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A History of Hydrogeology in Australia from Pre-European to the 21st Century

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Abstract: Australia is the last continent to be settled by Europeans. Previously the land was occupied by indigenous people for more than 40 0000 years that survived by using groundwater during dry conditions.

The newcomers brought skills and European style development, which in the process destroyed the natural environment. The spreading pastoralists initially dug wells for stock water, and then in 1878 the first artesian bore was drilled, beginning a nationwide surge of drilling for groundwater.

Australian States, who have primary responsibility for water, have periodically pooled their information and understanding together with the Federal government. This cooperation began with a series of conferences from 1912-1928, followed by the Australian Water Resources Council in place from 1962-1985. By this time the States and Commonwealth had each appointed small units of hydrogeologists, often in Geological Surveys. Whilst this phase was funded to explore and investigate new resources it also revealed that a number of groundwater systems were stressed; that there were many incidents of groundwater pollution and that groundwater behaviour played a critical role in the growing environmental problem of Stalinization. Since 1992, water management has been overseen by the Council of Australian Governments. The Council seeks to achieve efficiency and ensure that there is relatively uniform groundwater management as well as sustainability polices in all State and Territories.

Key words: history, Australia, groundwater resources, environment

1. Introduction

This paper traces hydrogeology in Australia from its indigenous beginning through the cultural change brought by British colonisation as well as the development of States and Territories and their federation into what is known as Australia. Recounted are the key scientific, legislative, social and economic factors that have shaped the understanding and development of groundwater and the related environment.

Throughout this time there has been a multitude of government agencies concerned with groundwater; each with its own priorities, skills base and culture. Some agencies published widely and others limited their writing to internal reports. In researching the history of hydrogeology of Australia I have searched what is readily accessible as publications or quasi-publications.

The methodology used is based on my own experience over nearly 60 years, the proceedings of national groundwater conferences, contributions to groundwater schools, groundwater maps, national guidelines, interstate agreements, policy and strategy documents, and relevant legislation by the various Australian jurisdictions. Noting that much of the groundwater investigations and development took place under the States and Territories charged with the responsibility for water under the Australian Constitution.

Given that Australia is the driest continent and infrequent availability of surface water over much of its

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area, indigenous people, settlers and government have seen groundwater as an important resource.

2. Aboriginal Survival Tied to Water

The Australian aborigines have lived in Australia for more than 40 000 years, based on the stratigraphical and archaeological studies at Lake Mungo, NSW [1]. They colonized Australia during the last glacial when sea levels were more than 65m below present sea levels and the climate was even drier than today. Nonetheless they would still have had to cross open seas from the north by water craft. Further with the invasion by Europeans in the late 18th century their traditional way of life had declined progressively across Australia and had disappeared nationwide by the 1980s. Indeed, in 1984 the last group of aborigines living the traditional hunter gatherer life, the Bindibu people of the Great Sandy Desert (Western Australia), were brought into settlement.

We are dependent mainly on earlier written observations by non-indigenous people about groundwater use by aborigines; we can surmise that for their survival over this long period of occupation in Australia, they would cling to streams and lakes where possible, but when these dried would have resorted to using groundwater. The groundwater features used were of two types: springs and shallow dug wells. The springs could be diffuse or as mound springs. The mound springs are characteristic of the western discharge zone of the Great Artesian Basin.

They have the appearance of mounds, created by precipitation of layered calcium carbonate from the discharging groundwater combined with dust and sand. Within a number of mounds springs there is evidence of aboriginal occupation up 30 000 years BP, as at Cuddie Springs [2]. Dug wells were used in arid parts of Australia. They were either in unconsolidated sediments alongside indurated, impermeable rock; or in inter dune swales [3] or in dry creek beds [4]. Walking tracks linked these sources of water. Bayly (1999) [5] records that knowledge of the type

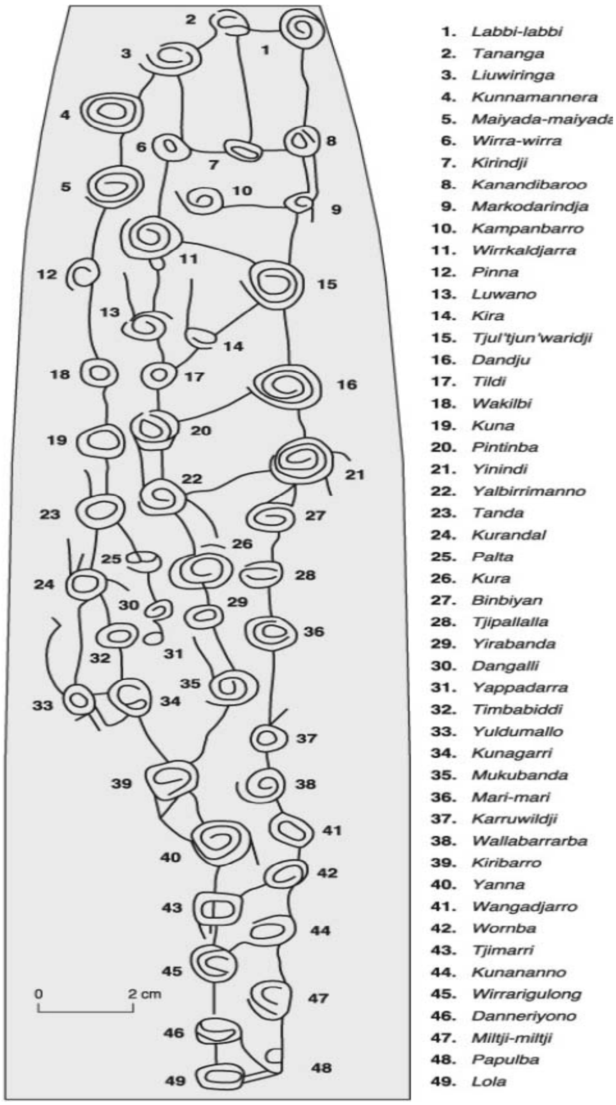


Fig. 1 An example of Australia's first hydrogeological maps. Stylized water sources in Great Sandy Desert (Western Australia), Bindibu Tribe (after Bayly, 1999 [5]).

and location of water sources was passed on through oral instruction and the use of stylized maps. The water sources were decorated as spirals on portable articles such as shields, woomeras and possum cloaks. The wave of British colonists, as they spread out across Australia, often utilized the same water sources that the aborigines were using. With much higher consumption of water because of the introduction of cattle, sheep and horses, and later rabbits and camels, the existing shallow wells and springs were often fouled in the process rendering the water unsuitable for drinking. This often caused conflict. Christian missions sometimes followed, invariably located at traditional sources of water

Later there was deepening of wells and damming of streams by the new settlers. In other words there was a change from a hunter-gatherer culture of the indigenous people to an agricultural and mining culture of the non-indigenous newcomers. In the very dry areas such as the Simpson Desert the aborigines were dependent on groundwater from native wells. Hercus (1985) [6], based on field investigation, past records and interviews, states that there were more than 9 native wells used by the Wangkangura people who dug narrow shafts up to 7 m deep, however with the 20th century departure of the aborigines these native wells fell into disrepair and are now silted over.

3. Arrival of Foreigners: Europeans, Chinese and Makassans

The first groundwater development by Europeans may have been by the Dutch crew of Duyfken, captained by William Janszoon, who made landfall at Mapoon, Cape York, Queensland, in 1606. From the oral history from aborigines the ship crew dug a well [7].

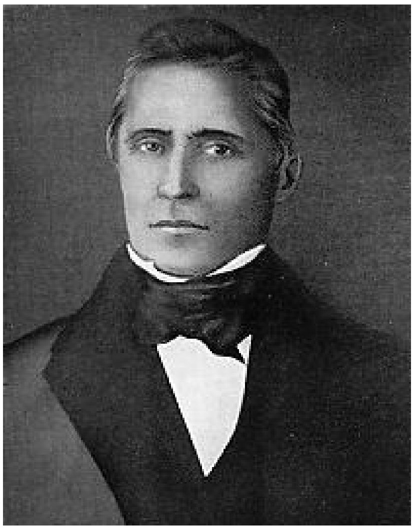
But the real and continuing start to groundwater development and hydrogeology began with British establishment of the Penal Colony in 1788 where Sydney is today, sited after earlier coastal exploration and surveying by Lieutenant James Cook, indeed Cook took water from a native well at Kurnell to the south of Sydney. In 1823 the New South Wales Act was passed by the British Parliament and a level of autonomous government was set up within the colony. The colony originally included the areas that later split off later as Queensland, Victoria, Tasmania and South Australia.

This settlement happened at a time when there were great advances in Europe in science and technology, amid the desire to spread the British Empire and develop new colonies. The rapid spread of agriculture and later mining by the British led to progressive extermination of the aboriginal culture and their hunter-gatherer way of life.

Settlers used surface water preferentially, often by occupying the stream valleys. The new settlers sought the aboriginal knowledge of the location of waterholes and where this was not forthcoming used coercion and threats. The newcomers were in competition with aborigines for water and appropriated land and water for their economic pursuits of new towns, agriculture and mining. In some cases this issue was resolved by fighting resulting in death.

Where perennial streams were absent the new settlers resorted to digging wells. Some settlers used the mystical guide of water diviners in the choice of sites for digging wells, but officially geologists were sought for their advice on groundwater occurrence. At an early stage, three experienced geologists made great pioneering contributions to Australian Geology: the Polish Count de Strzelecki who arrived in Sydney in 1839 and two British geologists: Rev W B Clarke who arrived in Sydney in 1839 [8] and A.R.C. Selwyn who arrived in Melbourne in 1852. All three concentrated on geologic mapping, and the search for earth resources of gold and coal. Clarke, who had graduated from Cambridge University, had been inspired by Sedgwick and had done geologic mapping and collected data on water wells in Suffolk, UK [9]. Selwyn had worked for the Geological Survey of Britain when Murchison was the Director, and became the first Director of the Victorian Geological Survey in 1856. Both Clarke and Selwyn undertook large mapping programs in Australia and made important discoveries of gold and coal. Their geologic expertise on groundwater occurrence was utilised by their respective colonial governments: Clarke was made Chairman of the Artesian Well Board in 1850 with the objective of finding groundwater for Sydney, and in 1857 Selwyn reported to the Victorian Parliament on the prospects of obtaining groundwater in that colony [10].

Rev W. B. Clarke



Sir P. E. de Strzelecki

Sir A. R. C. Selwyn

Fig. 2 Three outstanding pioneering geologists of the 19th century.

