resources in other States, in Table 5. The figures indicate that, although Western Australia comprises about 33% of mainland Australia, it has only 20% of the nation's renewable fresh marginal groundwater resources. The relatively low proportion renewable groundwater resources in Western Australia results from climatic factors and the large area of fractured rock provinces.

## Stored groundwater resources

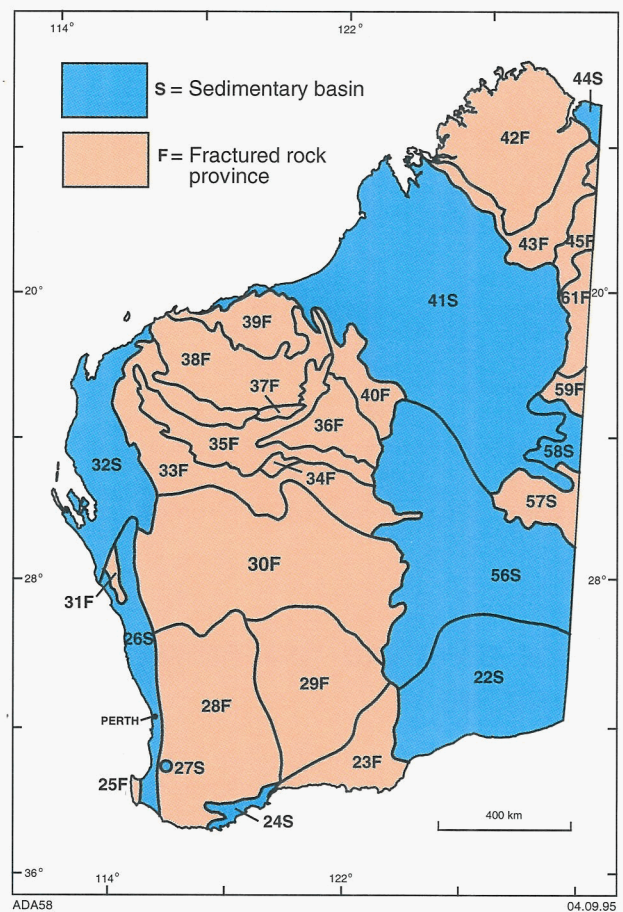
The stored groundwater resources are those held in storage within an aquifer or sequence of aquifers. They represent groundwater that has been emplaced within about the last 5000 years in unconfined aquifers and within about the last 100 000 years in confined aquifers.

In the sedimentary basins of Western Australia more is known about the geology than the groundwater resources they contain. Consequently for many aquifers, from their known extent and thickness it is possible to determine the volume of the aquifer and hence, by assuming 0.1% specific yield and a depth limit of 1500m (base of meteoric flow systems), the order of magnitude of the stored groundwater resources (Allen, 1991). Similarly, the stored groundwater resources have been estimated for the fractured rocks from their area and assuming 30 m of groundwater bearing rock with a specific yield of 0.01.

The estimated stored groundwater resources are listed in Table 4 and shown for comparison with the renewable groundwater resources in Figure 25. These estimates of stored groundwater resources are likely to be conservative. It is important to note that the estimates include fresh to saline groundwater, because currently it is not possible to define the extent of groundwater within specific salinity categories except in a few areas. The estimates, while not strictly comparable in terms of salinity, reveal that the fresh-saline, stored groundwater resources far exceed the fresh-marginal, renewable groundwater resources (less than 1%) and that the largest stored groundwater resources occur in the sedimentary basins (Fig. 25).

## Reliability of estimates

The renewable and stored groundwater resources are known with high reliability only in a few areas of the State. Elsewhere only the order of magnitude is known and even this is uncertain for some estimates of renewable resources. The uncertainty of the estimates emphasizes the lack of reliable data and difficulty in estimating groundwater resources. Consequently, in areas where aquifers with large potential resources have been identified (see Divertible resources), drilling



22S	Eucla	36F	Calyie-McFadden
23F	Albany-Fraser	37F	Sylvania
24S	Bremer	38F	Hammersley
25F	Leeuwin	39F	Pilbara
26S	Perth	40F	Paterson
27S	Collie	41S	Canning
28F	Yilgarn-Southwest	42F	Kimberley
29F	Yilgarn-Gold Fields	43F	Halls Creek
30F	Yilgarn-Murchison	44S	Bonaparte
31F	Northampton	45F	Ord-Victoria
32S	Carnarvon	56S	Officer
33F	Capricorn	57S	Musgrave
34F	Marymia	58S	Amadeus
35F	Bangemall	59F	Arunta

Figure 24. Groundwater basins and provinces in Western Australia

and testing are needed to confirm the estimated size of the resources, and in particular their salinity.

It should also be noted that experience in Western Australia has shown that methods used to estimate groundwater resources are usually conservative. Under operating conditions, up to twice as much water as estimated can commonly be obtained because most aquifers in Western Australia are full of groundwater, and when they are exploited increased recharge or leakage from adjacent aquifers occurs with resultant higher yields. Other factors such as local dewatering or increased recharge resulting from changed landuse can also be important.

**Table 5. Fresh–marginal renewable water resources in Western Australia compared with other States (data derived from AWRC 1987)**

	WA	NT	Qld	SA	NSW	Vic	Tas	Aust	WA %
Area (km <sup>2</sup> )	2 520 000	1 350 000	1 173 000	984 000	802 000	228 000	68 200	(a)7 125 200	32.8
Surface water (GL/y)	10 716	17 700	32 700	302	17 300	9 290	10 800	98 808	10.8
Groundwater (GL/y)	4 196	7 964	4 038	889	2 733	818	457	20 943	20.17
Total renewable water (GL/y)	14 912	25 664	36 738	1 191	20 033	10 108	11 257	119 751	12.5

## NOTE:

(a) Inconsistent with usually quoted but incorrect area of 7 682 000 km<sup>2</sup>

## Major divertible groundwater resources

The concept of divertible groundwater resources was introduced in the 1985 Review of Australia's Water Resources (AWRC, 1987). A major divertible resource was defined to be a resource developable by present or near-future technology and capable of yielding more than 0.5 GL/year, with the specific exception of Western Australia where a water resource developed for a reticulated water supply (even if less than 0.5 GL/year) was considered to be a major divertible resource. A minor divertible resource was a source too small or scattered to be diverted for major water supplies.

Accepting this definition, there are undoubtedly several hundred areas where fresh–marginal and brackish–saline divertible resources are obtainable. These areas are most likely to occur in the Perth and Canning Basins and in the Pilbara and Kimberley Provinces, but there are inadequate data to identify all the possible sites.

In a study for the Kimberley Water Resources Development Office (Allen et al., 1992) actual or potential fresh–marginal renewable groundwater resources greater than 10 GL/year (i.e. major divertible resources) were identified. The location of the resources (Fig. 26) was based on the known extent of major aquifers and their inferred recharge rates. Forty four possible sources ranging in yield from 10–390 GL/year (Fig. 27) and with an estimated combined yield of about 2500 GL/year (Table 6) were identified, mainly in the sedimentary basins.

The size and location of many major divertible resources need to be confirmed. Nevertheless, they indicate the potential for location and development of numerous large fresh–marginal groundwater resources adjacent to developing areas of the State.

## Utilization of groundwater resources

### Current groundwater usage

In Western Australia, groundwater provides 45–50% of all water used (WAWRC, 1984). Current abstraction is in the order of 450 GL from about 130 000 bores and wells, and since 1985 has increased at about 2–3%/year (Table 7) based on Geological Survey estimates.

Table 7 shows that the major use of groundwater (44%) is for irrigation of horticultural crops and private reticulation of lawns and gardens, followed by abstraction for public water supplies (36%) for about 100 towns and communities throughout the State (Fig. 10). Smaller but essential supplies of groundwater are used in the mining, industrial, and pastoral sectors. Of the groundwater utilized, about 275 GL/year, or 60% of groundwater abstraction in the State, is used in the Perth region (Davidson, 1995).

### Advantages of utilizing groundwater

In Western Australia, which experiences very high potential evaporation (Fig. 1), groundwater is the most widespread and most readily available source of small to large water supplies. There are extensive areas, however, such as in the region between Esperance and Kalgoorlie, where adequate groundwater supplies or supplies of acceptable salinity (without desalination) are difficult to obtain. Elsewhere, particularly in the Perth Basin, groundwater can often be obtained on-site. It can be readily exploited by dug wells or shallow bores capable of yielding small supplies (5 m<sup>3</sup>/day or less) for reticulation, domestic, and stock purposes, and by sophisticated multi-cased bores over 1000 m deep, equipped with large submersible pumps capable

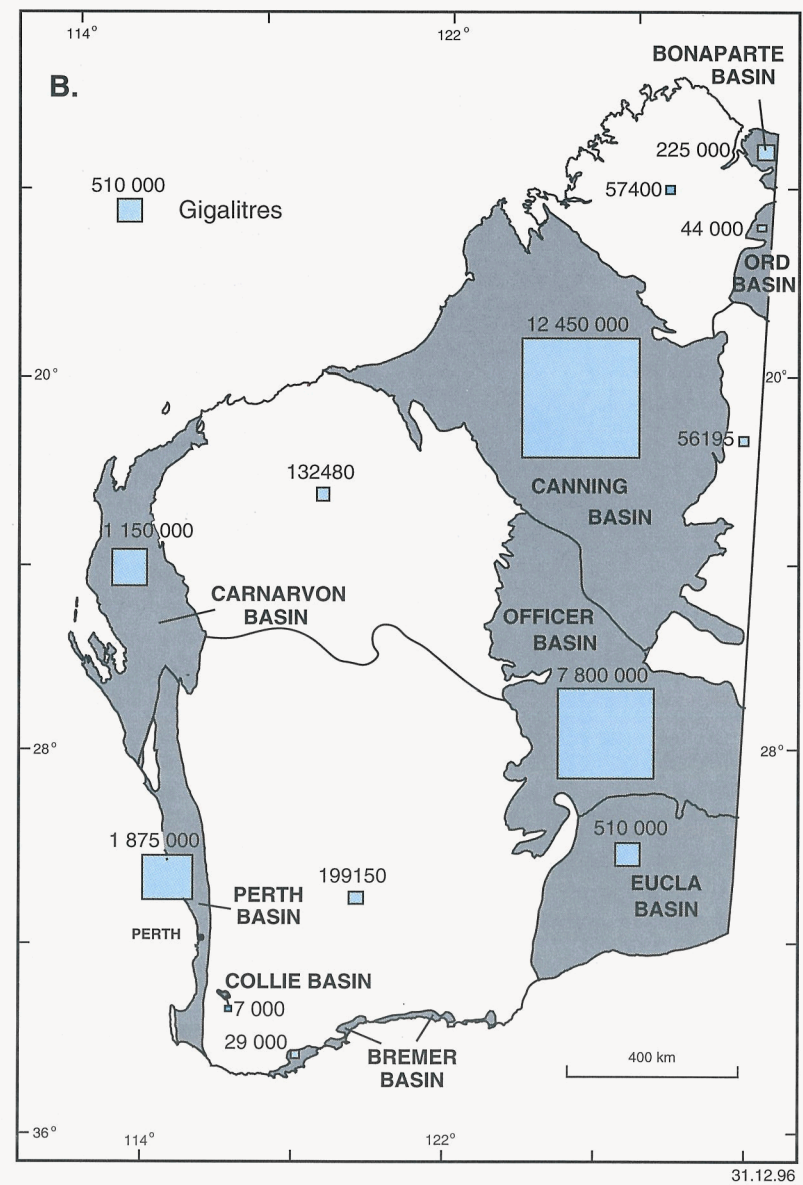
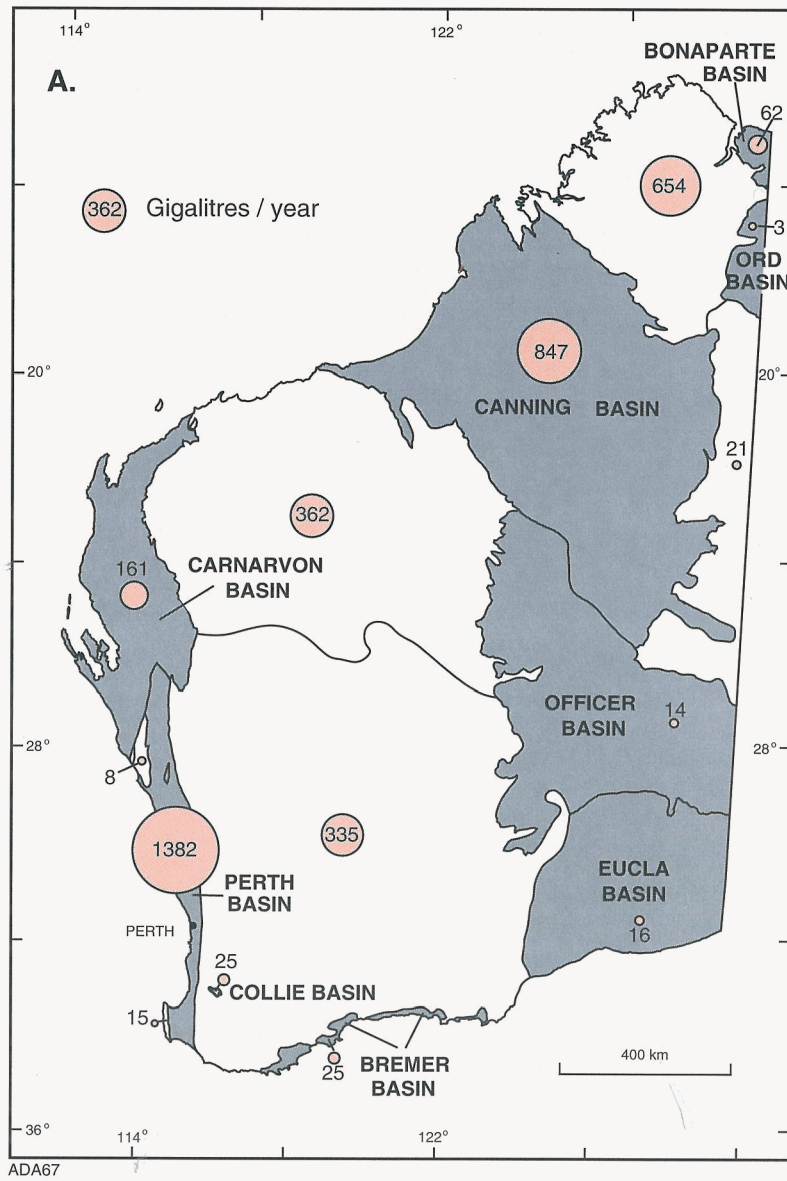