Gold was discovered in 1851 by Hargraves near Bathurst (NSW) and then shortly after in Victoria. This immediately led to the gold rush to Australia by British, Americans and Chinese, which in turn led to the establishment of the Geological Surveys and mining administration in New South Wales and Victoria. In other States, the appointment of a geological surveyor often preceded the establishment of Geological Surveys. The years of establishment of Geological Surveys or equivalent were for Victoria 1856 (just 21 years after the British Geological Survey was founded); Queensland 1868; New South Wales 1875; Tasmania 1883; South Australia 1893; Western Australia 1897 and Australia 1946.

This geological expertise was used sporadically from then on in the search for usable groundwater, whilst settlers were prospecting for groundwater. At the same period in Europe there were advances in the theory of groundwater flow. In 1856 Darcy laid the foundation of groundwater hydrodynamics in an empirical law based on laboratory experiments, include in a report [11] on the public water supply system in Dijon, France. Succeeded by extension to this work by Dupuit, Forscheimer, Thiem and many others; but there is little evidence of these advances bring accommodated in Australia until the 20th century when in 1957 Phillips [12] showed that Darcys Law could be derived from Navier-Stokes Equation where the ineria terms were negligible..

4. History of Colonial, State and Federal Legislation

For this thirsty continent of Australia, water, whether surface water or groundwater, has been an important geopolitical factor in its development. The trail of water legislation and formal agreements by the States, Territories and the Commonwealth are an official documented expression of the history of that development and associated challenges.

At an early stage of settlement British common law, or riparian rights, applied for both surface water and groundwater, but this soon changed. This change began in the dry north west of Victoria, the first State to apply irrigation, by introducing the Victorian Irrigation Act 1886. Under this Act there was a shift from riparian right to water to a right to reticulated water under a centralized administration. This philosophy was also discussed in 1891 at the Australasian Federal Conference. This was a precursor to the eventual legal system across Australia where groundwater became State property with ownership vested in the "Crown" or a public good.

Deakin, the Minister for Mines and Water in Victoria, who was later to become Prime Minister, was also of the view that the Murray R system should be federalized, but this proposition was objected to by the New South Wales delegates. A resolution was reached that would adequately protect the water rights of the States. It took the form of Section 100 of the new Commonwealth Constitution: "The Commonwealth shall not, by any law or regulation of trade or commerce, abridge the right of a State or of the residents therein to the reasonable use of the waters of rivers for conservation or irrigation". Deakin reluctantly supported the clause accepting that water would remain a residual power of the States, in favour of the broader interests of federation. Although these statutory changes were directed at surface water in particular, there was a consequential follow on for groundwater.

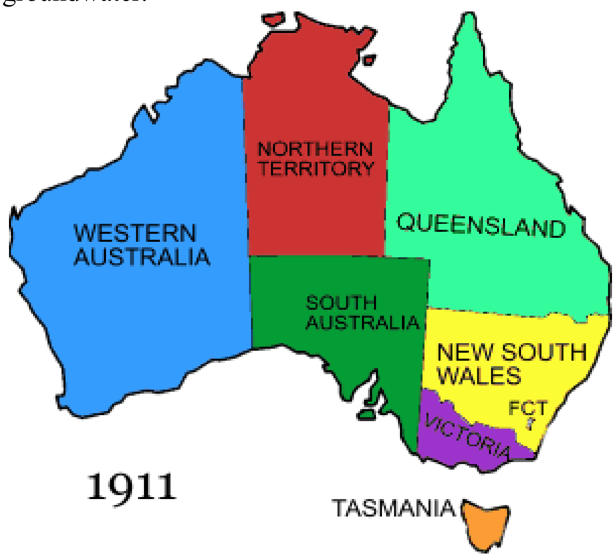


Fig. 3 Australian states and territories.

The early State groundwater legislation was mostly applied to artesian bores of the Great Artesian Basin in Queensland, New South Wales and South Australia. In New South Wales under the Artesian Water Act, 1897 controls also included sub-artesian bores drilled by the government. This was extended to private artesian wells in 1906 and required data from these wells. The Water Act, 1912 included additional controls, with a requirement for a license prior to drilling, but only applying to the western part of the State, later ratified by the 1955 amendment.

In Queensland the Water and Water Conservation and Utilization Act, 1910 included controls for artesian bores. This was further updated under the Water Act, 1926, requiring licenses for bores only in proclaimed areas. While legislation would prove critical for future water management in Queensland, it did not immediately prevent the diminution of artesian supplies throughout the 20th Century, when hundreds of natural springs ceased flowing.

In South Australia the first approach concerning artesian water was through the Pastoral Act 1904, which provided an incentive to drill by offering a remission of rental for 100 square miles around a new artesian bore on a lease.

In Victoria in 1865, following representation from a committee to the colonial parliament about the risk of degradation of the diffuse springs of carbonated mineral water through interference by gold mining the Hepburn Mineral Spring Reserve was created [13]: in effect making groundwater in this reserve and others to follow, a property of the Crown. Later, under the Mines Act, 1958 groundwater was gazetted as a mineral, i.e., property of the Crown, which enabled the Geological Survey within the Mines Department to undertake investigation drilling programs and collection of data on private bores. After a Public Works Enquiry the resulting State Development Report [14] listed a number of recommendations largely adopted in the Groundwater Act, 1970. It was run by two agencies: The Department of Minerals and Energy which included the Geological Survey, responsible for administering permits for drilling of all private bores and investigation programs; and the State Rivers and Water Supply Commission, responsible for licensing high yielding bores. A national review of groundwater legislation by Clark [15] led to changes. In 1989 the passing of the Water Act saw closer integration of surface water and groundwater and consequent restricting affecting hydrogeologists.

There also exists for the Otway and Murray Basins a strip along the border between South Australia and Victoria which is managed jointly by Groundwater (Border Agreement) Act, 1985. This Act was amended substantially in 2006.

In Western Australia the Rights in Water and Irrigation Act, 1914 controlled all artesian bores and sub-artesian bores in proclaimed areas. In 1971 an amendment was put forward requiring a completion report on all sub artesian bores, but was defeated. In the Northern Territory controls on water bores in proclaimed areas were added to the Control of Water Act in 1979. In Tasmania data on all water bores was required under the Underground Water Act, 1966.

By 1987 New South Wales and Victoria were still the only States requiring licences for the extraction from all large yielding bores, whereas the other jurisdictions of Queensland, South Australia, Western Australia and Northern Territory and required this for proclaimed areas.

Ultimately management of the groundwater has been the primary focus of legislation now included in holistic Water Acts for all States and Territories

5. Interstate Artesian Water Conferences (1912-1928)

Conceived through cooperative foresight of the States, a series of five interstate artesian water conferences [16] were held over the period 1912-1928 by leading public officers, geologists and engineers. This followed an earlier initiative in 1908 by New South Wales requesting the other States to form a consultative board to address artesian water issues.

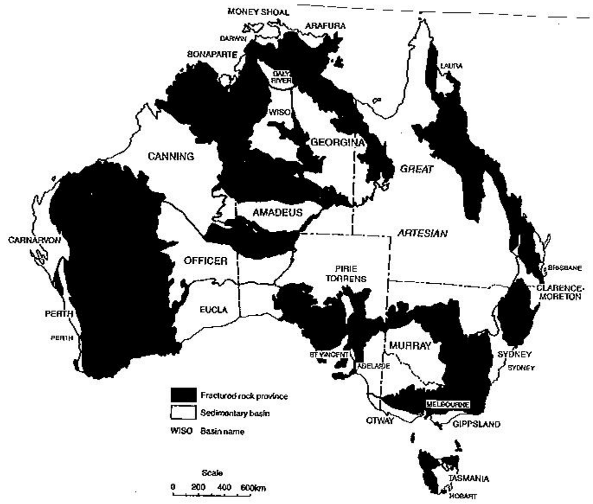


Fig. 4 Australian large groundwater basins.

Initially the other States, with exception of South Australia, were not willing, but by 1911 the other States had agreed.

At the first conference, held in Sydney in 1912, there was review of knowledge on the Great Artesian Basin and some geologic mapping of intake areas. The following nationwide far sighted resolutions were passed "in regard to the advisability of simultaneous action by the different States to provide for:

(1) The delimitation of the artesian areas.

(2) The carrying out of a hydrographical survey, including:

(a) the gauging of the flow of streams within the artesian areas;

(b) the measurement and recording of the flow of all bores.

(3) The adoption of a uniform system of collecting and designating rocks obtained in boring.

(4) The passing of legislation to prevent persons from boring for artesian waters without first obtaining a license, and for the general control by the State of all artesian bores in the public interest.

(5) The adoption, for facilitating comparison, of a common system of recording bore water analysis.

(6) The appointment, for the purposes of preventing the unnecessary multiplication of bores, of a permanent board of competent officials in each State board, without whose recommendation no new bores should be constructed.

(7) The adoption a system of bedding the casing upon an impervious stratum, and sealing it with cement, where possible, with a view to presenting leakage, and thus minimizing the decrease in flow from artesian bores".

For the second Interstate Conference on Artesian Water, held in Queensland in 1914, the members reported back on the progress made in each state; and participated in an enquiry travelling throughout Queensland over 15 days at which the community presented statements. Questions from the conference delegates were about controlling bores, bore construction, wastage of water and measuring pressure head and flow. Many of the pastoralists were of the view that diminution in flow was due to bore performance factors rather than reduction in basin storage. Also they argued against controlling water flow because of the extra cost in bore construction and the risk of generating leakage outside the casing. Despite these criticisms the "Committee took the view that artesian supply is a national asset, every member of the community has an interest in its conservation".

Each State had made progress by exploratory drilling, presenting maps showing bore locations and potentiometric maps for parts of the Great Artesian Basin and Murray Basin and mapping the intake beds in the Great Artesian Basin along the western slopes of the Great Dividing Range. Also there was evidence of diminution of flow from the artesian bores. For example in New South Wales for the period 1903-1908 the average rate of decrease of artesian flow per annum was 5.5%, increasing to 8% for the year 1913/14.

The third meeting was planned to be held in Adelaide in 1916, but was not held until 1921 because of World War 1. Considerable data had been collected over that time and in the case of the Great Artesian Basin, gave further confirmation of the intake areas and that the groundwater was not of plutonic origin.

At the Fourth Conference held in Perth in 1924, it was evident that there was a need to broaden the agenda beyond the Great Artesian Basin to all underground water in Australia. Eventually at the Fifth Conference at Sydney in 1928 it was resolved that all underground water, whether artesian or not was within the scope of the conference. Unfortunately this was the last of this series of Interstate Artesian Water Conferences. The next meeting was planned to be held in Adelaide in 1929, but by then the Great Depression had arrived.

The conferences had been a great stimulus for bore data collection, surveying bore elevation and location, monitoring bore yield and hydraulic head, investigation by government drilling programs, public participation and bringing the groundwater resource more into the political arena. It was a good example of Interstate cooperation, even if the Commonwealth was not represented.

Subsequently at a Brisbane meeting of the Australian Agricultural Council in 1937 the national scope of water conservation and irrigation was endorsed. An interstate conference on these aspects followed in Sydney in 1939, which resolved that the States and Commonwealth participate in a national investigation of underground water and there be a permanent advisory committee. Unfortunately this did not proceed as World War 2 intervened.

The States operated independently without formal collaboration until 1962 when the Australian Water Resources Council was established through the Commonwealth Department of National Development.

6. Australian Water Resources Council (AWRC) (1962-1986)

Established in 1962, the Australian Water Resources Council was set up by the Commonwealth and State Governments as a non-statutory body. Its principal objective was 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 can be carried out on a sound and scientific basis" [17]. Within the AWRC there was the Technical Committee on Underground

Water and the Technical Committee on Surface Water. The Technical Committee on Underground Water was established in 1963 as a central advisory body for government activities related to underground water resources in Australia to assist in evaluating proposals for Commonwealth grants to the States and the provision of adequate legislation for States and Territories, to control the investigation and use of underground water resources, to facilitate a program of hydrogeological study of the Great Artesian Basin; to meet training requirements for staff engaged in underground water investigations and to publish information and methods of storage and retrieval of data in a uniform way [18].

The Technical Committee on Underground Water compiled the groundwater part of the publication entitled, “Review of Australia’s Water Resources, 1963”, which was issued in 1965. The Review treated the occurrence of groundwater under three main rock groups — unconsolidated sediments, porous rocks, and fractured rocks. This was the first map showing the occurrence of groundwater in Australia as a whole. For each rock group the distribution of water qualities was shown in five salinity ranges: 0 to 1,000; 1,000 to 3,000; 3,000 to 7,000; 7,000 to 14,000; and above 14,000 parts per million (ppm). Areas of insufficient quality data were also shown. Tables listed the area in square miles for each salinity class for each rock group.

In 1975 the Groundwater Resources of Australia was published [19], Volume 1 included descriptions of the hydrogeology for each of the 3 rock groups and each State and Territory, with representative values where available of the hydraulic parameters, chemical composition and bore yields. Volume 2 included updated maps at 1: 5 000 000 scale for each of the 3 rock groups, with a map of the principal water resources.

An updated Review of Australia’s Water Resources 1975 [20] included tables with estimates of abstraction for 1974, and quantitative estimates of the potential groundwater resources ($m^3 \times 10^6$/yr), calculated from estimates of recharge and storage, for each rock/aquifer group, salinity class and State or Territory.

In 1964 the Commonwealth passed the States Grants (Water Resources) Act, 1964, enabling Federal Finance assistance to the States. This scheme boosted hydrogeological exploration, investigations, and personnel throughout Australia. Under the scheme exploratory drilling programs were expanded through the State drilling branches and also State Groundwater Groups. Contributions were on the basis of $2 Commonwealth for every $1 spent by the State.

Apart from the collaborative AWRC projects of the hydrogeological map and assessments of 1961 and 1975 there were important studies extending beyond State borders undertaken by the Bureau of Mineral Resources. This applied particularly to the Great Artesian Basin in the work of [21-23], and to the Murray Basin by [24], undertaken at the request of the Groundwater Working Group of the Murray Darling Basin Commission. This built on earlier studies by O'Driscoll (South Australia), Kenny and Williamson (New South Wales) and Lawrence (Victoria).

The two decades when the AWRC was operational were a period of huge advances in knowledge and understanding of the hydrogeology of Australia, assisted by official groundwater drilling by the States and Territories being given a great fillip through the grant arrangement. This period coincided with a burst of international textbooks on groundwater, Tóth’s theory on regional groundwater systems flow emerged, new techniques of quantitative groundwater analysis and complimentary hydrochemical interpretation. Australian hydrogeology was rapidly in step if not surpassing other western countries, facilitated by a number of AWRC sponsored international groundwater conferences where new information was shared, and the AWRC Groundwater Schools with lecturers selected from the groundwater agencies throughout Australia.

During this time there were also investigations by petroleum companies of the sedimentary basins in the search and development of petroleum. This helped in defining their geologic framework and structure both onshore and offshore. In some cases there was interaction between petroleum and groundwater. For example, at Roma in the GAB in 1900 during the drilling of a water bore natural gas blew into the bore at a depth of 1123 m. Alternatively development of the oil fields discovered in the offshore Gippsland Basin had caused a continual drop of 1 m /yr in the potentiometric surface of the lower Tertiary Latrobe Group aquifer onshore, indicating that these fields belong to the one hyrogeologic system [25]. Initially their control and revenue came under Victoria, but following litigation in the High Court in 1975 it was decided that beyond the low water mark the Commonwealth would be responsible. Later legislation following the Premiers Conference of 1978-1979 resulted in the Offshore Constitutional Agreement with the States having responsibility only for the narrow zone extending 3 nautical miles from the shore and the Commonwealth responsible beyond that.

7. Council of Australian Governments (COAG) (1992-Present)

In 1992, a system of managerial Federalism was introduced via the Council of Australian Governments (COAG) with membership of the Prime Minister, six State Premiers and two Chief Ministers of the Territories, to achieve an efficient and effective delivery of services in areas of shared responsibility. This covered a broad and crowded spectrum of government activities including financial relations, health, education, industry, indigenous advancement and resources. For water this brought with it emerging economic and environmental objectives replacing the old development objectives of AWRC. There was a need to achieve sustainable development of the natural resources in an economically efficient and effective manner by competition. Also the water economics of groundwater and surface water were becoming increasingly more consistent.

By 1994, a national framework for groundwater management, facilitated through the National Water Initiative and the National Groundwater Committee, was released. Preparatory documentation for the Framework recognized the importance of groundwater in Australia's natural resource base as well as the need for the "industry as a whole to pay its way". Issues such as efficient and sustainable use of water resources, full cost recovery and provision of adequate water for the environment were seen as areas of reform necessary to assist Australia's competitive position. Accordingly the Framework had the following objectives:

- Allocation of water to the environment and the need for balance between environmental and developmental concerns;
- Adoption of an integrated catchment management approach to water resource management;
- Pricing reform, including full cost recovery, the removal of cross subsidies, and provision for asset maintenance and refurbishment;
- Adoption of tradeable water entitlements;
- Clarification and consistency of property rights to water;
- Institutional and organizational reforms;
- Structural adjustment consequences and social impact of reform, and
- Community consultation and education programs.

This Framework generated consequential legislative and regulatory and structural changes within the States and Territories

Subsequently the Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ) prepared a paper in response to COAG's request; entitled, Water Allocations and Entitlement — a National Framework for the Implementation of Property Rights in Water. This paper is based on the more comprehensive report prepared jointly by ARMCANZ and the National Landcare Program-1995 "Towards a National Groundwater Management Policy and Practice. Also for indigenous rights this recognition had improved substantially since the passing of the Native Title Act, 1998; the water aspects of which have been accommodated to varying degrees by the States and Territories

In 1996 the COAG Task Force of Water Reform published a paper titled, "Allocation and the use of groundwater: A National Framework for Improved Groundwater Management in Australia". Among the recommendations were:

- Groundwater management policies should employ the principles of sustainable development
- Groundwater and surface water management should be better integrated
- States should develop groundwater management plans

The National Water Initiative in 2004 provided guidelines on the development of the Water Management Plans. These management plans sought to avoid over development and cater for the needs of the environment. The Australian Government introduced an agency, the National Water Commission, which functioned between 2004 and 2015 and was responsible for the implementation of water reform under the National Water Initiative.

There is a suite of State legislation which accommodates provisions for Management Plans.

8. The Quest for Groundwater: A Brief History of Selected Major Aquifer Systems and Groundwater Basins

Further national wide publications are as Refs. [26-35].

8.1 Deep Leads

The deep leads refer to buried fluvial sands and gravels of Tertiary age which now act as confined aquifers, but were deposited from ancient inland flowing drainage systems of the Great Dividing Range

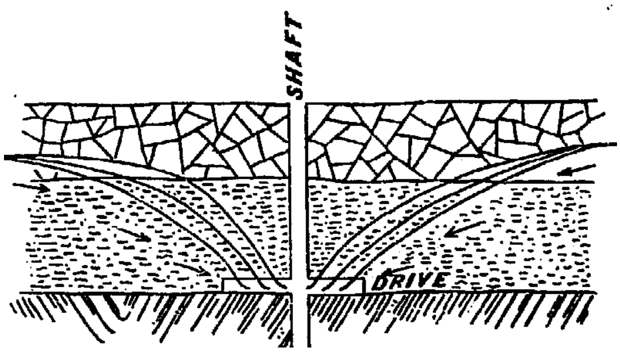


Fig. 5 Pumping from deep lead mines showing flowlines and expanding cones of depression (after Hunter, 1909).

of south-eastern Australia. Behind the highland front they are narrow and often auriferous, but beyond the highland front they continue as widening buried fans.

These aquifers have been developed extensively for groundwater irrigation, although their original interest was for placer gold in Hunters monumental work on the deep leads of Victoria [36], based on lines of exploratory bores and hundreds of gold mines from the 19th century, developed cross sections and a series of coloured geological maps which show the actual and inferred positions of the deep leads in Victoria. He also described the dewatering method designed to combat the groundwater hazard to mining: a shaft was sunk into the bedrock alongside the buried fluvial deposits and a bottom drive driven beneath the deep lead. Bores were then drilled upward into the lead to drain it to the bottom drive. The groundwater was then pumped from the bottom drive to the surface. In terms of the hydraulic impact caused by pumping he observed the effect on the water level was that of an "inverted cone" with the bores closest to the pumped shaft being affected first. Mining engineers were often involved in dewatering activities [37], with the large pumps powered by steam engines in hundreds of gold mines from 1854 onwards.

Hunter recognized that recharge was from rain and typically of the order of 10%. He also made the important comment about potential groundwater resources that, "One hitherto unconsidered phase of the whole deep lead question is the potential value of great bodies of sub-artesian water in all the tertiary plains and valleys of the State".