Figure 25. A. Relative size of renewable groundwater resources in basins and aggregated provinces in Western Australia B. Relative size of stored groundwater resources in basins and aggregated provinces in Western Australia

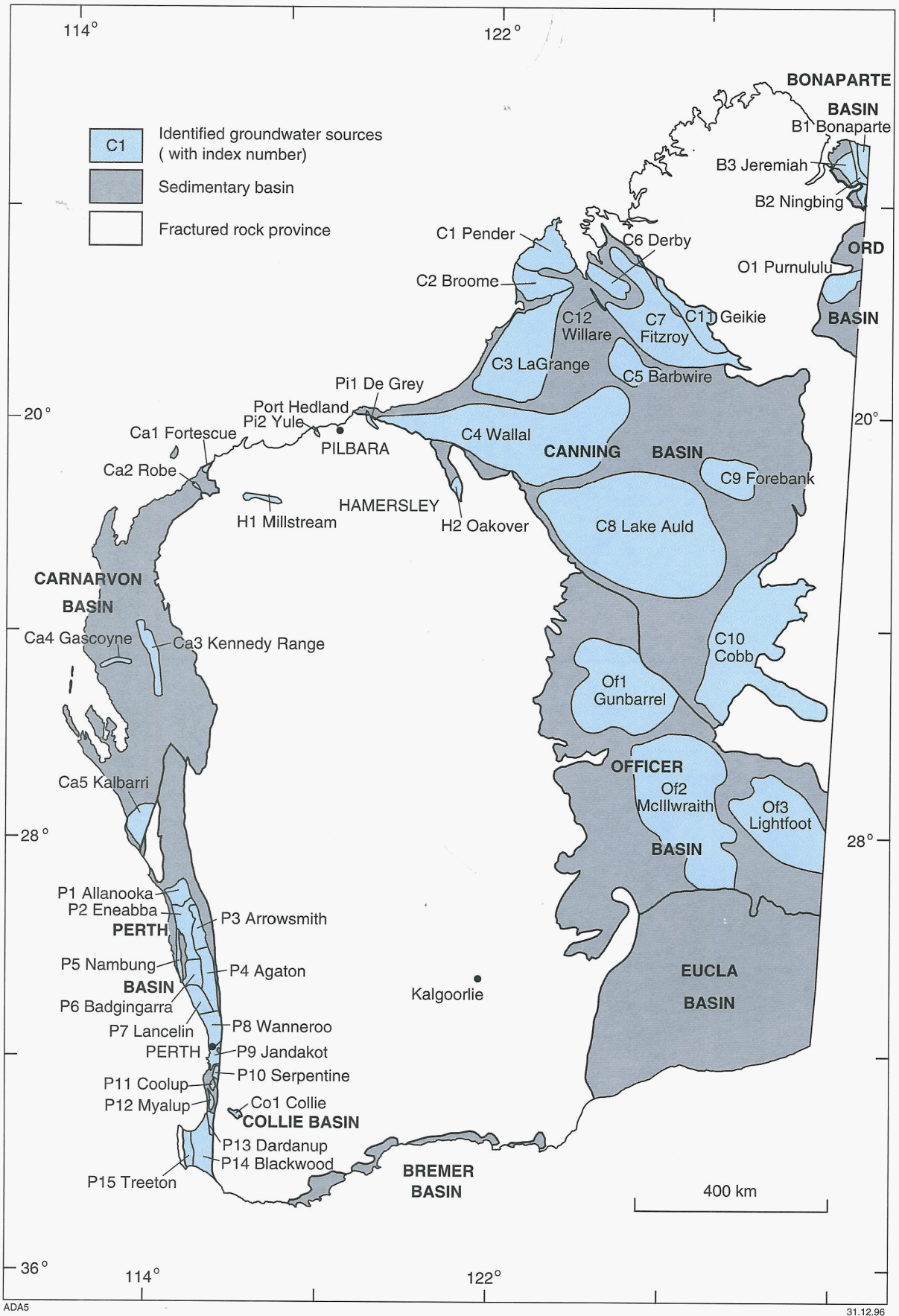


Figure 26. Location of major actual or potential groundwater resources capable of yielding more than 10 GL/year of renewable, fresh-marginal groundwater

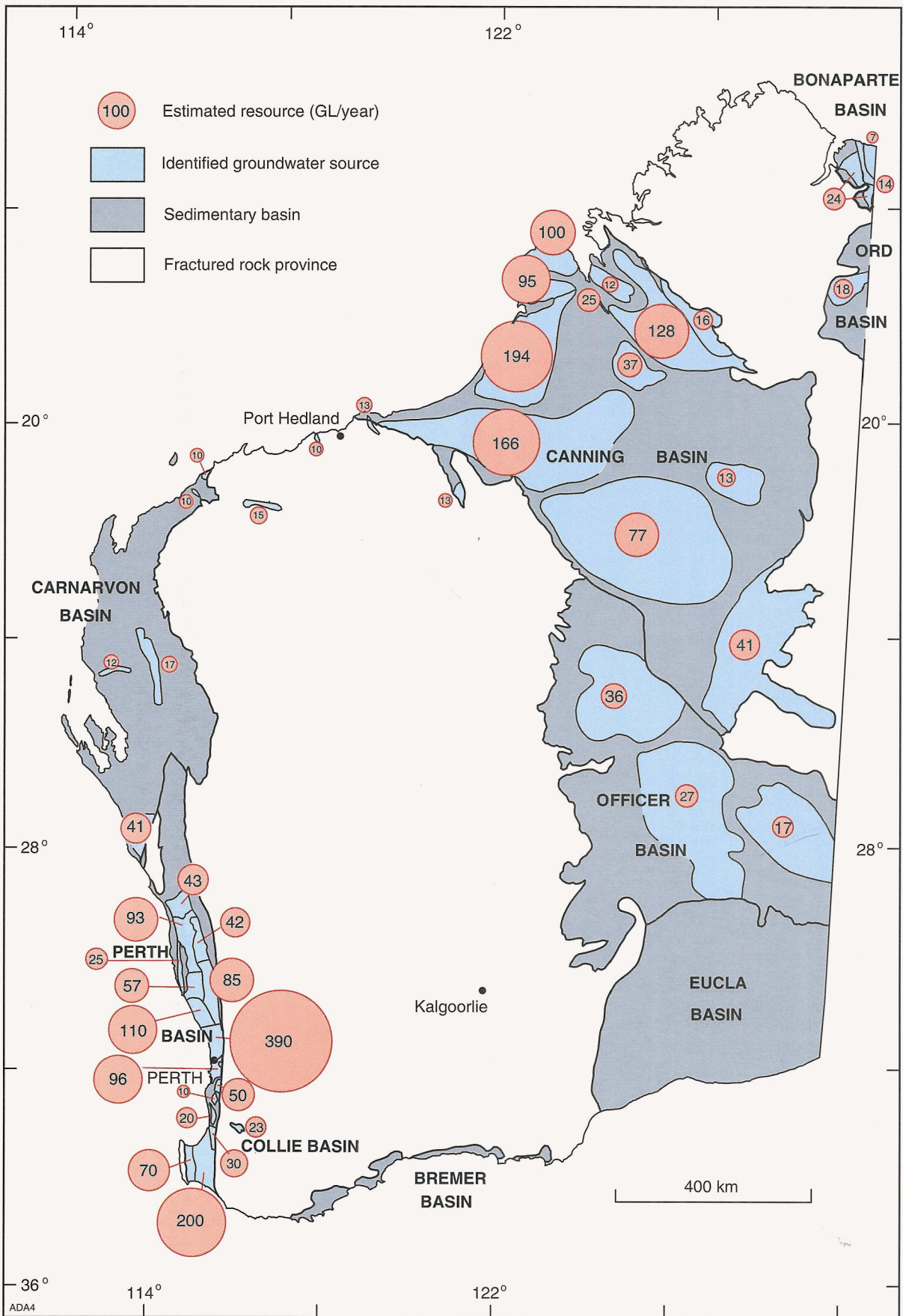


Figure 27. Estimated yield of major renewable fresh-marginal groundwater resources

**Table 6. Actual or potential, fresh–marginal, divertible groundwater resources of 10 GL/year or more in Western Australia (modified after Allen et al., 1992)**

<i>Basin/Province</i>	<i>Map reference(a)</i>	<i>Area (km<sup>2</sup>)</i>	<i>Aquifer(b)</i>	<i>Divertible resource (GL/year)</i>
Bonaparte	B1	1 200	Permian	10
	B2	1 174	Carboniferous	14
	B3	1 812	Devonian	24
Ord	O1	1 800	Devonian, Cambrian	18
Canning	C1	4 125	Cretaceous	101
	C2	4 200	Cretaceous	95
	C3	21 550	Cretaceous	194
	C4	43 875	Cretaceous, Jurassic	166
	C5	14 000	Permian	37
	C6	1 100	Jurassic	12
	C7	6 800	Jurassic, Triassic	128
	C8	68 338	Quaternary, Permian	77
	C9	7 750	Cretaceous, Permian	13
	C10	27 500	Permian	41
	C11	5 700	Permian	16
	C12	250	Devonian, Quaternary	25
Officer	C1	31 725	Permian	36
	C2	36 200	Permian	27
	C3	12 250	Permian	17
Carnarvon	Ca1	200	Quaternary	10
	Ca2	120	Quaternary	10
	Ca3	3 000	Cretaceous	17
	Ca4	185	Quaternary	12
	Ca5	2 700	Silurian	41
Collie	Co1	225	Permian	23
Perth	P1	1 930	Jurassic	43
	P2	3 410	Jurassic	93
	P3	1 870	Cretaceous	42
	P4	3 400	Cretaceous	85
	P5	910	Triassic	25
	P6	1 920	Jurassic	57
	P7	2 130	Quaternary Cretaceous, Jurassic	110
	P8	2 550	Quaternary Cretaceous, Jurassic	390
	P9	830	Quaternary, Cretaceous	96
	P10	350	Quaternary, Cretaceous	50
	P11	190	Quaternary, Cretaceous	10
	P12	300	Quaternary	20
	P13	560	Cretaceous, Jurassic	30
	P14	4 330	Jurassic	200
	P15	1 100	Triassic, Permian	70
Hamersley	H1	1 000	Quaternary, Cretaceous	15
	H2	1 400	Permian, Proterozoic	13
Pilbara	P11	500	Quaternary	13
	P12	500	Quaternary	10
			<b>Total</b>	<b>2 536</b>

## NOTES:

(a) See Figure 27

(b) See Figure 23

of yielding up to 10 000 m<sup>3</sup>/day (Fig. 28). Bores can be operated singly, or in wellfields such as the Wanneroo wellfield in Perth which comprises 30 bores into confined and unconfined aquifers collectively producing large quantities of groundwater (Fig. 7), comparable to the yield of some major dams (Table 8).

The cost of investigating and developing groundwater resources is usually low when compared with construction of dams. Also, if necessary, groundwater resources can be developed in stages as demand increases, in contrast

with dams and their infrastructure which require large capital investment and which may not be fully utilized for a long time after construction. In addition, groundwater may also have other advantages such as: it is generally free of chemical or biological contamination; supplies are secure and usually are not seriously affected by seasonal factors; the social and environmental impact of developing groundwater resources is minimal, or can be manipulated to minimize undesirable effects; and bores can be operated in various ways to induce recharge, or capture groundwater flow to increase the available groundwater resources.

Table 7. Estimated annual groundwater use in Western Australia in 1985 and 1994

	1985		1994	
	Volume (GL)	%	Volume (GL)	%
Town water supplies	60	16	70	16
Perth water supply	60	16	90	20
Private reticulation	85	23	100	22
Pastoral supplies	20	5	20	4
Irrigation	90	24	100	22
Mining	30	8	35	8
Industry	30	8	35	8
<b>Totals</b>	<b>375</b>	<b>100</b>	<b>450</b>	<b>100</b>

## Conjunctive use

The utilization in one scheme of surface and groundwater supplies together is referred to as conjunctive use and can have significant advantages, particularly in arid regions. If the sources are preferentially utilized and manipulated to take advantage of seasonal conditions, considerable improvement in the security and flexibility of the system can be obtained.