Since that time the deep lead aquifers associated with the valleys of the Namoi, Lachlan, Murrumbidgee and Murray in New South Wales [35, 39-41]; and Kiewa, Ovens, Goulburn, Campaspe, Loddon and Avoca in Victoria [42-45] have been intensely investigated and developed for irrigation

8.2 Great Artesian Basin

The Great Artesian Basin is a huge groundwater Basin covering 1.7 million square kms or 22% of the Australian land mass, which despite its chemical composition of its groundwater being unsuitable for irrigation contributes much to the economy and liveability of this mostly semi-arid area. The Basin forms a large synclinal structure of Mesozoic sediments, uplifted and exposed along its eastern margin, leaving the overall Basin tilted southwest. The basin sequence reaches a maximum thickness of about 3,000 m in the centre.

Several explorers alluded into its existence: Stuart in 1863 [46] stated that the flow from mound springs he found in South Australia might be "from some high ranges to the north-west or a large body of fresh water on elevated grounds"; whilst [47] referred to the loss of water from surface drainage system on the western slopes of the Great Dividing Range in Queensland, and considered that the interior of Australia would "ultimately be proved to be the storage reservoir". In 1878, midway between these two observations a bore drilled at Killara Station, north west of Bourke in New South Wales, encountered artesian water. Each of the three observations was part of the Great Artesian Basin: the mound springs as the discharge features, the losing streams reflecting recharge to The Great Artesian Basin and the artesian bores themselves lie in the through flow zone. The discovery of artesian groundwater combined with drilling equipment led to the search for artesian water throughout Australia.

The expectations of groundwater potential combined with private drilling for the pastoralists was so rapid that by 1884 a Royal Commission was established in New South Wales "for searching for and developing the underground resources supposed to exist in the interior of the Colony". Whilst in Queensland, following the drought and advice from R Logan Jack, the government geologist, and J B Henderson, the hydraulic engineer in the Department of Water supply, a bore was commenced at Thurrulgoonia in 1886 using a Canadian Pole tool rig; completed in 1887 at a depth of 330m, with a small artesian flow. With the discovery of artesian water in that State there was rapid increase in the number of bores there; but by 1893 the two original proponents of this development, in Jack and Henderson [48], were advocating control of artesian wells, including the collection of data and that efforts be made to reduce wastage. But it was not until 1910 that the Water Act was eventually passed to control further development.

By 1894 Jack declared that the Blythesdale Series of conglomerate and sandstone on the western side of the Great Dividing Range was the principal intake unit in Queensland. By 1914 geologists in the Geological Surveys of Queensland and NSW began mapping the intake areas, collecting bore data of lithologic logs, hydraulic head, flows, and samples for chemical analyses [49]. So that potentiometric maps, though not standardized for density, were drawn and with derived flow directions. By 1900 the boundary of the GAB had been defined; but the investigations from now on were handicapped by basin size and isolation [50]. Indeed the need to use private wells for monitoring was contentious with many owners voicing their objection to the Committee at the Interstate Artesian Water Conference 1914.

With development of the groundwater water resource there was a progressive decline in hydraulic head and flow from almost all bores, with some ceasing to flow [51-53]. Initially the rate of decline was high, but lessened over decades to almost zero in some area; interpreted to mean a new steady state had developed there.

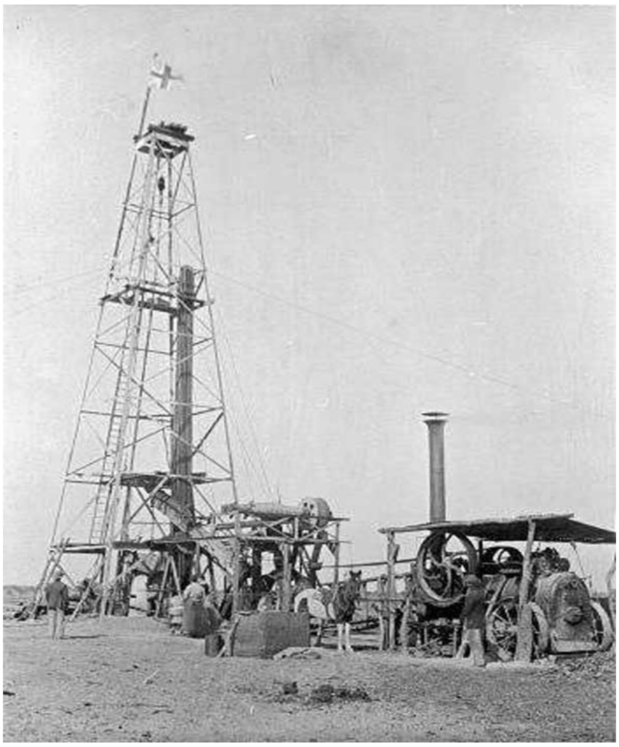


Fig. 6 Artesian bore derrick with steam engine, near Bourke c1902 (Museum Vic collection).

Fig. 7 Killowen artesian bore, near Bourke c1902 (Museum Vic Collection).

Early on it was appreciated that the groundwater was suitable for human consumption and stock, but because it was of sodium bicarbonate composition, it was found to be unsuitable for irrigation.

David [54] provides an understanding of the hydrodynamics referring to flow under steady state conditions being dependent on hydraulic head distribution, but that "elastic deformation of an aquifer is an important factor in producing (bore) flow".

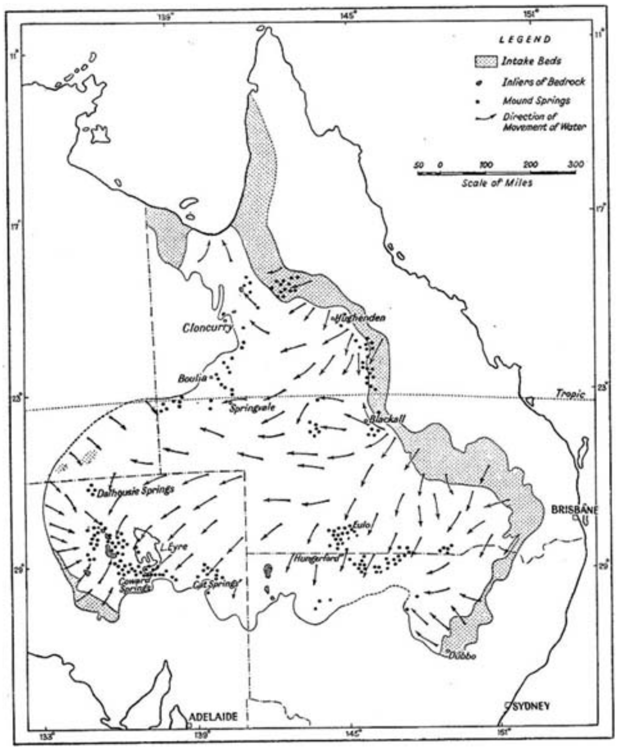


Fig. 8 Groundwater flow pattern of the Great Artesian Basin (after IAWC 1912-28; Ward, 1951).

The monitoring of flowing bores to determine the hydraulic head without closing down the bore and having to wait a long time for recovery was solved by using a modified version of the Sternberg method as described by Hazel [55], whereby through a recovery test for a couple of hours a representative value for the hydraulic head could be calculated.

Habermehl of the Bureau of Mineral Resources undertook a basin wide investigation of the Great Artesian Basin, during the 1980s and 1990s which incorporated earlier studies by the States. Habermehl and Lau [56] published a hydrogeological map of the whole basin at 1: 2 500 000 scale, as well as showing sections, depth to basement, hydrochemistry, flowing bores, non-flowing bores and petroleum bores. There have been surges of hydrogeological investigation as documented by Habermehl.

The BMR began regional transient modelling of the Great Artesian Basin in 1975 with the GABSIM model [57], followed by the GABHYD model [58] more recently transient models: GABFLOW [59] and GABBran [60]. A large number of smaller models have been developed related to the coal seam gas, environmental studies, mining projects and stream — groundwater interaction.

Apart from the groundwater development for the pastoral industry, there has also been significant development related to mining. Most important is the discovery of an ore body of copper and uranium in northern South Australia outside the GAB where the Olympic Dam mine was established shortly after. Water for that mine is extracted from well fields in the discharge area of the GAB near the southern end of L Eyre and transported via a 200 km pipeline to the mine. This extraction has caused some depletion in flow of the neighbouring mound springs [61, 62].

8.3 Murray Basin

There was a stimulus for drilling for groundwater in northwest Victoria following the discovery of artesian water in the Great Artesian Basin. There was scientific speculation about the occurrence of groundwater in what is now know as the Murray Basin. Murray, a Government Geologist, was of the view that there was a strong possibility that good quality groundwater would be found in northwest Victoria, flowing in a south westerly direction from the Great Artesian Basin [63]. Later the NSW Geological Survey demonstrated that an impermeable bedrock barrier between Broken Hill and Cobar isolated this water from the north from what was to be known as the Murray Basin.

Subsequently between 1886 and 1892, two N-S lines of exploratory bores were drilled under contract, one between Nhill and Milmed in the Big Desert and the other between Corack to the eastern side of L Tyrrell (Don Jon). But only a limited amount of data was collected and no water analysed [64], [65]. In this way we had the beginning of the groundwater investigations of the entire sedimentary pile to bedrock. The Victorian Department of Water Supply in 1890 concluded that the water there was sub-artesian.

Kenyon [66] undertook a large deep exploratory drilling program of the Mallee country of NW Victoria, supported by paleontological analysis by Chapman [67], indicated where the boundary was between the fresh and saline groundwater. This helped greatly in planning a conjunctive water supply there. A large channel system of stock and domestic water delivery followed for the area underlain by saline groundwater to the east, leaving the area to the west dependent on fresh groundwater for their permanent supply.

For New South Wales there were two early groundwater reports by the Geological Survey: one west of the Darling R Kenny [68] and the other east of the Darling R Mulholland [70]; for South Australian reports [69-71] and for western Victoria [72]. These reports included inventories of bore data, water quality data, geologic cross sections, potentimetric maps and some new official drilling results. Some insight into background and foresight of these men can be given by glimpsing at the brief portrait of Claus Gloe. A versatile geologist; graduated in geology at the University of Western Australia in 1938 and began working on petroleum geology in Papua New Guinea. WW2 intervened and he returned to Australia. Later he joined the Victorian State Rivers and Water Supply Commission working as a geologist investigating big dam projects and groundwater. He compiled an "underground water resources of the Victorian part of the western Murray Basin and gained an MSc for this work at the University of Melbourne in 1947, one of the earliest to gain a post-graduate degree in hydrogeology in Australia. Later he joined the Geology Branch in the State Electricity Commission which developed brown coal by open cut where he had to deal with a number of dewatering issues.