In Western Australia, the Perth water supply is a good example of conjunctive use increasing scheme yield and providing security of supply. Some activities undertaken are:

- use of excess surface water in winter while resting groundwater resources
- increasing use of groundwater during periods of drought or to meet peak demands
- blending of fresh surface water with marginal confined groundwater to increase available water
- conjunctively using unconfined and confined aquifers to regulate effects of variable seasonal recharge.

Other examples of water supply schemes relying on conjunctive use are the West Pilbara water supply utilizing water from the Harding Dam and groundwater from a surficial aquifer at Millstream; the former Geraldton water supply which utilized water from a dam and several borefields at Wicherina; and the Menzies water supply which utilizes separately or together groundwater and water from a small local dam. There is scope for other conjunctive use schemes, particularly in areas of fractured rock aquifers.

## Strategic water supplies

Access to water resources is particularly important in times of national emergencies and natural disasters. Surface water resources are vulnerable to terrorism or warfare and natural disasters such as droughts, floods, earthquakes and volcanic activity. Groundwater being

Table 8. Wellfield yield (1992) and design annual net yield from dams for selected town water supplies (slightly modified from Allen et al., 1992)

Town/Scheme	Annual abstraction (GL)
Derby	1.15
Broome	2.60
Port Hedland (Yule)	3.20
Port Hedland (De Grey)	3.50
Newman (and mine)	(a) 13.00
Pannawonica	(a) 1.80
Paraburdoo (and mine)	(a) 6.30
Tom Price	(a) 8.00
Karratha (Millstream)	(b) 10.00
Exmouth	0.09
Carnarvon	5.26
Geraldton (Allanooka)	8.60
Perth (Mirrabooka)	23.70
Perth (Wanneroo)	25.30
Perth (Gwelup)	12.30
Perth (Pinjar)	5.50
Bunbury	6.00
Busselton	4.00
Albany	1.90
Esperance	1.60

Dam (Town)	Designed annual net yield (GL)
Harding (Karratha-Dampier-Wickham)	20.0
Mundaring (Agricultural & Goldfields W.S.)	22.3
Canning (Perth)	36.4
Serpentine (Perth)	63.6
South Dandalup (Perth)	17.9
Wungong (Perth)	20.9
North Dandalup (Perth)	22.0

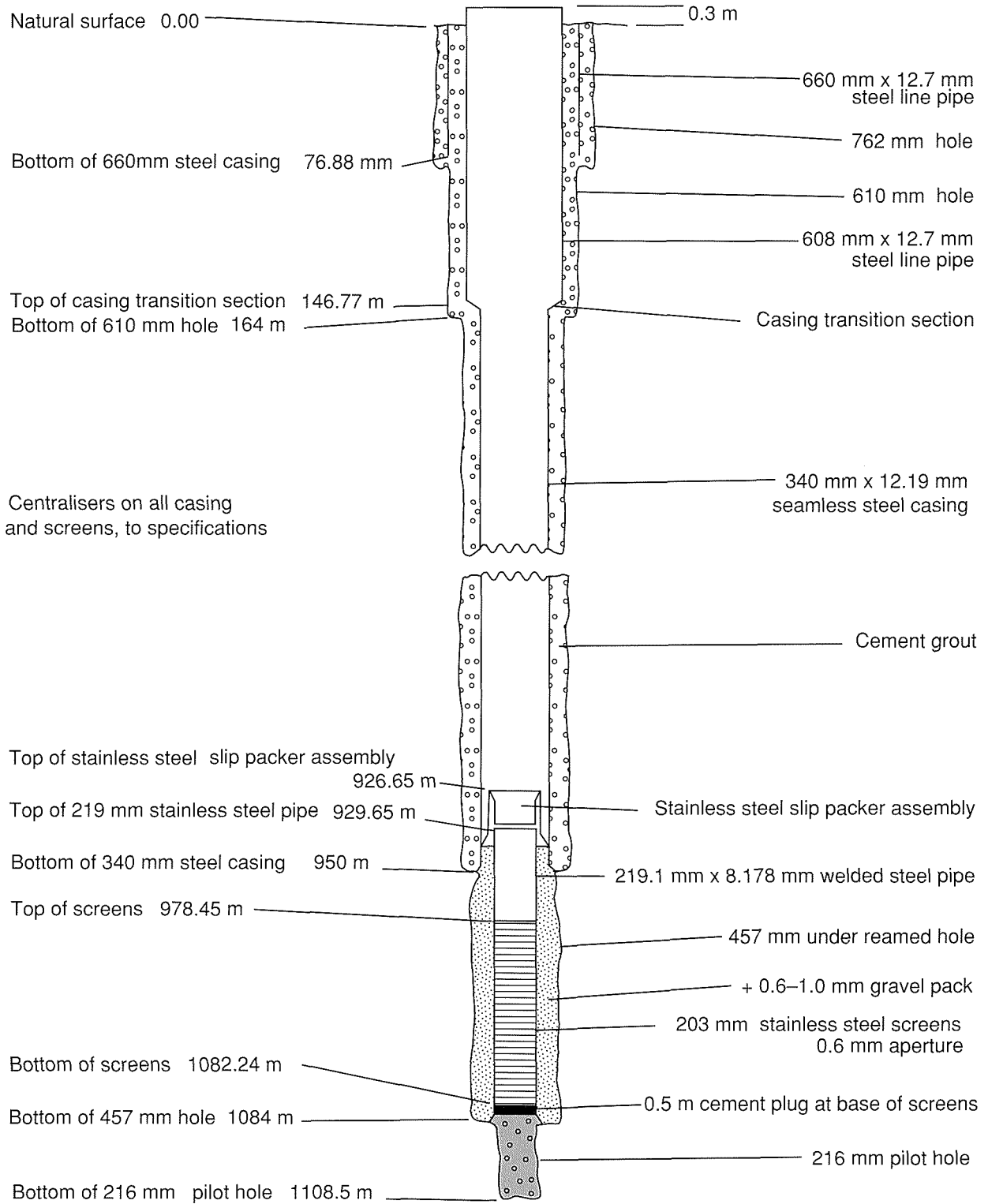
### NOTES:

- (a) Licenced abstraction  
 (b) Wellfield capacity: conjunctive use with Harding Dam

more distributed, with a degree of natural protection, and capable of ready development, consequently has considerable strategic importance.

## National emergencies

In the event of terrorism or warfare, surface water supplies may be accidentally or deliberately contaminated, and dams and reservoirs may become military targets. In a nuclear war (or accident) not necessarily involving Australia, surface water resources may become contaminated by airborne radioactive materials and be unusable for days or years. Surficial aquifers would be less vulnerable and confined sedimentary aquifers would be unaffected because of their depth, local intake areas and slow rates of groundwater movement. Consequently the confined aquifers with their level of protection and potential to provide large supplies of groundwater comprise a very important, readily developable strategic resources.



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Figure 28. Diagram showing construction of large-yielding production bore

## Drought

Droughts are part of the climatic regime regularly experienced in Western Australia, and have been attributed to climatic effects resulting from the El Niño Southern Oscillation Phenomenon, volcanic activity, and greenhouse effects resulting from increased concentrations of carbon dioxide and other gases in the atmosphere. Droughts directly affect surface water resources but generally only have limited impact on groundwater resources, depending on the nature of the aquifers.

During periods of drought, groundwater recharge is reduced and watertable levels may fall. This generally does not severely affect groundwater resources in surficial or sedimentary aquifers which have large quantities of groundwater in storage. In fractured rock aquifers with limited storage, however, significant lowering of water level (up to 6 m) may occur and be accompanied by an increase in groundwater salinity. Since about 1970 there have been various instances of widespread failure of pastoral bores in the Kimberley, Pilbara, Murchison, and north Eastern Goldfields. This has resulted from lack of recharge, compounded by the relatively shallow depth of many bores and wells, leading to their failure when the watertable has fallen.

In confined aquifers that are full of groundwater, pressures decline in times of drought but the aquifers remain full. This groundwater, like money in the bank, can be drawn on in times of need and if necessary can be overdrawn and 'repaid' by later resting the aquifer and allowing pressure to recover when recharge occurs. Thus the large quantities of groundwater in storage within aquifers (except some fractured rock aquifers) can provide secure water supplies during periods of drought. Consequently, in Western Australia, groundwater provides important secure water supplies and, as in the case of Perth, some insurance against drought and independence from total reliance on surface water supplies.

## Artificial recharge

In arid and semi-arid regions, when rainfall runoff occurs it is usually a short-lived event. Consequently, in various parts of the world it is common to attempt to retain this runoff in dams or to induce its infiltration into aquifers where the water is protected from evaporation, and from which the water can be utilized as required. The diversion or impoundment of surface runoff into engineered structures from which infiltration can occur is termed artificial recharge. It is practiced extensively in various parts of the world, and in Australia, notably in Queensland.

Artificial recharge is generally undertaken by means of large infiltration basins into unconfined aquifers, particularly alluvial sands and gravels, eolian sands, and cavernous limestone. It is also undertaken via boreholes into confined aquifers but this is generally technically more difficult and useful mainly for small-scale recharge or waste disposal.

In Western Australia, the only operating large-scale artificial recharge scheme is at Newman where water from

the Ophthalmia Dam is recharged from infiltration basins and the reservoir itself, into an unconfined aquifer (Clarke and Kneeshaw, 1983). The purpose of the scheme is to store limited surface runoff in an unconfined aquifer into which a substantial volume has been pumped. This ensures minimal evaporation losses and the availability of the water for several years until it is required for the town water supply or mining activities.

Experiments to determine acceptance rates of confined aquifers have been undertaken at Carnarvon (Allen, 1972) and in Perth but were abandoned because of low infiltration rates and technical problems. Successful small-scale artificial recharge is undertaken on Barrow Island and at Dongara where brines are pumped back into petroleum reservoirs, and at Kwinana where industrial effluent is disposed by pumping into a confined aquifer.

Large-scale unintended artificial recharge occurs in the Perth Metropolitan area where urban runoff is directed into about 900 stormwater basins (Cargeeg et al., 1987) from which it infiltrates the unconfined aquifer. No reliable estimates have been made but it is likely that 100–200 GL/year are recharged to the aquifer from these sources. Large quantities of water are also unintentionally recharged to groundwater from public water supply dams such as at Wicherina and from thousands of leaking farm dams, mainly in the Southwest agricultural zone. There are also numerous instances where landowners direct surface runoff into dug wells and effect artificial recharge.

Currently, groundwater recharge is not widely practiced in Western Australia but as pressures grow to conserve drainage water or wastewater, the practice of artificial recharge will increase. The main problem will be the identification of suitable sites within aquifers and quality considerations, particularly concerning salinity and nutrients in the recharge water.

## Groundwater desalination

The lack of suitable supplies of fresh water in some parts of Western Australia has necessitated desalination of brackish–saline groundwater for domestic consumption and other uses. Early desalination plants were based on distillation, but since the 1960s de-ionization and reverse osmosis have been the main methods used.

From 1894 to 1903, prior to the completion of the Mundaring–Kalgoorlie pipeline, numerous privately operated distillation plants were used at Coolgardie, Kalgoorlie and other mining centres to provide water for prospectors. Over 40 wood-fired plants, which contributed to clear-felling of trees around some of the mining centres (Fig. 11), are said to have operated in Coolgardie utilizing local saline groundwater.

Apart from distillation of groundwater for use by locomotives at Geraldton (and formerly also at Kalgoorlie), desalination of groundwater did not resume until the 1960s. From 1963 to 1970, distillation of seawater and saline groundwater supplemented the Rottnest Island water supply, but ceased because of technical difficulties (Herbert and Moffatt, 1970). In 1977, a reverse osmosis

plant was constructed by the Public Works Department for the Denham town water supply. It is still operating and reduces brackish artesian groundwater of about 4500 mg/L TDS to 150–500 mg/L TDS, and currently produces about 0.08GL/year.

Various mining companies in the Eastern Goldfields also operate small reverse osmosis or de-ionization plants to obtain low salinity water for domestic use or for specialized purposes in treatment plants, usually using brackish to saline groundwater from surficial and fractured rock aquifers. Various other small-scale proprietary desalination plants, utilizing groundwater, provide water for domestic supplies on pastoral properties and remote tourist resorts.

Western Australia has practically inexhaustible sources of brackish groundwater suitable for desalination, particularly in the sedimentary basins where perhaps 90% of the stored groundwater resources (Table 6) are brackish to saline, and also in surficial aquifers on the fractured rock provinces. The importance of these brackish resources has been recognized and where practicable they are being identified and quantified in the Geological Survey groundwater assessment program. Desalination technology is improving, and provided low-cost energy sources such as natural gas or solar energy are available, desalination may increase in importance, particularly in the Yilgarn–Goldfields and Albany–Fraser Provinces and in the Carnarvon Basin.

## Hydrothermal groundwater

Hydrothermal groundwater is here considered to be groundwater with a temperature  $\geq 35^{\circ}\text{C}$ . It is warmed principally by the flux of heat from the interior of the earth as the groundwater moves slowly within circulating flow systems. Typically the geothermal gradient is about  $25^{\circ}\text{C}/\text{km}$ , but local higher gradients (geothermal anomalies) occur where there is volcanic activity; zones of deep-seated fluid flow; concentrations of radiogenic minerals; or sequences of sedimentary rocks with low thermal conductivity that retard the heat flux. Hydrothermal groundwater generally occurs below depths of 1–2 km in the deep sedimentary basins, or at shallower depths where there are geothermal anomalies.