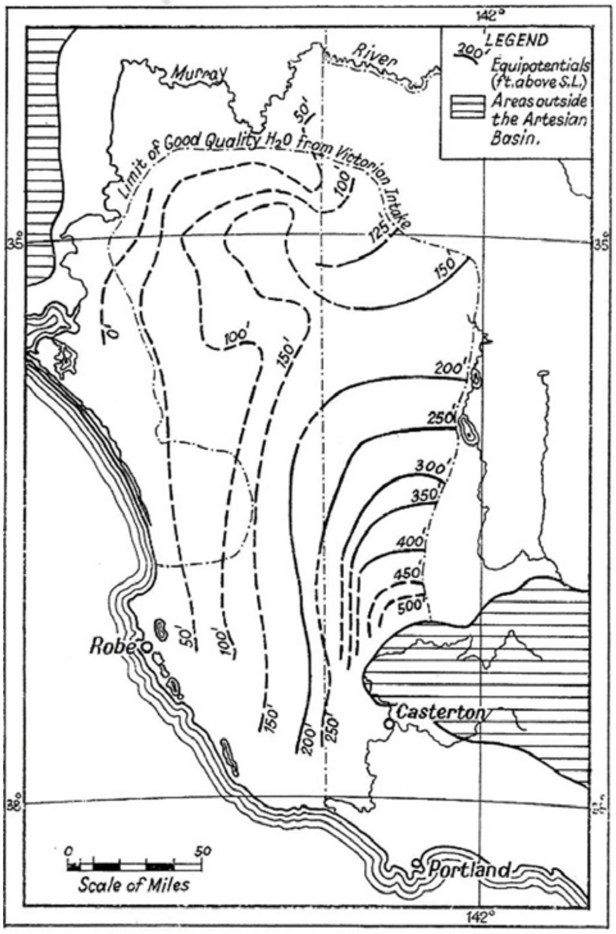


Fig. 9 Isopotentials of the south western Murray Basin (after IAWC, 1914; Ward, 1951).

O'Driscoll [74] produced a major hydrogeological study for the South Australian portion of the Murray Basin based on the available data from over 10 000 bores. This included a rigorous structural and stratigraphic framework supported by the micropalaeontology of Ludbrook [75], hydraulic gradients, calculations of groundwater velocity, hydrochemistry, and risks of pollution. A similar report by Lawrence [44] with emphasis on the Victorian portion of the Murray Basin used all available bore data, the results of numerous pumping tests, placed in the context of the regional groundwater flow systems theory proposed by Tóth based on his work in Canada. Computer applications for contouring hydrochemical parameters as well as simulation of steady state flow of 2D sections, mapping of groundwater discharge features and hydrochemical parameters relative to the conservative chloride ion,

Further regional reports followed with [45] [42] and the integrating report of Brown and Stephenson [24] which made extraordinary advances in geological interpretation and the impact of groundwater on the environment, particularly in terms of salinity.

A reshaped Federal/State body replacing the River Murray Commission by the Murray Darling Basin Commission overseen by ministerial council (MDBMC) representing the States of South Australia, NSW, Victoria and Queensland and the Commonwealth. It took an holistic view. Soon it directed a the hydrogeological map at 1: 1 000 000 scale of the Murray Basin be compiled [76] and shortly afterwards the more detailed 1: 250 000 map hydrogeological maps series coordinated by Evans of the Bureau of Mineral Resources. A strategy for the Basin was developed which recognized saline groundwater discharge to the Murray R and measures to control this.

The Murray Darling Basin Commission introduced a cap on surface water diversions in 1997 to protect the health of the rivers and environment; this also presented a challenge for groundwater resource management [77] as landowners looked for an alternative. Landowners responded by increasing groundwater extraction and in 2001/2 there was a dramatic increase, particularly in NSW. This increase in groundwater extraction in turn caused concern about exceeding the sustainable yield and where effective connectivity existed with streams, reducing their flow. There are now pressures to better integrate management of groundwater and surface water.

8.4 Perth Basin

The Perth Basin is a 1000 km long and narrow coastal basin located along the western coast of Western Australia, bounded on the eastern side by the Darling Fault. Groundwater extracted from the basin is a major source of water for Perth and a number of other towns in south-western Western Australia.

The presence of groundwater in this basin was found at an early stage. With the founding of the Swan River Colony in 1829 settlers used water from shallow wells and springs as well as lakes and small streams. The first artesian bores sunk in Australia were in 1871 at Kelmscott, near Perth, under the instruction of the Government geologist, H Y L Brown. Later Forman [78] of the Geological Survey Western Australia identified confined aquifer systems of sand and gravel near Perth: the upper two of Tertiary age and the deepest of Lower Cretaceous age. He also indicated that intake for the Perth Basin was directly by infiltration of rainfall and streams flowing from the plateau east of the Darling Fault. Natural groundwater discharge was offshore [54].

The Perth Basin was the focus of exploratory drilling by the Geological Survey of Western Australia from 1962 and accompanied by developmental drilling by the Western Australia Water Authority. In the 1970s the number of bores had increased markedly and by 1980 there were 63 000 bores. By 1990 many Perth households were heavily dependent on groundwater tapped from the unconfined Quaternary sand aquifer and Mesozoic sandstone [79], [80]. Recharge is from rainfall, particularly over water table mounds and discharge is to wetlands which now have high environmental value.

8.5 Mineral Springs

Although there are several occurrences of cold carbonated mineral water found elsewhere in Australia the most important is the Daylesford-Hepburn area of central Victoria where there are over a hundred mineral springs located at the base of the valleys in Ordovician sediments.

John Hepburn, a pioneering pastoralist, is credited as discover of the first mineral springs in c1838. Subsequently more mineral springs were found. By 1851 reef gold was discovered in the Daylesford-Hepburn area, followed by a gold rush and many mines being sunk. Some mines dried nearby mineral springs: Dewatering of Frenchman's Mine being caused the Hepburn minerals springs to stop flowing resulting in the State Government closing the mine following public protests [81]. The Mineral Spring Act, 1912 enabled Mineral Spring Reserves to be gazetted and protected. A Committee was formed to manage the springs.

Beginning in late 1960s to 1994 there was a series of investigations [82], [83], [84]. Pumping tests revealed that the folded and fractured Ordovician where anisotropic; whilst deeper drilling indicated that there were two flow systems: a shallow open one and a deeper regional and closed system, as well as the carbon dioxide being derived from rock water reactions (Shugg, pers com). Subsequently Cartwright et al [85] , based on isotopic evidence, have supported a volcanic origin for the carbon dioxide.

9. New Areas of Hydrogeology Emerge in the 1960s and 1970s

Whilst earlier groundwater investigations were almost exclusively concerned about finding groundwater to use, hydrogeologists were beginning to recognize other groundwater issues and complexities. Humans had carelessly disposed of waste, cleared native vegetation for agriculture, irrigated with excess water, and engineered surface drainage systems. These actions had raised threats of groundwater contamination, triggered Stalinization to streams and land and caused unplanned interaction between surface water and groundwater. Hydrogeologists through their understanding and existing data from observation bore networks, made important evaluations and predictions which led to controls being implemented.

9.1 Pollution

In the 1960s reports of groundwater contamination began to emerge: e.g., Simmonds [86] on groundwater pollution in Queensland and Smart [87] on pollution of the Botany Sand Beds, New South Wales. In recognizing that groundwater pollution was a problem groundwater groups in the States and Territories played an important advisory role. Initially this was usually provided to public health agencies. For example, in Victoria potential sources of pollution such a landfills were the responsibility of the Department of Health under the Health Act, 1958, which then referred to the Groundwater Section of the Victorian Geological Survey for comment. By 1970 the Environment Protection Authority of Victoria had been established. It had broad responsibilities controlling pollution of air, water and land. But there were some hiccups regarding recognition of actual and potential risks of groundwater pollution by the new authority with regard to disposal of liquid industrial waste in "sanitary landfills".

In Canberra an incident drew public attention to the risk of groundwater pollution in a dramatic way. On 10 February 1977 there was an explosion in the basement of the Civic Centre Cinema in which plumbers were working, that resulted in one death. This explosion was caused from the ignition of vapour from petrol floating on the water table. The petrol had leaked from a nearby Service Station [88]. The incident focussed attention on groundwater pollution. Most of the investigations were undertaken by consulting companies for clients concerned about pollution from their activities transgressing into neighbouring properties, design and management of waste disposal sites and clean up of service stations prior to sale. The number of investigations climbed to thousands, with remediation carried out on a much smaller number of sites.

By the early 1970s there was legislation for control and management of groundwater pollution for each jurisdiction through amendments to existing Water Acts and new Environment Protection Acts:

NSW State Pollution Control Commission Act 1970
Water Disposal Act 1971
Q Clean Water Act 1971
SA Water Resources Act 1976
Tas Underground Water Act 1966
Environment Protection Act 1973
Vic Groundwater Act 1969
Environment Protection Act 1970
Catchment and Land Protection Act 1994
WA Environment Protection Act 1971
ACT Control of water Ordinance 1964.

A national inventory of known groundwater pollution incidents and legislation was compiled by Jacobson and Lau [89] at the request of the AWRC Technical Groundwater Committee. They listed 106 groundwater contamination incidents. All aquifers impacted were shallow and unconfined to semi-confined. Remedial measures had been undertaken in 23 cases and of these 15 had been effective. In 1991 a report on the status of groundwater contamination was compiled [90] along with guidlines for sampling [91].

In 1995 The National Water Quality Management Strategy was developed by the Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ) and the Australia and New Zealand Environment and Conservation Council (ANZECC). This strategy provided guidelines [92], [93], [94], [95], [96] to help government and communities manage the quality of water resources to meet current and future needs. The review of these guidelines [97] showed that many jurisdictions had used these national guidelines to develop groundwater policy and regulations, i.e., by preferring the command approaches rather than market forces.

For example, in Victoria guidance was provided by two State Environment Protection Policies: "Groundwaters of Victoria", gazetted 1997, under which policy beneficial uses are protected and planning schemes and permits issued under the Planning and Environment Act 1987 [98] and; "Prevention and Management of Contaminated Land", gazetted 2002. The Victorian Environment Protection Authority has a number of statutory functions including issuing licences, works approvals, pollution abatement and clean-up notices and the environmental auditing system. Similarly for New South Wales which has powers under the Contaminated Land Management Act 1997. The Environment Protection Authority of NSW has published guidelines for the assessment and management of groundwater contamination, for auditors, sampling and for remediation. Although the authorities in both States have an overall role the actual investigations are undertaken by consultants and the cleanup of contaminated sites is to the satisfaction of licensed auditors.

Also developed, often in conjunction with the Planning Authorities and local government are regulations for the collection and disposal of waste, in a way which would not cause pollution of groundwater. Each State or Territory has a regulated system for landfills for different waste types, such as domestic, industrial and hazardous. The industrial wastes usually require a special facility such as Tullamarine Waste Facility has been for Victoria.

Hazardous wastes in Victoria and NSW continue to be stored away, awaiting treatment or approved method of disposal. The selection of such a disposal site has not been accepted so far by the public. For Victoria in 1981 an intractable waste site was selected in the western suburbs of Melbourne as the decision made by the then Premier of Victoria, but there was considerable opposition. It became an election issue, and there was a change of governing party and this decision was revoked. Another attempt was made in 2007 with a site selected near Mildura. But with considerable opposition from the public in that area the government decided against this site and favoured new technologies to treat the waste.

Other special categories not resolved are nitrate pollution from agricultural practice [99] and disposal of nuclear waste. Although Australia with only one reactor, at Lucas Heights, generates only a small amount of radioactive waste the Commonwealth Government has made a number of attempts to choose a site locally for nuclear waste disposal, but opposition by the States or the public have thwarted these attempts. Indeed Western Australia has specific legislation to prevent a nuclear storage facility in that State.

9.2 Salinization

The phenomena of land and streams becoming more saline through a process dependent on changed groundwater behaviour, is referred to as salinization. It is a serious environmental problem throughout Australia. The first observations of salinization were recorded in western Victoria by George Robinson in 1853 and in south-western Western Australia by Wood [100]. These were cases of dryland salinity caused by the first tree clearing, but later it was salinization caused by irrigation that sparked political attention.

In the eastern States a major cause of salinization was the spread of irrigation water to arid and semi-arid land, pumped from the Murray R and its tributaries. Ultimately through increased infiltration the water table rose. As a consequence in the depressions where the water table was shallow, salts were concentrated in the soil by evaporation. Similarly the water table rose beneath irrigation areas caused salting in nearby depressions and developed regional water table mounds that ultimately pushed saline groundwater into adjoining streams.

This irrigation began through the initiative of private irrigators: by the Chaffey brothers at Mildura, alongside the Murray R in 1886 and by McCaughey, alongside the Murrumbidgee R at Yanco in 1900. But this private irrigation development was soon changed to State ownership of surface water and irrigation infrastructure to the farm. Each State established a rural water authority to supply and administer water for irrigation. There were interstate disputes about water use and drainage, but by 1915 an agreement was signed by the New South Wales, South Australia, Victoria, Queensland) and the Commonwealth, leading to the establishment of the River Murray Commission in 1917 to share water between the States. With growing concern about of the salinity of the Murray R two major reports were commissioned by the River Murray

Commission. They were: Gutterridge, Haskins and Davey [101], a comprehensive technical report; and Maunsall and Partners [102], which based on economic analysis, favoured the construction of saline groundwater interceptor schemes between the irrigation districts and the Murray R for its water quality protection. These reports were both good comprehensive technical documents which recognized there was a serious problem for salinity of the Murray R leading to an increase in salinity downstream and over time. This threat was of particular concern to South Australia, located downstream, where the State capital of Adelaide and the industrial town of Whyalla were dependent on the Murray R for a major proportion of their supplies: in 1944 the Morgan to Whyalla pipeline was completed and in 1956 the Mannum to Adelaide pipeline was completed.

For a period much of the investigation on salinization in eastern Australia was taken in Victoria: The Soil Conservation Authority (Vic) had a small team working on dryland salinity beginning in the 1970's [103]. Early significant papers on salinization in the Mallee and catchment in the highlands included those of [104]; [105], [106], [107]. Other hydrogeologists at the Soil Conservation Authority included Day, Ryan and later at the Centre for Land Protection Research, Reid and others

At the same time dryland salinization was recognised as a threat to agriculture in south-western Western Australia [108]. From 1952 onwards the Soil Conservation Authority of Western Australia carried out investigations on salinity. In 1982 the Salinity Research Committee reported to Parliament, an important international seminar on salinity was held, and the Soil and Land Conservation Act 1945 amended, recognising land and water salinity as land degradation. During this period there was technical cooperation on dryland salinity between Western Australia and Victoria.

For Victoria following the Parliamentary Public Works enquiry on salinity control and drainage the Australian Labour Party won office in April 1982 and quickly established an all-party Parliamentary Select Committee on Salinity and a Salinity Bureau headed by G Hunter. After re-election for a second term in 1985 the government formed a Ministerial Task Force on Salinity.

The Salinity Committee of the Victorian Parliament produced a series of reports from 1982 to 1984. One of these reports by Dwyer Leslie [109] included a working paper by Macumber, which emphasised that salinization was a groundwater problem, in which changes by European settlement land use progressively disrupted the previous groundwater equilibrium to cause a rise in the water table and increased hydrostatic pressure in the deeper sediments. In 1988 Victoria published its strategy for managing land and water salinity: Salt action: Joint Action [110].

Up to 1987 the interstate management of the surface water of the Murray drainage system was by River Murray Commission, charged with providing equitable sharing of the water of the Murray Darling system between the States. With jurisdictions more aware of the salinity problem and the environment, in November 1985, 12 ministers representing the Commonwealth and relevant States. They agreed to an ongoing ministerial council, a change from the RMC to the Murray Darling Basin Commission with broader environmental responsibilities for the Murray Darling Basin as a whole. At its inaugural meeting in Sydney in 1988 it was decided to produce a groundwater map of the whole of the Murray Basin at 1: 1 000 000 scale with the Bureau of Mineral Resources as the coordinating agency. Later, following on from the 1:250 000 map of the Bendigo sheet [112] the Murray Darling Basin Commission published a series of 26 1: 250 000 hydrogeological maps covering the Murray Basin in South Australia, New South Wales and Victoria.

For the Murray Darling Basin Commission major steps included:

1989/90: A salinity and drainage strategy produced 113]. Salinity target at Morgan SA is to maintain salinity below 800 uS/cm (480mg/l TDS)m [112].

1995: A Cap imposed on surface water extraction

2004: The National Water Initiative governments agreed on actions to achieve a more cohesive national approach to the way Australia manages, measures, plans, prices, and trades water.

2004: The Living Murray Initiative First Step, to recover 500 GL for the environment.

2007: The *Water Act 2007* commenced on March 2008 and key reforms for water management in Australia began to be implemented.

2008: The *Water Amendment Act 2008* amended the *Water Act 2007* to transfer the functions of the Murray–Darling Basin Commission to the Authority and for arrangements in the Basin Plan to meet critical human water needs.

2012: The Basin Plan eventually became law in November 2012 providing a coordinated approach to water use across the Basin's four States and the Australian Capital Territory. The Plan and its development were contentious with many of the farming communities, particularly in New South Wales, opposed to checks on surface water and groundwater.

An important feature of the Murray Darling Basin management was the disposal of saline water; either from the rising water table, irrigation drainage from lines of protector interceptor bores alongside the Murray R. According to Hostetler and Radke [113] there were 150 saline water disposal basins to which this saline water is diverted. Thus in order to protect agricultural land or river quality from salinization some land, usually in the lower parts of the catchment, had to be "sacrificed" for its disposal. The choice of land to be sacrificed could be difficult. For example, in Victoria it was proposed by the State Rivers and Water Supply Commission, to use the large natural salina of Lake Tyrrell as a disposal basin, but after later being assessed by in Maunsell and Partners to be uneconomic, it was abandoned and another site of the Mineral Reserve Basin, of smaller gypsum playas, requiring a shorter pipeline, was then proposed as a better saline water disposal site. In 1985 the Rural Water Commission (formerly the SRWSC), commenced construction .This was objected to by the local farming community, and court action resulted with the farmers losing the court case in 1986. However shortly after this court decision the Government deferred the Mineral Reserve Scheme indefinitely [115].

For understanding the range of hydrogeologic processes contributing to dryland salinization of land and streams and in choosing effective amelioration measures two national workshops were held in 1998 [116].. Generic hydrogeologic models, shown through 2D vertical slices, were developed as representative of the processes of dryland salinization in Australia. A number of factors were involved, including topography, salt stores, geology, with the overriding and uniting factor the groundwater flow systems following Tóth's classification of local, intermediate and regional flow paths. The local flow systems have shallow depths, and recharge and discharge areas are close together; regional flow systems have deep circulation depths and recharge and discharge areas are separated by considerable distances and they are often overlain by local and intermediate flow systems. The local flow systems have shallow depths, and recharge and discharge areas are close together, and hence salinity control measures are more likely to be effective in a shorter time period than in the case of regional flow systems which have deep circulation depths and recharge and discharge areas are separated by considerable distances [114].

9.3 Groundwater - Surface Water Interaction

Groundwater surface water interaction in streams, lakes, playas and wetlands is dynamic and varies in sGpace and time. In general way this has been known for a long time from either the groundwater view point or the surface water view point, but since 1992 with the water reform of COAG these processes have been a focus of attention.

An early comment by Howitt, a geologist with the Victorian Geological Survey, perhaps known better for his critical review of Chaffey brothers autocratic control of irrigation alongside the Murray R at Mildura, makes the comment on the ephemeral streams of central Australia, "I am inclined to believe these creeks are slowly running underground since the rain" [117] implying groundwater surface water interaction occurs there.

By 1912 at the first Interstate Artesian Water Conference, triggered by decline in flow in the artesian bores of the newly developed Great Artesian Basin, with losing streams in the adjoining Great Dividing Range losing water were included in objectives for future studies. By the time of the second conference in 1914 the geologist, Saint-Smith reported on mapping the porous sandstone Blythesdale formation intercepted by these streams ; whilst Bunning ICAW was designing a network of stream and rain gauges to monitor the losing streams.

For the semi-arid Mallee area of the west central portion of the Murray Basin, there was in effect a regional conjunctive scheme put in place. To the west of the Wimmera R and northward to include Murrayville good quality groundwater was found, outside this area to the east and north the groundwater was saline and unusable. It was eventually decided through the government in the early 1900s that for the area of good quality groundwater it would be entirely dependent of this groundwater resource, but where the groundwater was of poor quality it would be dependent for stock and domestic supplies water be dependent stock and domestic purposes on channelled surface water drawn from the Murray River to the north and the Wimmera R catchment to the south [118].