The geothermal gradients in the Canning, Carnarvon and Perth Basins, based on petroleum exploration data, have been mapped by Bestow (1982) in a review of the potential for geothermal power generation in Western Australia. Surveys of geothermal gradients have also been undertaken by the Geological Survey in various exploratory bores in the Perth Basin (e.g. Appleyard, 1991). These studies have confirmed the presence of hydrothermal groundwater in some deep aquifers and the presence of local geothermal anomalies associated with faulting and the presence of low conductivity confining beds. Hydrothermal groundwater is also likely to occur in the Bonaparte and Officer Basins which contain thick sequences of sedimentary rocks.

In the Canning Basin hydrothermal groundwater is known from several springs (e.g. Wynne Spring) and from

artesian bores at Derby (Myalls bore) and Broome (Maitland, 1913). Hydrothermal groundwater occurs extensively in the Birdrong and Tumblogooda Sandstones in the Carnarvon Basin (Bestow, 1982; Allen 1987), probably as a result of the presence of widespread low conductivity confining beds, and has been encountered in the Bibbawarra (Pelican Hill) artesian bore (Maitland, 1913) and other artesian bores. In the Perth Basin, hydrothermal groundwater has been obtained from artesian bores in the Yarragadee Formation at Dongara (Maitland, 1913), Busselton, and especially in Perth (Allen, 1979).

In Western Australia, hydrothermal groundwater has been utilized mainly in Perth. Groundwater from an artesian bore at the Perth Zoo was used for Turkish baths from about 1910 to 1969 and has also been used to warm the reptile enclosure at the Zoo. A reputed hot spring on the Swan River foreshore at Nedlands, used for bathing and now a part of Perth's folklore, was actually an uncontrolled artesian bore plugged in 1956. Hydrothermal water is used in a wool scouring works at Jandakot and also in a laundry at Graylands Hospital. At Derby and near Carnarvon, warm artesian groundwater is used by locals and tourists for bathing and at Busselton has been considered for heating a swimming pool.

There is considerable potential in Western Australia for obtaining hydrothermal groundwater for spas, low temperature electricity generation (Bestow, 1982), flash distillation, greenhouses and other applications. The major drawbacks to its exploitation are the depth and expense of bores required to utilize the groundwater, and problems with re-injection or disposal of the generally brackish or saline groundwater.

## Mineral waters

In Australia, the National Health and Medical Research Council defines mineral water in Section 08 of the Food Standards Code as 'groundwater obtained from subterranean water-bearing strata that in its natural state contains soluble matter'. Mineral waters may be carbonated naturally or by addition of carbon dioxide. Those which are not carbonated may alternatively be described as spring water.

In Western Australia, the consumption of mineral water has grown markedly during the last decade, as a result of fashion and health awareness. Many mineral waters are imported but there is also a local mineral water industry. Some proprietary brands of mineral water produced in Western Australia are Karri Country, Weaver and Locke, Summit, Natures Garden, Pura, Deep Spring, Aqualante, Spring Dew, Salute, Aqua Vital and Country Fresh (Health Department, 1991).

The sources of the Western Australian mineral waters are not well publicized but most are believed to be springs in the higher rainfall areas of the Yilgarn–Southwest and Leeuwin Provinces, and from artesian and sub-artesian bores in confined aquifers in the Perth Basin. Local and imported mineral waters have been the subject of a food monitoring program (Health Department, 1991), and samples have been analysed for compliance with

bacteriological and chemical standards, and to permit chemical comparison of different brands.

## Problems arising from utilization of groundwater resources

### General

Pumping groundwater from unconfined aquifers lowers the watertable and dewateres the aquifers, whereas in confined aquifers the water level (piezometric surface) is lowered by reduction of pressure in the aquifer. These effects may be local or widespread depending on the number of bores, bore yields, and physical properties of the aquifer, and can result in various changes to the environmental regime.

### Drying wetlands

In Western Australia, groundwater abstraction can affect wetlands, and the ecosystems they maintain, as a result of pumping from unconfined and confined aquifers. In the Perth region, where most known cases occur, abstraction of unconfined groundwater for public water supplies has been shown to affect water levels in shallow lakes such as Jandabup and Nowergup, and also to affect susceptible trees and pasture where the watertable has been lowered. Some lakes such as Perry Lake are affected by local private abstraction. Pumping confined aquifers has been shown to affect the watertable at Serpentine and may slightly affect the watertable level over part of the Gnangara Mound (Davidson, 1995).

Intermittent pumping of a wellfield near Millstream in the Pilbara has to be carefully monitored to minimize effects on local important wetlands, and pumping for the Geraldton water supply has diminished flow from Allanooka Spring, affecting local vegetation. Pumping from confined aquifers is known to affect pools on the Collie River in the Collie Basin. However, with the exception of the Perth region, very few cases of pumping affecting wetlands are known. Seasonal effects of fluctuating watertable levels are well known and some of these have been incorrectly blamed on groundwater abstraction.

### Seawater intrusion

A proportion of the groundwater which originates from rainfall recharge on the land surface rejoins the hydrological cycle when it discharges into the sea. Unconfined groundwater discharges at about low water mark over a tapering wedge of seawater which may extend up to about 1 km inland (Fig. 5). The position of the seawater wedge is determined mainly by a balance between recharge and groundwater discharge. Confined groundwater usually discharges further offshore by seepage or from localized discharge areas, particularly along faults. Depending on the geology, a vertical sequence of saltwater wedges extending

shoreward for various distances may occur, and these may also move inland in response to pumping and cause seawater intrusion. Where lenses of fresh groundwater overlie seawater on islands and beneath some coastal dunes, as the groundwater discharges during the dry season the lens diminishes in thickness, with a resultant upward movement of the seawater somewhat analogous to seawater intrusion.

A seawater wedge extends all around the coast where unconfined groundwater discharges from the fractured rock provinces and the sedimentary basins (Fig. 16). It is well developed where sedimentary or surficial aquifers border the coast but is likely to be very irregular where fractured rocks or karstic sedimentary rocks occur. Where sedimentary basins border the coast, there is evidence for freshwater occurring offshore (Davidson, 1995) and seawater wedges in confined aquifers are inferred to occur several kilometres off the coast. Their position is likely to be dependent on the geology and on the recent geological history, particularly the 130 m lower sea level experienced about 20 000 years ago, which caused meteoric groundwater to move considerable distances seaward beneath the continental shelf.

If groundwater outflow is reduced by pumping, a compensating inland movement of the seawater wedge referred to as seawater intrusion occurs. As a consequence, bores located above the seawater wedge or near the inland toe of the wedge may become saline by upconing or inland movement of the seawater wedge. Similar upconing with a resultant increase in groundwater salinity may occur if pumping is from fresh groundwater lenses overlying seawater.

Seawater intrusion is known to occur in unconfined aquifers at Derby, Broome, Exmouth, Carnarvon, Perth (particularly around the Swan Estuary), and Albany. In confined aquifers, seawater intrusion is known only from Derby, Mandurah and locally in Bunbury. There are also numerous examples of bores and wells in groundwater lenses at Broome, Port Denison, Lancelin, Perth, Mandurah, Busselton, and Koolan and Rottneest Islands becoming saline as a result of upconing of underlying seawater. Most of the known occurrences of seawater intrusion are minor, and at this stage of groundwater development in Western Australia seawater intrusion is not a significant problem, but eventually it may become serious, particularly in the unconfined aquifer in parts of the Perth region (e.g. around the Swan Estuary).

### Land subsidence

In some parts of the world where confined groundwater from alluvial or deltaic deposits is utilized, pumping has led to pronounced subsidence as a result of dewatering and compaction of silt and clay interbedded with the aquifers. Concern about the possibility of subsidence resulting from pumping of confined aquifers in Western Australia has been frequently raised. No case of subsidence resulting from pumping is known, however, and monitoring in the Perth Metropolitan area has not detected any evidence of subsidence. It is considered that, because of the age,

composition, and environment of deposition of most aquifers in Western Australia, subsidence is unlikely to be a problem.

## Change in groundwater quality

Usually the quality of groundwater from a particular well is very consistent. Seasonal variations in salinity, nitrate, and iron have been reported from bores in the surficial aquifer underlying Perth (Cargeeg et al., 1987), and minor changes in salinity and other parameters are known from some wells in confined multi-layer aquifers, particularly at the commencement of pumping before the yield from each aquifer has stabilized.

Long-term changes in groundwater quality may occur as a result of diversion of groundwater flow from other parts of an aquifer as at Carnarvon (Allen, 1972), or by upward or downward leakage into confined aquifers. Salinity of groundwater from wells in fractured rock aquifers may increase when low salinity groundwater is depleted and is replaced by the inflow of underlying or adjacent more saline groundwater, or may vary if there are different contributing fracture systems (Allen and Davidson, 1982). However, the largest variations in groundwater quality are usually caused by seawater intrusion (see Seawater intrusion), or by introduction of man-made substances into aquifers (see Groundwater contamination).

## Impact of environmental changes on groundwater resources

Prior to European settlement, a dynamic balance existed between the climatic regime, groundwater systems, and the native vegetation at the interface between the surface and groundwater environments. This balance has been altered by clearing native vegetation for agriculture and to a lesser degree by pastoral, forestry, mining, and urban development which has altered recharge and discharge rates of the groundwater flow systems. Concomitantly there has been a change in the quality of the groundwater recharge resulting from the changed landuse, particularly from broad acre use of fertilizers and agricultural chemicals, and from urban and industrial activities.

## Land and stream salinization

At the time of first settlement, there were extensive saline areas in the arid to semi-arid interior of Western Australia in salt lakes along the palaeodrainage systems (Fig. 17). These ranged in area from a few hectares to more than 2500 km<sup>2</sup> (e.g. Lake Mackay and Lake Disappointment). Elsewhere, local land salinization occurred naturally on areas of saliferous strata and at some groundwater discharge sites. Some rivers such as the Murchison and Irwin were brackish, and at the end of summer brackish riverine pools were present along many rivers, particularly in the Southwest. Unseen were large quantities of salt present in deep, confined flow systems in the sedimentary basins and particularly in the shallow unconfined

groundwater flow systems in the Southwest agricultural zone (Yilgarn–Southwest and Albany–Fraser Provinces).

In the Southwest agricultural zone, extensive land clearing has been undertaken for cereal farming and establishment of pasture. The clearing commenced soon after first settlement in areas such as York, and has expanded in a series of bursts in response to economic and social factors. Periods of expansion occurred at the turn of the century after the world wars, and particularly during the 1960s and 1970s when Government policy and the availability of very efficient machinery for clearing bushland resulted in widespread clearing.

Not known at the time was the interaction between the native vegetation and the underlying groundwater systems. In particular, the coincidence of a clayey, deep-weathered profile on fractured rocks, low topography, poorly integrated drainage, and seasonal rainfall with a relatively high salt content predisposed the region to the concentration of salt in soil profiles, and the occurrence of sluggish, brackish to saline, groundwater flow systems in balance with the vegetation. The native vegetation adapted to the conditions, limited the amount of recharge, and by evapotranspiration maintained the watertable within a small range and concentrated salt in the soil profile and in the groundwater (Fig. 29).

After clearing the vegetation, the water balance was profoundly changed (Fig. 29). Clearing and ploughing increased recharge, and perennial crops and pastures utilized only a fraction of the rainfall previously transpired by the native vegetation. Consequently there has been a substantial increase in recharge, resulting in a gradual rise in watertable levels, an increase in stored groundwater, and mobilization of salt previously stored in the weathering profile. Within five to twenty years after clearing (depending on area), the watertable has risen leading to the formation or expansion of saline seeps, the death of remnant vegetation and reduced crop production. This has occurred mainly along the valleys of second and third order drainage lines and to a minor extent in some site specific areas where the geological conditions focus local groundwater discharge. The raised watertable levels have contributed saline groundwater to stream base flow, and runoff from salinized areas has caused a marked increase in salinity of previously fresh rivers (Fig. 30).

The association between increased stream salinity and clearing was noted at the turn of the century and by the mid 1920s there was a general understanding of the factors producing land salinization (Wood, 1924). Subsequently there was a lack of concern until the 1960s and 1970s when various surface water supplies became threatened by increased salinity of runoff derived from salinized areas and saline groundwater discharge (Schofield et al., 1988). This resulted in considerable research, principally by the CSIRO and Public Works Department (now Water Authority), into the causes of, and means to ameliorate, stream salinization. Somewhat later, the Department of Agriculture, in cooperation with the Geological Survey, commenced research into land salinization affecting productive farmlands.

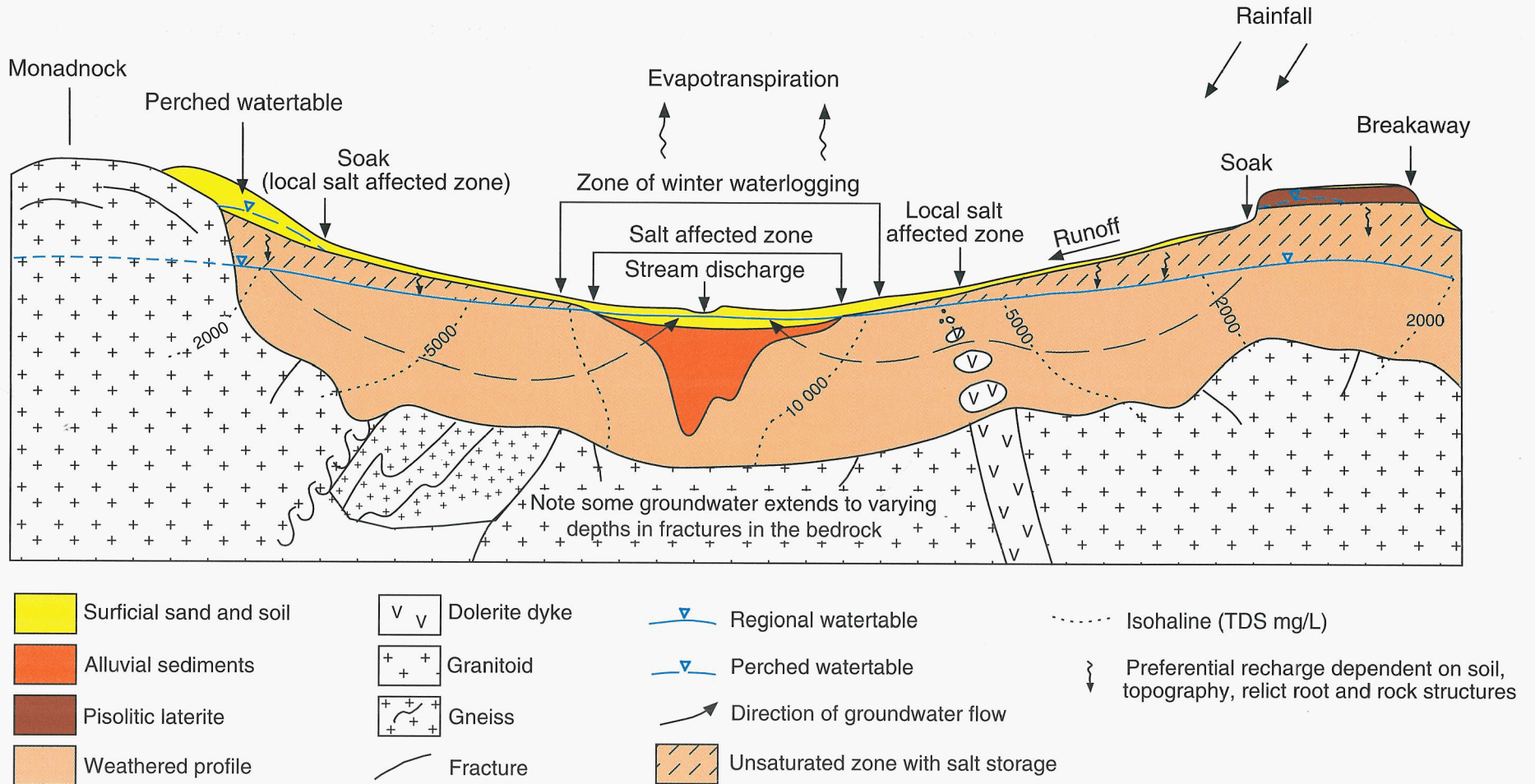


Figure 29. Diagram showing main topographical, geological, and groundwater factors contributing to land and stream salinization

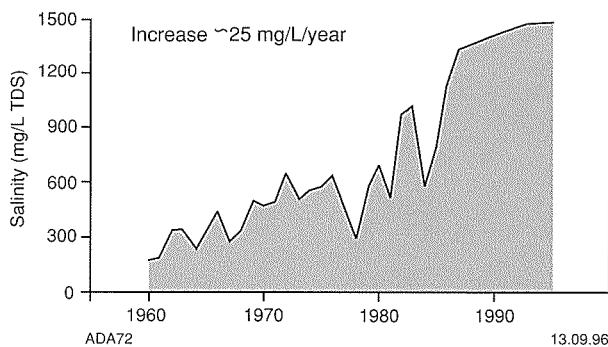


Figure 30. Increasing salinity of the Denmark River (1960–1993)

Currently, according to George (1990), about 170 000 km<sup>2</sup> of land has been cleared for agriculture in the region pre-disposed to land salinization. Of this, about 2.8% is affected by salinization and during the 10 years 1979–1989 the area was increasing at about 180 km<sup>2</sup> per year. This, and other forms of land degradation, are resulting in significant loss of agricultural production.

The changed water balance has also affected the salinity of many previously fresh–marginal wetlands (e.g. Lakes Towerrining, Toolibin, Dumbleyung) which have become saline or are being threatened by increased salinity. Some of these lakes have important environmental attributes, and in the case of Lake Toolibin efforts are being made to remedy the increasing salinization (Stokes and Martin, 1986). However, the most serious consequence of the changed water balance (Schofield et al., 1988; Schofield, 1989) has been the discharge of saline groundwater in base flow or the incorporation of salt in runoff from salinized areas, resulting in the increase in salinity of many rivers and streams (Fig. 31). This has had serious consequences for the ecology of rivers and streams and for some planned and existing surface water based supplies such as the Collie Reservoir (Loh and Stokes, 1981).

The raised watertable levels have also affected other sources of water supply. Many formerly fresh or brackish wells have been abandoned as the fresh groundwater has been displaced by saline groundwater. Similarly, many farm dams have been affected as the watertable has risen, and there has been inflow of saline groundwater into the base of the dams, limiting their usefulness particularly during the summer.

The mechanisms controlling land salinization are now reasonably well known, although at a local scale a variety of hydrogeological conditions may operate. However, it is clear that, because of the widespread nature of the problem, the various site-specific controls, and the volume of salt storage, there is no ready solution to the problem. Various agricultural, drainage, and engineering strategies are being developed to minimize land salinization. The strategies seek to manage the groundwater flow systems at a small catchment scale so that remedial measures are undertaken in the appropriate areas, and to minimize

‘downstream’ effects. To assist this, a new generation of hydrogeological maps utilizing computer aided drafting, and allowing transferability of data, ready up-dating, merging of data sets, and production of maps at working scales of desired areas, is being undertaken by the Geological Survey (Laws et al., 1993). The mapping provides a regional overview and a basis for effective planning and management to limit land and stream salinization.

## Waterlogging and drainage

Alteration of the hydrogeological balance by clearing on flat areas of the Swan Coastal Plain (Perth Basin) has resulted in seasonal raised watertable levels and water-logging. In some areas, this has necessitated the construction of major drains as well as a wide network of road and farm drains to discharge the excess water into the ocean or estuary systems. Very large quantities of water are discharged in this way, and despite concerns about nutrients, methods of conserving or artificially recharging this water may need to be considered in the future.

One effect of this recharge has been the increased size and permanency of some wetland features. In the Perth region, the beds of Lake Claremont, Lake Joondalup, Herdsman Lake (and others) were previously utilized for market gardening and grazing. Raised watertable levels have resulted in lake water persisting throughout the year except in times of drought. Thus, some of the lakes are larger than at first settlement and are artificial in the sense that they result from alteration of the groundwater regime.

## Groundwater contamination

Groundwater contamination is considered to be any direct or indirect alteration of the chemical, physical, biological, or radiological integrity of groundwater. The term ‘contamination’ is preferred to ‘pollution’ which has emotive connotations, and because alteration of groundwater quality does not necessarily limit its usefulness or have adverse environmental impacts. Groundwater contamination occurs when foreign substances or organisms that alter the composition of the native groundwater are introduced from the land surface to the watertable. The sources of contamination are usually human activities, but may also be natural phenomena such as surges of seawater, ash from large bushfires or concentrations of animals.

The major sources of contamination arising from human activities are shown in Figure 32. Of these, the most severe contamination generally results from point sources such as accidental or deliberate disposal of liquid wastes such as chemicals and waste waters, or leachate from landfill sites. Contaminants from these sources move down to the watertable where they mix with the groundwater; float on the water table; or sink toward the base of the aquifer. The contaminant then generally tends to move in the direction of groundwater flow and forms a plume that gradually disperses or degrades with distance from the source. Other significant widespread contamination may result from non-point source contamination resulting from

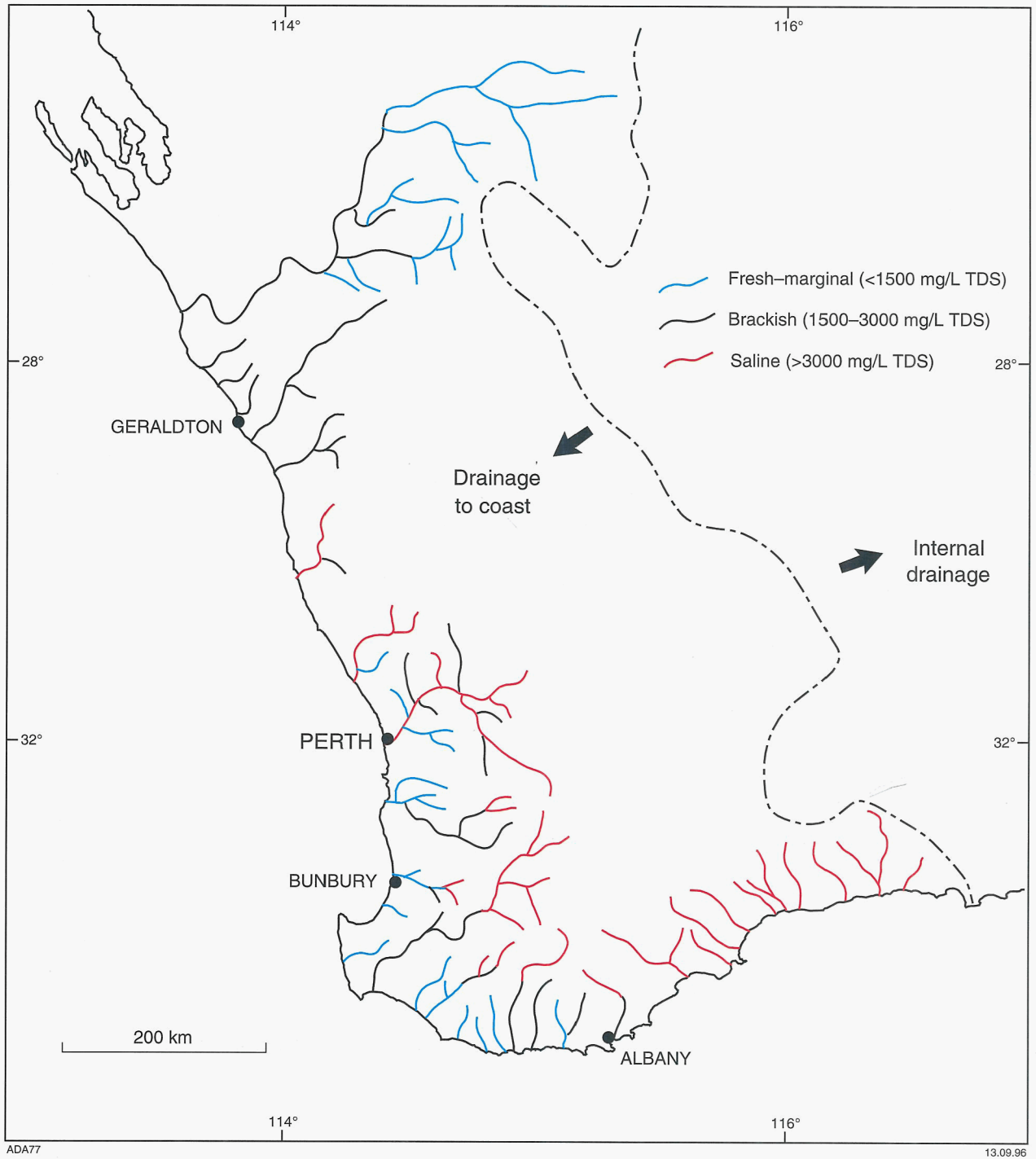
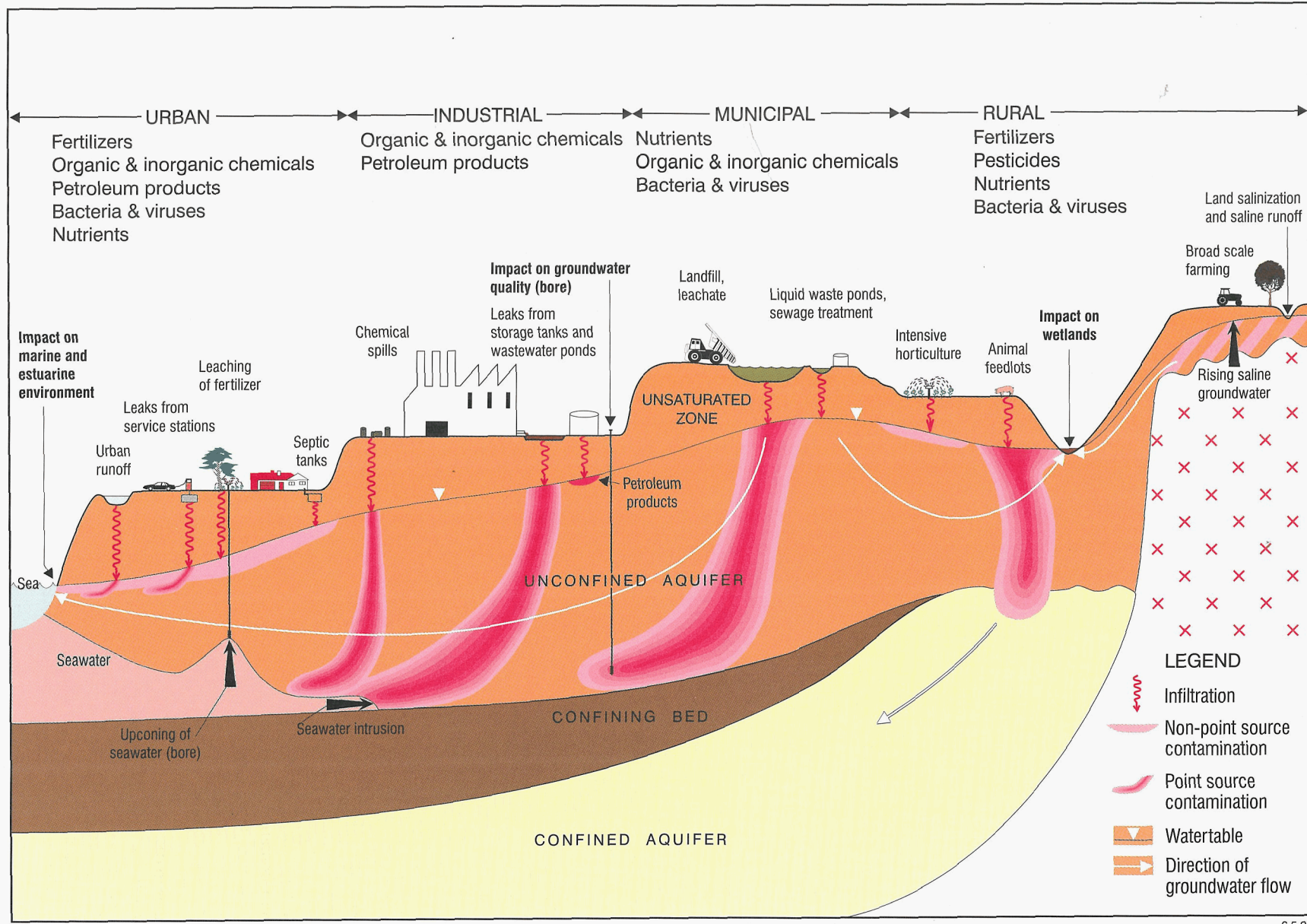