In the mid 1960s in the Burdekin delta in Queensland artificial recharge scheme commenced. This allowed for conjunctive use of groundwater and surface water. In times of surplus surface water there was artificial recharge through pits, to be stored underground for the use of groundwater users [119].

In another situation groundwater surface water link was obvious, in this case of surface water was developed to the detriment of stream flow: During the drought, (1967/68) the Ovens R, a supplier of water for Wangaratta, had ceased flowing. This was attributed to groundwater extraction for irrigation from a number of excavations along the Ovens R valley, avoiding a charge for water used. With no existing controlling groundwater legislation at that time emergency legislation was passed. The Water (Further Amendment) Act 1967 7590 "authorised the Commission (SRWSC) to control abstraction from excavations and other bodies of water that are replenished by a watercourse"

This drought affecting south eastern Australia also focused attention on stream regimes and recession curve analysis. It was observed at the perennial stream flow was reduced on many stream to the base flow component derived from groundwater discharge.

The surface water data bases of stream flow and EC (as a surrogate of salinity) were being used to better understand catchment behaviour. Gutteridge Haskin and Davey in the review report for the Murray R drainage system [101] calculated this flux of saline groundwater discharge to the river based on mass balance of monitored segments of the lower reaches of the Murray R. By the beginning of the 1970s lines of operating interceptor bores were being installed alongside prone zones of the Murray R to protect the quality of the river water. In some cases for low flood streams located in areas where the groundwater was saline, such as the Wimmera R, there is incomplete mixing of saline groundwater discharge and the fresh surface water, with saline groundwater discharge lying at the base of deeper sections only to be removed at times of high flow.

By 1975 modelling of conjunctively used water resource systems in alluvial valleys, using the Callide R valley as the case study, was a good pioneering effort with recommendations on future area to be developed [120].

By 1970 the environmental movement was in full swing with numerous environment protests. It was dawning upon the better informed public that much of the developed zones alongside streams and wetlands had come at a cost environmentally. In particular the shrinkage of wetlands meant they could no longer act as sanctuaries where ecosystems could thrive in time of drought. The close link of groundwater with ecosystem type and distribution was used to map groundwater discharge features In the Mallee area of the botanical indicators there was zonation of vegetation around salinas related to water table depth and salinity [44].

For the Perth Urban area there are 80 lakes and wetlands where the water table outcrops, acting as groundwater through flow systems which have high environmental value. The same shallow aquifers that fed these lakes and wetlands is also tapped by tens of thousands of bores There was, with public concern about their preservation, including from risk of them drying from nearby groundwater abstraction. This situation prompted a comprehensive water balance study [79].

At the political level in 1992 there was a somewhat abrupt and coordinated change to water management in Australia, which optimizes economic and environmental outcomes. The creation of COAG in 1992 led in 1994 to agreed water reform and environmental recognition at the national level and for the States and Territories. This was succeeded by other initiatives to reinforce the 1994 water reform agenda.

This included that groundwater and surface water be integrated as the one water resource where they are connected, [121] [122] and that the environment be accommodated by national principles for the provision of water for ecosystems designed "to sustain and here necessary restore ecological processes and biodiversity of water dependent ecosystems" by means of environmental water allocations.

Achievement along these lines has not been easy, particularly because the understanding and appropriate data is often not available

In 2012 a workshop looking specifically at connected systems concluded the implementation of conjunctive water system management was patchy to date and drew attention to the risk of double accounting where base flow may considered as groundwater and surface water on the other hand [123].

In 2017 Bureau of Meteorology is currently preparing a national atlas on ecosystems using weather and water data bases and remote sensing e.g. Landsat.

10. Evolution of Tools and Specialities

10.1 Drilling Rigs and Pumps

Early in the 19th Century, wells were dug by hand and lined with timber or bricks. They penetrated a short distance into the water table; water was extracted by a wind mills, bailer or hand pump. This was a laborious and slow way to tap groundwater and could provide only a tenuous supply where there was natural fluctuation of the water table.

By the late 19th century, drilling rigs were the favoured means for tapping groundwater; having the advantage of being safer, faster and penetrating deeper. Firstly hand operated rigs were used, and then diamond drill rigs, calyx plants, Canadian pole rigs and percussion rigs. The diamond drilling rigs were mostly used in mineral exploration, but were also used on occasions for drilling water wells. The Canadian pole rig differs from the percussion or cable rig mainly by using wooden rods instead of cable. The percussion rigs at that time used Manila hemp as the cable. The calyx drill rigs, invented in Australia, used a toothed collar bit, with water fed through a swivel and hollow rods. The engines for these rigs were steam powered. Also instead of a derrick being erected for drilling each bore portable rigs became more common. Some rigs combined several methods to cope with different conditions. At this time many of the wells were drilled by private drilling contactors, but the State agencies also started to get their own drilling rigs as well as use contractors.

The petroleum industry was emerging in the USA and with it the development of the mud rotary rigs and geophysical logging of bores by a suite of e-logs including temperature, spontaneous potential and gamma ray logs. This enabled aquifer depths and their groundwater quality to be determined before construction, as well as facilitating stratigraphical correlation between bores. Nonetheless percussion rigs were often used for groundwater investigation as they did not need to run 24 hours a day, and were enabled to water sampling and measurement of d hydraulic head at different depths progressively during drilling. Casing, mainly steel, was used in all wells and the use of stainless steel screens in sand and gravel aquifers was becoming more common in the late 1950s. Later in the 1960s the down-hole hammer rigs enabled rapid drilling of indurated fractured rocks.

A great debt is owed to water well drillers. Often, particularly in the exploratory years they worked in remote areas under rudimentary living conditions, collaborating with hydrogeolgists requiring rock and water sampling programs, special well design and pumping. By way of an insight into the life of a driller during the 1950s and 60s, Sid Goad was one who had returned from army service and sought an independent way of life. He operated a cable tool rig — a Hydromaster and had one assistant. His accommodation was initially in a tent, then later a wooden hut that was dismantled and reassembled between sites, for the latter part of his drilling career he lived in a caravan, moving from site to site. He was known for an incident when one of the Minister's constituents reported he was not working the whole day. A check revealed he was on annual leave.

By the 1970s, there was licensing of the private well drillers in most States and later reciprocal recognition between States. National guidelines for standardizing construction were developed [124].

Extraction of water was simple in the case of the artesian wells of the Great Artesian Basin, but elsewhere wells were invariably sub artesian and required pumping. The original windmills with their reciprocating pumps began to be purchased from North America in the late 1850s. Soon after local blacksmiths and carpenters in rural areas began to manufacture windmills, including Brown at Beeac, Bryan Brothers at Colac, Harrison at Camperdown and Alston at Warrnambool. Although the most famous are the Southern Cross windmills originated from the Griffith mills in Queensland [125]. Later, from the 1950s onward, deep well turbine pumps and electric submersible pumps became common.

10.2 Groundwater Mapping

The first geologic mapping in Australia began by Clarke and Strzelecki in the early 19th century. This continued through the Colonial geological surveys. The first Geological Survey in Australia was the Victorian Geological Survey, begun in 1856, which under the Director of A.W. Selwyn published a map of the whole of Victoria at a scale of 8 miles to 1 inch (1: 506 880) by c1866.Other colonial Geological Surveys were progressively established in the latter part of the 19th Century, with the mapping coverage of the larger States completed in the 20th Century.

Groundwater maps of restricted areas using bore and mine data began to be included in reports by the end of the 19th Century [126], but it was not until 1965 [127] that the groundwater map of Australia as a whole was produced. This map showed subdivision of the rock type: porous (sedimentary basins), unconsolidated (shallow) and fractured rock and classes of salinity of groundwater based on the suitability for drinking, stock and irrigation, as well as areas where there was little or no information. This mapping was improved [19] [128] by a set of maps, one for each of the major aquifer types (shallow unconsolidated, sedimentary basins, fractured rocks and principal aquifers) at 1: 5 000 000 scale. Also State Groundwater Maps soon began to be published in

Queensland [129, 130], Victoria [131] and South Australia [132, 133], Western Australia [134] and NSW [135]. Complimentary the topographic National Mapping and Geologic Mapping Series 1: 100 000 and 1: 250 000 some detailed groundwater maps at these scales began to be published. These included 1: 250 000 Forbes [136], Ballarat [137], and 1: 100 000 Bendigo [111] Western Port [138]. These maps also included cross sections indicating aquifers and groundwater quality. Also produced were hydrogeological maps of large groundwater basins crossing State borders in the Murray Basin [76], and the Great Artesian Basin [56] and for Australia [32]. Hydrogeologic maps up to this time included new sub surface hydrostratigraphy in correlating aquifers and aquitards, whilst map production was transitioning from cartographic techniques to the more efficient CAD and CAM techniques.

There is now through the internet a close interconnection between the data bases, which now include large stores of bore data in GIS systems to allow greater flexibility and access , provided one is familiar with the software, such as by Visualization Victoria [139] were maps can be produced in 3D and 4D.

10.3 Pumping Tests — A Way to Groundwater Hydraulics

Following on from overseas developments in the analysis of pumping tests by Boulton, Jacobs, Thiem, Theis, Hantush, Papadopoulos and Walton, in the late 1950 pumping tests began to run and analysed in Australia by T Chapman, T McMahon, E. O’Driscoll, W Williamson and K Woodyer. This methodology rapidly spread to others in the 1960s through the lectures given at the Australian Groundwater School through lectures by S. Lohman and J. Ferris of the UCGS and C. Hazel and his reference texts [55, 140]. Pumping tests were commonly incorporated in groundwater exploration and investigation drilling programs under the Australian Water Resources Council regime. These tests provided values of the hydraulic parameters of transmissivity, hydraulic conductivity and storage coefficients of aquifers across the nation as well as information on delayed drainage, inter-formational flow and boundary effects, which in turn were used for regional quantitative analyses.

In 1990 the standards for pumping tests For Australia [141] were released.

10.4 Groundwater Modelling

Initially, modelling of groundwater systems took the form of analog models; firstly by the physical Hele Shaw models in 1960s for simulating saline water intrusion in the Westernport Basin (J Carrillo -Rivera, pers com), then by electric analog models [142], which were applied by Thompson [143] to artificial recharge simulations in the Mitchell R valley.