Figure 31. Salinity of major rivers in southwestern Western Australia



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Figure 32. Major sources of groundwater contamination arising from urban, industrial, and rural activities in Western Australia

leaching of fertilizers or a large number of minor sources such as septic tanks. Unconfined groundwater is relatively accessible from the surface environment and is most vulnerable to contamination. In particular, groundwater in fractured rock aquifers or karstic sedimentary aquifers may be easily contaminated because of the ready access and movement of contaminants in fractures or solution openings, and the relatively small volumes of groundwater in storage. In contrast, unconfined groundwater in sedimentary and surficial aquifers has a measure of protection provided by the soil cover, depth to watertable, adsorptive and reactive materials in the aquifer, and micro-organisms.

Confined groundwater has a high level of protection because of the retardation of contamination provided by overlying aquifers and confining beds, and because of the generally slow rates of groundwater movement. However, contamination can occur in areas of outcrop, from overlying unconfined aquifers and via wells. If contamination does occur it may persist longer and be more difficult to remediate than in other aquifers.

It is said that aquifers have long memories. In contrast to surface water, once contamination has occurred it may take decades or centuries for it to disperse naturally in groundwater flow or be removed by biochemical processes. Consequently, although the contamination cannot be seen it persists, and there are several examples in the Perth region of severe contamination being detected many years after it originated. In this respect, groundwater contamination can be an environmental time-bomb that may suddenly appear, making water supplies unusable and having serious environmental effects in discharge zones where it may affect rivers, wetlands, estuaries or the sea.

A number of techniques have been developed for cleaning up groundwater contamination. These rely mainly on containing the contaminated groundwater or pumping it for treatment and then using or re-injecting it back into the aquifer. These measures are expensive and of limited effectiveness. The best policy is prevention rather than cure.

In Western Australia, possibly more than elsewhere in Australia, groundwater contamination is a very serious issue because of the State's dependence on groundwater and because of the widespread occurrence of sandy soils that provide minimal retention of most groundwater contaminants. Consequently, particular care has to be taken to prevent contamination of public water supplies and minimize impact on wetlands. This is of particular concern in Perth on the Gnangara and Jandakot Groundwater Mounds.

Studies to determine the extent and severity of groundwater contamination in the Perth Basin, where most of the State's population resides, have been undertaken by the Geological Survey. About 1000 actual or potential point sources of contamination (not including petrol stations) have been identified in the Perth Basin (Hirschberg, 1993). This study showed that most contaminated sites occurred in the Perth metropolitan area and confirmed that the most severe groundwater contamination was in the Kwinana industrial area as previously described by Hirschberg

(1989). It concluded that, excepting Perth and other major population centres, groundwater contamination from point sources in the Perth Basin was not severe. Following this finding, a survey to determine the extent and severity of non-point contamination from agricultural activities has been undertaken by the Geological Survey (Hirschberg and Appleyard, 1996). In addition, maps of the Perth Basin showing the vulnerability of groundwater to contamination (Appleyard, 1993) have been produced with the objective of guiding land planning decisions so that groundwater contamination is minimized. Maintenance of groundwater quality may eventually be more important than the quantity, especially in Perth.

## Climate change

The process of climate change is very complex and involves interactive solar, planetary, atmospheric, oceanographic, geological, and biological processes. There have been large climatic changes within the last 1.5 million years (Pleistocene) during which there has been an alternation of glacial and interglacial periods that have had global impact on climate. The degree of climate change has varied according to latitude, geographic location, regional topography, and other factors.

In Western Australia, it is considered that at the beginning of the Pleistocene most of the State was probably arid to semi-arid, but since the last glacial maximum 20 000 years ago the arid and semi-arid zones have contracted to about their present position and sea level has risen about 130 m to its present position (Wyrwoll, 1993). During this period, there is evidence for some short periods of high and low rainfall and a more prolonged arid period about 4500 years ago (Backhouse, 1993).

Since the 1980s, evidence has been obtained that carbon dioxide and other gases have increased markedly in the atmosphere as a result of industrialization. This has given rise to concern about the 'Greenhouse Effect', the entrapment of solar energy leading to global warming and change in climate. There has been extensive research and debate about the degree and nature of any changes that may occur. Various studies using computer-based models predict global temperature increases up to 5°C accompanied by a rise of sea level up to 1 m in the next 50 years. The uncertainty involved in these predictions and uncritical acceptance and speculation about the results has been criticized by various authorities (e.g. O'Brien, 1990). Nevertheless, at least from a geological perspective, the climate is changing in some direction.

Some studies suggest that the north of Western Australia may experience more rainfall while the southwest may experience a severe reduction in rainfall. Assuming that these conclusions are correct, Sadler et al. (1988) have considered the possible consequences of a decline in rainfall in the southwest. They concluded, inter alia, that streamflow could decrease by 45% and increase in salinity, and that recharge to surficial aquifers could be reduced. As a result, groundwater abstraction from the unconfined aquifers may have to be reduced to minimize undesirable impact on wetlands, and to limit seawater intrusion.

Similarly, Ghassemi et al. (1991) have undertaken a nationwide review of the possible impact of climate change on the major aquifers in Australia (including the Perth Basin). They concluded that the effects of climate change on groundwater resources would be beneficial in some regions and detrimental in others. In Western Australia there could be detrimental effects on the surficial aquifers in the Perth Basin as a result of reduced recharge, and seawater intrusion resulting from a rise in sea level, whereas in the arid and semi-arid regions increased rainfall intensity could facilitate recharge and consequently increase available groundwater resources.

If climatic change accompanied by significant changes in rainfall occurs, it will have a direct effect on the unconfined groundwater resources and minimal or muted effect on the confined groundwater resources, depending on their source of recharge and location of intake areas. The unconfined groundwater resources probably will respond mainly to changes in the intensity and duration of rainfall events, rather than total rainfall, and consequently are likely to be less affected than surface water resources. Confined groundwater resources will be largely unaffected by any climate change because of the large volumes of groundwater in storage and because leakage from overlying unconfined aquifers will only be minimally affected.

## Groundwater and the future

### Current situation

Prior to European settlement, aboriginal Australians, who have occupied Western Australia for about 40 000 years, presumably had minimal effect on the hydrological cycle. Since the commencement of European settlement 150 years ago, and particularly during the last 40 years, major changes have occurred as a result of altered land use and to a minor extent by groundwater abstraction. These changes have resulted from the increasing population and accompanying urbanization, industrialization, and expansion of agricultural, pastoral, forestry, and mining activities. The hydrological cycle has been changed mainly by clearing native bushland, affecting evapotranspiration, runoff, and groundwater recharge. In some areas it has also been affected by damming rivers and export or import of surface water resources.

The impact of changed land use has been most profound in the agricultural zone in southwest Western Australia (Fig. 13), where about 10% of the State has been almost completely cleared of the original bushland for broad scale agriculture and pasture. The changes to the vegetation have affected the microclimate and resulted in changes to the water balance, resulting in increased recharge to the underlying groundwater flow systems. This has led to a rise in watertable levels of unconfined groundwater (and locally confined groundwater), mainly in the Yilgarn–Southwest Province and Perth Basin (Fig. 29), resulting in extensive land and stream salinization, and widespread waterlogging in predisposed areas. Elsewhere, the effects of pastoral activities, mining,

forestry, and woodchipping have had mainly local effects on the groundwater regimes.

Accompanying European settlement has also been point source and non-point source groundwater contamination of the unconfined groundwater resources. Point source contamination is associated mainly with industrial areas in the Perth Basin and with mining activities, whereas non-point source contamination is widespread in the Perth Basin and possibly in the agricultural areas of the Yilgarn–Southwest Province associated with agricultural activities. In contrast, contamination of the confined groundwater resources is minimal as a result of the protection provided by the geology.

Use of unconfined groundwater resources in some coastal towns has resulted in local, small-scale, seawater intrusion which generally reverses on cessation of pumping or occurrence of seasonal rainfall. In confined aquifers, localized seawater intrusion is known only at Derby, Mandurah and Bunbury. There has been widespread lowering of artesian pressure: in the Carnarvon Basin due to numerous free-flowing bores; in the Perth Basin in the vicinity of Perth as a result of pumping mainly for public water supplies; and in the Eastern Goldfields near Coolgardie as a result of pumping confined surficial aquifers for mining water supplies. The most severe impact on the confined groundwater resources has been in the small Collie Basin (Moncrieff, 1993) where there has been widespread lowering of groundwater pressures and dewatering of some aquifers to allow coal to be mined, and to provide groundwater for cooling purposes in the Muja coal-powered electricity generating station.

### Future role of groundwater

The availability and relatively low cost of development should ensure that groundwater will be a major source of water supply in Western Australia for the foreseeable future. Currently, about 45% of all water utilized is from groundwater but as the population grows, and mining and other developments expand into more remote areas of the State, available fresh-marginal, or brackish-saline groundwater resources will be utilized increasingly.

Major demands for groundwater are likely to arise in Perth and possibly in other towns such as Port Hedland, Carnarvon, Geraldton, and Bunbury. New or increased demands for groundwater may also arise in the mining areas in the Pilbara and Eastern Goldfields, for value adding industry, and possibly for irrigation.

Scope exists for considerable expansion of currently utilized groundwater sources and the development of major unutilized sources (Fig. 26). These sources occur mainly in the sedimentary basins and are well located for some town supplies but are distant from most areas of major mining activity. If demands for large groundwater resources arise, the size and the extent of the indicated resources would need to be verified and long pipelines may be necessary. In some cases, conjunctive use with surface water resources or artificial recharge could be practical solutions. If large fresh-marginal groundwater resources are not available, desalination of brackish or saline

groundwater could be practical if cheap sources of energy are available.

## Ecologically sustainable development

The concept of ecologically sustainable development (ESD) arose out of the 'World Conservation Strategy' (ICUN, 1990), and was refined and developed in 'Our Common Future' (WCED, 1987), widely known as the Brundtland Report. In this report ESD was defined as '... development which meets the needs of the present without compromising the ability of future generations to meet their own needs'. The principles outlined provide a unifying concept that seeks to integrate economic and social development while providing a measure of environmental conservation and adopting some responsibility to future generations. The implementation of these principles in an Australian context is evolving (e.g. Zarsky, 1990) and they are being embedded within national economic and environmental policies (e.g. Landcare) and in water planning in Western Australia (Sadler et al., 1988).

The development of groundwater resources raises numerous social, economic, ecological, and inter-generational issues pertinent to ESD. In Western Australia, with its large dependence on groundwater, the application of principles consistent with ESD needs to be addressed if orderly, equitable and responsible management of groundwater resources is to be undertaken. Some practical groundwater issues that need to be addressed within the framework of ESD are:

- protection of water quality
- establishment of principles for the equitable utilization of groundwater storage which is a legacy of hundreds or thousands of years of recharge
- development of management and allocation practices that adopt an holistic approach to groundwater flow systems (equivalent to surface water catchments) from recharge to discharge and which are cognizant of the role of groundwater in the environment.

## Innovative developments

In addition to developments such as artificial recharge, desalination, and use of groundwater as a source of geothermal energy, other innovative uses of groundwater and aquifers are being undertaken or developed elsewhere in the world. Some of these may become issues in Western Australia, especially in the Perth region.

The development of horizontal drilling by the petroleum industry may have application in exploitation of groundwater resources. The technique involves commencing with a vertical well, deflecting the drill at a predetermined depth and drilling horizontal with a computer-guided drill string. The technique is applicable only to some confined aquifers but offers the prospect of

exploiting large horizontal rather than vertical sections of aquifers, greatly increasing the yield from individual bores.

Aquifers can be used as storage sites. At present some toxic waste disposal is undertaken into deep confined aquifers containing saline groundwater. In these locations, toxic wastes can be stored for millennia. Of particular interest are oil and gas fields where geological conditions have formed proven viable traps. When all the available gas or oil has been extracted these sites could be used as repositories for toxic wastes. The currently operating oil and gas fields in the Perth Basin may present these opportunities. Confined aquifers can also be used as sites for natural gas storage in favourable localities. It is possible that in the future such a site may need to be found near Perth to ensure against breakdown of the natural gas pipelines supplying Perth and to meet peak demands.

Groundwater in aquifers may also be used for heat storage. Warm water can be pumped into an aquifer where the heat is retained, and later pumped out as required and the heat removed through heat exchangers. This may have application in some industrial areas, especially in the Perth Basin.

## Conclusions

Groundwater is a major earth-sourced natural resource of Western Australia. Its availability has been a major determinant in the settlement and development of the State for town, pastoral, mining, industrial, and infrastructure water supplies. Currently, about 45% (450 GL) of all water utilized is from groundwater and this is likely to increase steadily for the foreseeable future.

Western Australia's groundwater resources occur within the complex fabric of rocks which form the State. Together with climatic and topographical factors, these control the location, size, and salinity of the resources. They are far more widely available than surface water resources but in a large part of the State are limited in their size and by their salinity.

The groundwater resources are not observable or readily measured and have only been reliably assessed in a few areas, in particular in the extremely important Perth Basin where most of the State's population resides. In the remainder of the State, apart from some key areas, the groundwater resources have generally been assessed only at a reconnaissance level.

Based on the current understanding of the State's geology, and climatic and hydrogeological data, there are at least 40 mainly undeveloped sources capable of yielding large (greater than 10 GL/year) renewable, fresh-brackish groundwater supplies located mainly in the southwest and northern parts of the State. There are also very numerous minor and site-specific sources capable of yielding smaller supplies of fresh-brackish groundwater and virtually inexhaustible, brackish-saline stored (non-renewable) resources, mainly in the sedimentary basins.

At present, large-scale groundwater abstraction occurs mainly to the Perth Basin, in the vicinity of Perth (60%

of usage). Elsewhere, excepting about 40% of the State which is uninhabited, groundwater abstraction is widely distributed, or concentrated in local areas. There is scope for considerable further development of small and large fresh–marginal renewable groundwater sources, and even more scope for the development of mainly non-renewable brackish–saline sources. Nevertheless, because of the uneven distribution of groundwater resources, especially the widespread occurrence of fractured rock aquifers, there are some areas where suitable supplies of groundwater are not obtainable.

The effect of widespread clearing of bushland in the southwestern 10% of the State has altered the hydrogeological balance. This has resulted in widespread land and stream salinization and waterlogging in areas predisposed to these effects. This has focused attention on groundwater, not only as a source of water supply but also as an important environmental agent that causes salinization, and maintains streams, wetlands, and some dependent vegetation and ecosystems.

In the immediate future, the main problems involving groundwater are likely to relate to quality rather than quantity and are likely to be most severe in the Perth region and Southwest. These problems are likely to be point source groundwater contamination from industrial activities; non-point source contamination from urbanization and broad-acre agriculture, and land and stream salinization.

Current groundwater management has evolved to meet local problems as well as drawing on other national and international experience. At this stage in the development of using the State's groundwater resources, there is an opportunity for improving groundwater management particularly by taking an holistic approach to management of flow systems, within the framework of ecologically sustainable development. This needs to be underpinned by an adequate knowledge of the groundwater resources not only in the Southwest but throughout the State. This can be achieved by appropriate exploratory drilling and hydrogeological mapping as currently undertaken by the Geological Survey. This should eventually enable more effective management of the groundwater resources and minimization of the environmental consequences caused by changes to groundwater flow systems.

In a mainly arid region such as Western Australia, the identification, mapping and management of the groundwater resources should be seen as a strategic State responsibility to minimize or avoid problems experienced elsewhere, and as an investment in the future. Currently it is considered that there is inadequate understanding about the location, quantity, and quality of the State's groundwater resources to enable their management and to assist State development.

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## Glossary

<b>abstraction:</b>	Pumping groundwater from an aquifer	
<b>alluvium (alluvial):</b>	Detrital material transported by streams and rivers	
<b>aquifer:</b>	A geological formation or group of formations able to receive, store and transmit significant quantities of water	
<b>arid:</b>	Having a relatively dry climate with less than 250 mm annual rainfall insufficient for crops to grow without irrigation	
<b>artesian bore:</b>	A bore in a confined aquifer in which groundwater is under sufficient pressure to flow at the ground surface	
<b>artificial recharge:</b>	Diversion and ponding of runoff or waste water to facilitate infiltration into an aquifer so that the water can be used	
<b>base flow:</b>	That portion of river and streamflow coming from groundwater discharge	
<b>basin:</b>	A discrete Phanerozoic age geological structure containing sedimentary and sometimes volcanic rocks and groundwater resources within porous, permeable formations	
<b>bedrock:</b>	General term for solid rock underlying unconsolidated materials	
<b>bore:</b>	Drilled small diameter well, usually lined with steel or plastic casing for the purpose of obtaining or monitoring groundwater	
<b>brackish:</b>	Water containing between 1500 and 3000 mg/L of total dissolved solids, tasting slightly salty	
<b>brine:</b>	Water containing more than 35 000 mg/L of total dissolved solids	
<b>catchment:</b>	Land area drained by a river (drainage basin)	
<b>colluvium (colluvial):</b>	Detrital material transported by gravity down slopes	
<b>confined aquifer:</b>	An aquifer located between upper and lower layers of low permeability	
<b>confining bed:</b>	Layer or sedimentary bed of low permeability	
<b>conjunctive use:</b>	Use of different sources of water, generally surface and groundwater, which are then drawn upon in the most economical and effective manner	
<b>contamination:</b>	Change of water quality by addition of constituents derived from human activity or natural processes	
<b>crystalline rock:</b>	Igneous or metamorphic rock consisting of interlocking mineral grains	
<b>dewatering:</b>	Removal of free-draining water resulting in lowering of the watertable and reduction of groundwater in storage	
<b>diagenesis:</b>	The chemical and physical changes that occur in sediments after depositing during and after lithification and exclusive of metamorphisms	
<b>divertible resource:</b>	The average annual volume of groundwater that could be removed, using current technology, from developed or potential groundwater sources on a sustained basis without causing adverse effects or long-term depletion of storage	
		<b>drainage basin:</b> Land area drained by a river (catchment)
		<b>environmental/social use:</b> Allocation of water made for the purpose of maintaining wetlands for ecological, cultural or aesthetic reasons
		<b>eolian:</b> Wind-blown; deposit formed by wind action
		<b>ephemeral stream:</b> A stream with short-lived, irregular flows
		<b>estuary:</b> The seawater or tidal mouth of a river where fresh water comes into contact with seawater
		<b>eustatic:</b> Pertaining to worldwide changes of sea level.
		<b>eutrophication:</b> Process by which the chemistry and biota of bodies of water become destabilized by enrichment with plant nutrients, most commonly nitrogen and phosphorus
		<b>evapotranspiration:</b> A collective term for water discharged to the atmosphere by evaporation and transpiration
		<b>fault:</b> A fracture in rocks or sediments along which there has been an observable displacement
		<b>fluvial:</b> Pertaining to streams and rivers
		<b>formation:</b> A lithologically distinctive stratum or sequence of rocks deposited during a finite period and constituting a mappable unit
		<b>fractured rock aquifer:</b> Crystalline rocks that yield economic supplies of groundwater from fractures or weathering profiles
		<b>fractured rock province:</b> Areas of crystalline rocks corresponding with major tectonic units and with some hydrogeological uniformity
		<b>fresh:</b> Water containing less than 500 mg/L of total dissolved solids, and generally suitable for drinking
		<b>groundwater:</b> Water occurring below the land surface in the saturated zone in pores or fissures, generally in motion and part of the hydrological cycle
		<b>groundwater province:</b> General term for basins and fractured rock provinces subdivided on a geological basis for the purpose of groundwater classification and data presentation
		<b>herbicide:</b> Type of chemical designed to kill plants
		<b>hydraulic conductivity:</b> A measure of the rate at which water moves through a porous medium
		<b>hydrogeology:</b> Science concerned with the study of groundwater occurrence and movement and its relation to the geological environment
		<b>hypersaline:</b> Excessively saline; with a salinity substantially greater than that of seawater
		<b>insecticide:</b> Type of chemical designed to kill insects
		<b>inflow:</b> Flow of groundwater into an aquifer
		<b>intermittent stream:</b> Stream that flows for brief periods, usually after rainfall

<b>irrigation:</b>	Controlled application of water to crops where water requirements are not met by rainfall	<b>sedimentary aquifer:</b>	A porous and permeable aquifer such as sand, conglomerate or limestone occurring in a sedimentary basin
<b>karst:</b>	A type of topography produced by solution and collapse of limestone formations	<b>sedimentary basin:</b>	An area containing a thick, laterally extensive sequence of sedimentary rocks that have not been severely deformed or altered
<b>lacustrine:</b>	Pertaining to lakes	<b>self supply:</b>	Water obtained by landholder for own domestic, industrial or agricultural use
<b>laterization:</b>	Process of deep weathering in humid climates producing a layered weathering profile up to 30 m thick distinctly different from the parent material	<b>semi-arid:</b>	Climate with annual rainfall 250–500 mm
<b>leachate:</b>	Water that has percolated through soil containing soluble substances and that contains certain amounts of these substances in solution	<b>solution channel:</b>	Tubular or planar channel formed by solution of calcium carbonate in limestone
<b>leakage:</b>	Vertical flow of groundwater from one aquifer to another, generally through a less permeable layer	<b>specific yield:</b>	The volume of water that an unconfined aquifer releases from storage per unit surface area of the aquifer per unit decline in the watertable
<b>marginal quality:</b>	Water containing between 500 and 1500 mg/L total dissolved salts, in the upper range of acceptability for drinking	<b>storage coefficient:</b>	The volume of water that a confined aquifer releases from storage per unit surface area of aquifer per unit decline in the potentiometric surface
<b>non-point source:</b>	Contamination from broad areas (e.g. farming activities)	<b>stratigraphy:</b>	The science of rock strata, concerned with the succession and age relations of strata and their form, distribution, lithology, and fossil content
<b>nutrient:</b>	Any inorganic or organic compound needed to sustain plant life, especially nitrogen and phosphorous	<b>subcrop:</b>	Area of a geological formation concealed by relatively thin surficial sediments
<b>outcrop:</b>	Portion of the land surface occupied by a particular geological formation	<b>surface water:</b>	An open body of water such as a stream or lake
<b>outflow:</b>	Flow of groundwater out of an aquifer	<b>surficial aquifer:</b>	Aquifer in surficial sediments which may overlie sedimentary basins and fractured rock provinces
<b>palaeodrainage:</b>	Former ancient drainage systems rendered largely inactive by eustatic and tectonic activity	<b>surficial sediments:</b>	Geologically recent alluvial lacustrine and coastal plain sediments
<b>perennial stream:</b>	Stream that flows all year	<b>sustainable yield:</b>	The amount of groundwater that may be abstracted from an aquifer in perpetuity without adverse impact
<b>permeability:</b>	A measure of the rate at which fluid or gas can move through a porous medium	<b>tectonic:</b>	Pertaining to the geological forces involved in the faulting, folding and movement of rocks
<b>pesticide:</b>	A collective term for material used to control pests such as insecticides, herbicides, fungicides and bactericides	<b>throughflow:</b>	The process or amount of groundwater flowing through an aquifer
<b>physiography:</b>	The study of landforms	<b>transmissivity:</b>	The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient
<b>physiographic province:</b>	A region in which landforms differ significantly from adjacent regions	<b>transpiration:</b>	Life process by which water is taken up from the soil through plants and passed into the atmosphere as vapour
<b>point source:</b>	A discrete source of groundwater contamination	<b>unconfined aquifer:</b>	An aquifer overlying a relatively impermeable layer which is saturated from the watertable (at atmospheric pressure) downwards and generally with free vertical infiltration of recharge from the surface
<b>porosity:</b>	The ratio of the volume of voids to the total volume of a rock material	<b>unconsolidated:</b>	Sedimentary material that is generally not cemented and in which the constituent grains are free to move
<b>potentiometric surface:</b>	The level to which water from a confined aquifer will rise	<b>water balance:</b>	A technique for assessing the groundwater inflow and outflow components in an aquifer
<b>rainfall:</b>	Water that falls as rain (not synonymous with precipitation)	<b>weathering:</b>	Process whereby surface rock materials are broken down and chemically altered by exposure to the atmosphere and biological agents
<b>recharge:</b>	The water that infiltrates the watertable originating from rainfall and streamflow	<b>well:</b>	A hole or dug excavation designed to facilitate the abstraction of groundwater (term also applied to drilled bores)
<b>renewable resources:</b>	The amount of groundwater that accrues each year from recharge	<b>wellfield:</b>	A group of wells or bores used together to provide a groundwater supply
<b>runoff:</b>	That part of rainfall that is discharged from the landsurface in overland flow	<b>yield:</b>	The amount of water that can practically be pumped from a well/bore or aquifer
<b>salinity:</b>	A measure of the concentration of total dissolved solids (TDS) in water		
<b>salinization:</b>	The accumulation in the soil or concentration in streamflow of soluble salts resulting in adverse environmental effects		
<b>saline:</b>	Water containing more than 3000 mg/L of dissolved salts		
<b>scheme supply:</b>	Reticulated water supplies for domestic, industrial and agricultural use		
<b>seawater intrusion:</b>	Landward or upward movement of groundwater originating from seawater		

## Appendix 1

## Some major events in hydrogeology in Western Australia

<i>Year(s)</i>	<i>Event</i>	<i>Reference</i>
1830–1891	Groundwater from wells and springs used for Perth domestic water supplies	Parr (1927)
1860	Governor Kennedy Fountain constructed on Mounts Bay Road.	Parr (1927)
1871	First artesian bore; a flow from 23 m encountered in a 52 m exploratory bore for coal near Kenwick on the Canning River	Passmore (1912)
1885	Report by E. T. Hardman to Parliamentary Commission concluding artesian groundwater was unlikely to be obtained in Perth, but large quantities of non-artesian groundwater were probably available	Parliamentary Papers (1885)
1887	First reticulated water supply in Western Australia constructed at Fremantle utilizing groundwater, initially from wells and later from galleries constructed between 1888 and 1895, and artesian bores drilled in 1902 at Fremantle Gaol	
1888	Geological Survey founded, and headed by H. P. Woodward, the first permanent 'Government Geologist'	Playford (1990)
1894–1895	Midland Junction artesian bore was drilled to 152 m and encountered artesian groundwater, marking the commencement of utilization of artesian groundwater in Western Australia	
1894 (?1892)	Artesian groundwater found in deep exploratory bores for coal in the Collie Basin	Woodward (1895)
1895–1902	Large-scale desalination of groundwater at Coolgardie and Kalgoorlie, until Mundaring–Kalgoorlie pipeline was completed; desalination continued for some time in other mining centres in the Eastern Goldfields	
1895	Publication of <i>Mining Handbook</i> by Geological Survey with brief discussion of possibilities for location of artesian groundwater	Woodward (1895)
1896–1897	Diamond drill hole reputed to be deepest bore in Southern Hemisphere at that time, drilled to 915 m in granite at Coolgardie to test for artesian groundwater. The bore was drilled contrary to the advice of the Geological Survey and proved unsuccessful. A proposed bore at Kalgoorlie was not proceeded with and subsequently planning for the Mundaring–Kalgoorlie pipeline commenced	
1897–1932	Twenty-one artesian bores sunk for Perth Metropolitan Water Supply	Parr (1928)
1897–1905	About forty private artesian bores drilled in Perth	Maitland (1913)
1897–1925	Statewide exploratory drilling for artesian groundwater for town water supplies at Wyndham, Derby, Broome, Onslow, Carnarvon, Geraldton, Dongara, Yardarino, Moora, Rottnest Island, Cookernup and Bunbury	Artesian water conferences (1912, 1914, 1921, 1924)
1902–1914	Drilling and utilization of sub-artesian groundwater in Eucla Basin for Transcontinental Railway construction and operation	Maitland (1915)
1902–1912	Mines Department Goldfields Water Supply Branch constructed about 250 successful bores, wells and dams along tracks used by prospectors in the Eastern Goldfields, Pilbara and Kimberley regions and also along various stock routes	Mines Department Annual Reports (1902–1912)
1903–1930	The Pelican Hill (Bibbawarra) bore was drilled to explore for groundwater and coal near Carnarvon and encountered a large flow of warm brackish artesian groundwater; subsequently about 100 artesian or sub-artesian bores were drilled in the Carnarvon Basin for the pastoral industry	Maitland (1904); Allen (1988)
1908–1910	Construction of 51 wells on Canning Stock Route, utilizing shallow unconfined groundwater mainly in Canning Basin	
1912, 1914, 1921, 1924	Interstate, artesian water conferences with major Western Australian contributions in 1912 and 1924; a description of the known artesian basins and details of bores provided in 1912 report	Artesian water conference reports (1912, 1914, 1921, 1924)
1919	Publication of report on artesian water resources in Western Australia	Maitland (1919)

## Appendix 1 (continued)

<i>Year(s)</i>	<i>Event</i>	<i>Reference</i>
1928	Advice provided to Government on the 3500 farm project in the northern wheatbelt	Blatchford (1928)
1932	First attempt at distinguishing and correlating major artesian aquifers encountered in Perth	Forman (1932)
1942–1944	Numerous bores drilled by the Army for military camps and bases during World War II	Geological Survey File 22/1942
1946–1961	Post-war investigation of groundwater-based water supplies for Geraldton, Port Hedland, Esperance, Exmouth, Wittenoom; advice on groundwater supplies for various pastoral properties and areas in northern wheatbelt	Geological Survey Annual Reports (1946–61)
1947–1956	Bureau of Mineral Resources regional mapping of Canning and Carnarvon Basins and compilation of groundwater data	Guppy et al. (1958); Condon (1977)
1950–1973	Kimberley Cattle Station subsidized drilling program, about 150 bores with an aggregate depth of about 9000 m and 66% success rate drilled to distribute grazing and arrest erosion, particularly in Ord River catchment	
1952	Publication by the Geological Survey of the Perth and Environs Water Resources maps (3) of existing bores and wetlands	Gray et al. (1952)
1954–ongoing	Recommencement of drilling for artesian (confined) groundwater for Perth water supply	O'Hara (1973)
1959–1979	Completion of regional 1:250 000 geological mapping of Western Australia in collaboration with the Bureau of Mineral Resources; establishment of the geological framework for groundwater resources assessment, collection of a large amount of bore and well data for each sheet and brief descriptions of the groundwater resources of varying usefulness	Explanatory notes accompanying maps
1960–1970	About 100 private artesian bores drilled for irrigation in the Swan Valley	Allen (1981b)
1961	Reorganization of the Geological Survey and formation of the Hydrogeology and Engineering Geology Division, following ministerial approval in 1957	Geological Survey Annual Reports (1957, 1961)
1961–ongoing	Commencement of systematic assessment of confined groundwater resources in the Perth Basin, commencing with the Byford Line near Perth	Berliat (1963)
1962	Commencement of assessment of unconfined groundwater resources in Perth region	Allen (1976)
1963	First review of Australia's groundwater resources	MacKay (1963), AWRC (1965)
1964–1987	Commonwealth–State National Water Resources Assessment Program; numerous exploratory drilling projects in Western Australia	WAWRC (1989)
1964–1987	Upgrading and expansion of numerous groundwater-based town water supplies including Geraldton and Port Hedland by Public Works Department in cooperation with Geological Survey	
1964	First (international) hydrogeological consultants work in State to establish groundwater-based water supplies for Northwest Cape USN communication facility	
1964–1988	First major deliberate disposal of acid, iron-rich industrial effluent into an unconfined aquifer (Australind). Monitored and studied intensively since 1974, by the Geological Survey and others	Bestow (1981)
1964–1987	Iron-ore boom and establishment of groundwater-based water supplies for Goldsworthy, Shay Gap, Tom Price, Paraburdoo, and Newman by Australian-based hydrogeological consultants	
1966	Major groundwater-based water supply and pipeline developed at Allanooka for Geraldton town water supply	
1966–1971	Nickel boom large-scale exploration for groundwater resources in Eastern Goldfields by consultants for mining companies	

## Appendix 1 (continued)

<i>Year(s)</i>	<i>Event</i>	<i>Reference</i>
1967–ongoing	Hydrogeological consultants establish and operate in Western Australia	
1969–1970	Large-scale drought relief drilling program undertaken by the Geological Survey on behalf of the Government to locate groundwater supplies in the eastern and northern wheatbelt	Lord (1970, 1971)
1970	Establishment of pioneering, inland, groundwater-based irrigation scheme at Wiluna, by J. Parr	
1971	Commencement of large-scale use of unconfined groundwater for Perth water supply (Mirrabooka Scheme)	O'Hara (1973)
1971–1985	Geological Survey second hydrogeologist and provides support facilities to the Metropolitan Water Authority to assess and advise on groundwater in Perth region	
1972	First investigation in Western Australia of leachate from a landfill site by the Geological Survey for the Metropolitan Water Authority at Hertha Road, Stirling	Bestow (1977)
1972–ongoing	Commencement of studies of effects of bauxite mining on groundwater regimes in the Darling Range by the Geological Survey and others	Bestow (1976)
1972–1987	Studies of effects of logging for wood chipping on groundwater recharge and salinity by the Geological Survey and others	Martin (1987)
1972–ongoing	First large-scale groundwater remediation of groundwater contamination by Alcoa at Kwinana	
1972–ongoing	From beginnings in the mid 1960s by CSIRO, acceleration of studies of land and stream salination by CSIRO, Water Authority, Geological Survey and Department of Agriculture	
1973–1985	Construction of over 80 deep bores (artesian monitoring bores) to define and monitor Perth's artesian groundwater resources by the Metropolitan Water Authority under direction of the Geological Survey	Allen (1981a)
1973	Major groundwater-based water supply and pipeline developed on De Grey River for Port Hedland town water supply	Davidson (1973)
1975	Geological Survey updated estimates of Western Australia's groundwater resources in national 'Review of Australia's Water Resources 1975'	AWRC (1976)
1977–1978	Drought and water restrictions in Perth leading to drilling of about 30 000 private bores	Farrell (1981)
1977	First detailed investigation of a wetland in Western Australia by the Geological Survey for the Metropolitan Water Authority	Allen (1980)
1980–ongoing	Commencement of gold boom and in Eastern Goldfields groundwater exploration by consultants; extensive use made of saline groundwater resources for mining activities	
1980–1981	Drought relief drilling program in part of wheatbelt, under direction of Geological Survey	
1981	Commencement of trial hydrogeological mapping by the Geological Survey	
1981	Construction of Karratha–Perth natural gas pipeline and extensive use of groundwater (located by consultants) during construction phase	
1982	A review of Western Australia's geothermal energy potential	Bestow (1982)
1982	Commencement of first large-scale artificial groundwater recharge from Ophthalmia Dam at Newman	Clark and Kneeshaw (1983)
1982–1987	Perth Urban Water Balance Study undertaken for Metropolitan Water Authority with major hydrogeological input by the Geological Survey	Cargeeg et al. (1987)

## Appendix 1 (continued)

<i>Year(s)</i>	<i>Event</i>	<i>Reference</i>
1983	First major conjunctive use water supply scheme in Pilbara for Karratha–Dampier–Wickham, based on groundwater from Millstream and the Harding Dam	
1983	Establishment of Western Australian Branch of International Association of Hydrogeologists under chairmanship of R. Vogwill	
1984	Discovery and announcement of the availability of very large fresh groundwater resources in southern Perth Basin, found during groundwater resources assessment program	
1985	Drought relief drilling program undertaken by Geological Survey in Kimberley	
1985	Merger of elements of Public Works Department and Metropolitan Water Authority to form Water Authority of Western Australia; decision to keep Hydrogeology Section in Geological Survey and to second hydrogeologists to Water Authority	
1985	Review of Australia's water resources with revised estimates of Western Australia's groundwater resources by the Geological Survey	AWRC (1987)
1986	Cessation of National Water Resources Assessment Program but continuation of State funding for groundwater assessment	
1987	Publication of first hydrogeological map of Australia with input from Geological Survey	Lau et al. (1987)
1987	Establishment of Division of Water Resources in CSIRO, providing further groundwater research capability in Western Australia	
1988	Construction of deepest and highest-yielding bore in Western Australia by the Water Authority: bore W257, depth 1108.5 m, yield 8000+m <sup>3</sup> /day, near Wanneroo for Perth water supply	
1988	Publication of first 1:250 000 scale trial hydrogeological map (Perenjori).	McGowan (1988)
1989	Publication of 1:2.5M scale hydrogeological map of Western Australia.	Commander (1989)
1990	State funding for groundwater assessment suspended and Mines Department Drilling Branch closed	
1990	Drought relief drilling program undertaken by Geological Survey in Kimberley	
1990	Reviews of the groundwater resources in the major sedimentary basins in Western Australia, for Australian Water Resources Conference in Perth	AWRC (1990)
1991	Actual and potential sites of point source groundwater contamination identified in the Perth Basin	Hirschberg (1993)
1992	Preparation by the Geological Survey of a review of the major groundwater resources in Western Australia for the Kimberley Water Resources Development Office	Allen et al. (1992)
1993	First map showing vulnerability of groundwater to contamination in the Perth Basin	Appleyard (1993)
1993	First new-generation hydrogeological map produced using computer-aided techniques enabling easy updating, transference of data in digital format and production of maps at any desired scale, to assist National Landcare program	Laws et al. (1993)
1993	Re-instatement of groundwater assessment program as an initiative of the State government	
1993	Commencement of input into a computer database (AQWA base) of over 100 000 groundwater bore and well records held by the Geological Survey, funded by the National Landcare Program	
1994	Parliamentary Select Committee reports on Metropolitan Development and groundwater supplies recommending protection	Board (1994)

## Appendix 1 (continued)

<i>Year(s)</i>	<i>Event</i>	<i>Reference</i>
1995	Establishment of Centre for Groundwater Studies as a partnership between CSIRO Division of Water Resources, Geological Survey, University of Western Australia, Water Authority of Western Australia, and others	
1994	Publication of a major review and compilation on Perth's groundwater resources	Davidson (1995)
December 1995	Transfer of Hydrogeology Section of GSWA to Water and Rivers Commission	