Digital models were then developed overseas in the 1970s and 1980s. Locally, Lawrence [44] adapted the finite difference steady model of Freeze for large sedimentary basins and applied this to the Murray Basin, The BMR developed the GABSIM model and applied this to the Great Artesian Basin Ungemach [57] and Townley rewrote the finite element model of Sa da Costa, Wang and Connor, a numerical finite element model known as AQUIFEM-1. Subsequently this was developed further by Townley and used commercially by the State Rivers and Water Supply Commission of Victoria in the early 1980s.

Kalf and Woolley [144] applied digital modelling of the alluvial aquifer at Wagga Wagga, New South Wales. For the GAB Seidel [58] reported on the efforts in discretization of data on the GAB provided by Habermehl to apply a transient finite difference model, GABHYD. Merrick [145] modelled the highly stressed Lower Namoi aquifer to assist in water management. Other modellers prominent from this time include Henry, Doherty, Johnston, Lockington, Merrick, Middlemiss, Ross, Telfer, Welsh, Werner, R. Williamson, and many others.

Since that time there has been an increase in the number of modellers, a proliferation of software packages with greater ease of input of data and improved output presentation. Models have increased complexity, some including solute transport and surfacewater-groundwater interaction, but MODFLOW packages continue to be the most commonly used.

Concerned about the reliability of the predictions of the modelling and their importance of the management decisions two comprehensive sets of guidelines have been developed: those by the Murray Darling Basin Commission [146] with particular interest for the Murray Darling Basin, and by the National Water Commission [147]. Both guidelines stress the importance of preliminary step of conceptualization

10.5 Geophysics

In the 1960s, especially through the Bureau of Mineral Resources and the NSW Irrigation and Water Supply Commission, seismic refraction and resistivity surveys were carried out in the alluviated highland valleys to determine the location of the deep lead aquifers.

The Bureau of Mineral Resources and the Victorian Geological Survey also undertook e-logging of new mud rotary drilled bores beginning in the 1960s to help determine accurate aquifer depths, groundwater quality and assist in stratigraphic correlation. Much of logging by the Victorian Geological Survey was to assist in the groundwater investigation and development programs of the thick coastal sedimentary basins of the Otway Basin and the Gippsland Basin. The e-logs included spontaneous potential, resistivity long normal and short normal and temperature. Gamma ray logs were run in percussion drilled bores throughout Murray Basin by Geological Survey of Victoria and in the Great Artesian Basin by the Bureau of Mineral Resources. Electromagnetic surveys were run on a regular basis in the 1980s to determine the extent of saliniization in the irrigated areas of NE Victoria. Remote sensing, beginning with Landsat series in the early 1970s has been used in throughout Australia for mapping salinity distribution. From Radar shuttle missions digital elevation models have been developed throughout Australia by CSIRO and Bureau of Mineral Resources since 2009 to assist in defining the topography of basins and bore elevations in remote areas.

10.6 Hydrochemistry

From late in the 19th century the Geological Surveys and Water Agencies were running chemical laboratories with the capacity to analyse waters. The main analytes were Ca, Mg, Na, HCO_3, Cl and SO_4. At that time there was not a uniform way of reporting analyses. South Australia reported CO_3 plus HCO_3 as CO_3. Several different units of concentration were used: eg SA used in grains per gallon, New South Wales used parts per hundred thousand and Victoria used parts per million (ppm). Later, from the 1970s analyses were reported nationally in milligrams per litre (mg/l); electrical conductivity (EC) in micro Siemens per cm and pH were added, NO_3 and K were routinely added later on. For specific field studies the parameters of Eh, alkalinity, pH and EC were measured in the field, and samples filtered and acidified for trace metal analysis.

Until the mid-1960s the chemical analyses were almost exclusively concerned with water quality rather than the genesis of groundwater. This was reflected in the groundwater maps emerging in the 1980s , which distinguished five salinity classes based on their suitability for human consumption, irrigation and various types of stock of < 1000 mg/l TDS, 1000-3000 mg/l TDS, 3000-7000 mg/l TDS, 7000-14000 mg/l TDS and > 14000 mg/l TDS.

Some hydrogeologists extended the use of chemical analysis to relate to the solid phase mineralogy of the aquifer and residence time. Cheboterov [148] of the Geological Survey of South Australia in a classic series of papers, derived from groundwater analyses worldwide, demonstrated that there was an overall evolution of groundwater from $CaHCO_3$ water in recharge areas to NaCl type waters toward the end of flow lines. In the meantime Anderson [149] for surface water used a parameter of oceanic number based on the chloride ion proportion for sea water to indicate the influence of cyclic salts in surface water. This approach was modified for groundwater to ratios of other ions relative to the conservative chloride ion [44, 150-153]. This helped to identify such processes as mineral dissolution, cation exchange, sulphate reduction, concentration by evapotranspiration and evaporite dissolution.

Within Australia two major chemical types of groundwater warrant special mention. They are the NaCl and $NaHCO_3$ types: The NaCl type is widespread throughout Australia. There was earlier controversy about the groundwater in some marine sediments where it was considered that connate water could have been trapped in the low permeability marine sediments in the Murray Basin [44], but it is generally accepted that the NaCl waters in Australia are principally due to concentration by evapotranspiration of cyclic salts carried in by rainfall. Indeed this process is used in intake areas to give estimates of recharge.

NaHCO3 type groundwater characterizes some of the deep sedimentary basins such as the Great Artesian Basin and the coastal Otway Basin. Johns [151, 152] for the Otway Basin concluded that the $NaHCO_3$ groundwater may be the action of carbonic acid on alkali feldspar, hydrolysis of clay minerals with exchangeable sodium, and cation exchange between Ca and Mg in the water and adsorbed sodium in the sediments. Blake [154] for the Otway Basin identified complimentary changes from Ca kaolinite to Na smectite. This process is supported by Herzeg [155] for the Great Artesian Basin who from carbon isotope mass balance also indicated that the addition of CO_2 is released from a fermentation process.

In the 1970s a few laboratories in Australia began analysing environmental isotopes of carbon, hydrogen, and oxygen. This provided additional data compared to the ordinary chemical analyses to help constrain physical processes. Early work was directed at estimating groundwater recharge [156], [157], but later work addressed groundwater discharge; inter-aquifer mixing, groundwater-surfacewater interaction, paleohydrology, and the salinisation process. Also possible was the dating of groundwater by carbon 13, tritium, and chloride 36. This data was incorporated in a number of papers by Allison, Cartwright, Cook, Barnes, Herzeg, Hughes, Ivkovic, Love, Weaver, and many others. This new hydrochemical information was emerging at the same time as numerical modelling and in a number of cases provided cross checking on groundwater flow rates.

Also emerging at this time was the issue of the pollution of groundwater and it was the subject of the first AWRC groundwater conference [158]. Investigation required careful and representative sampling and protocols were developed. Analyses required higher levels of detection and a large range of hydrocarbons and trace metals. Water sampling was critical to obtaining reliable samples for analysis and in 1981 Riha of the Geological Survey of Victoria invented the bladder pump to avoid the introduction of air into the samples.

10.7 Computers and Accessible Bore Data Bases

In the early 1960s the State groundwater data bases were still in the form of paper files, but later on the bore hole data were digitized. For Victoria bores were located originally according to Parishes and allotments, as Parish plans were the only detailed maps there at that time. Automatic processing began with the 80 column punch cards in the first comprehensive groundwater bore database assembled by the Geological Survey of Victoria in the late 1960s . After 1969, a permit to drill groundwater bores was required, and the information captured by the licensing process was added to the database. This included groundwater investigation or observation bores drilled by other government agencies of the State Rivers and Water Supply Commission, the Soil Conservation Authority and the State Electricity

Commission and subsequent equivalents, although these agencies also kept their own bore databases. From the mid 1980s onwards a digital database, compiled from the existing records of all Government bores and private bores, was progressively assembled on a mainframe computer. Organisational changes in 1988 led to the Victorian Groundwater Data Base now at the Rural water Commission, subsequently being named the Groundwater Management System until 2013 when the system migrated to Water Measurement Information System.

At the national level an effort was made to induce some uniformity into multitude of groundwater data bases in Australia by the publication of the standards of interchange of water resources data [159]. This has been a guide to each groundwater agency in the type of data stored in each data base and standardization of terminology, location and elevation. But it was not until 2014 that a national system by the Bureau of Meteorology: National Groundwater Information System based on information stored in each of the State groundwater data bases, with such information as the groundwater levels and groundwater entitlement. Now a nationally consistent groundwater chemistry web based portal to analyze and download groundwater chemistry and environmental isotope data is being developed by the Bureau of Meteorology and Geosciences Australia [160].

11. Education and Training

At an early stage in hydrogeology in Australia geologists and engineers were required to be versatile with hydrogeology just a fraction of their work. Initially they came from Europe, particularly Britain, and with little or no training in hydrogeology they were expected to "learn on the job."By the 1940s the situation had changed little except that personnel were educated in Australia, though still without formal training in hydrogeology. By the 1950s some States had begun to appoint personnel specifically as hydrogeologists though still without any formal training in hydrogeology. With increased groundwater exploration and development by the States in the 1960s, boosted by Federal grants there was a pressing need education in groundwater.

11.1 History of the Australian Groundwater School, Other Short Courses and Universities

The Technical Committee on Underground Water of the AWRC identified education and training in hydrogeology as crucial. The AWRC held the first Groundwater School in Adelaide in 1965. It was of two weeks duration and intended to train groundwater practitioners in the theory and application of techniques to better understand, investigate, assess, develop and manage groundwater resources. The lecturers came mainly from government authorities but also included some from universities and the Commonwealth and Scientific Research Organisation (CSIRO).They included D Armstrong, R Sheppard, J Holmes, W Williamson, E O'Driscoll, B Credlin and C Bleys, Smith, and G Burton.

For the next two schools, the principal lecturers were invited from the United States Geological Survey (USGS) with Stan Lohman for the second school in 1967 and Dr John Ferris for the third school in 1970. For the 4th, 5th and 6th Schools, C Hazel from the, Queensland Irrigation and Water Supply Commission was the principal lecturer. His lectures were consolidated into a reference book on groundwater hydraulics [55] and were metricated for the 5th School in 1975.

The cost of running the Schools was met by the Commonwealth and State governments and there was no registration fee for representatives from those contributing organizations. Each organization was able to send as many participants as it chose.

With Federal Funding support the two new groundwater centres were established in 1988. The Centre for Groundwater Studies in Adelaide and the Centre for Groundwater Management and

Hydrogeology at the University of NSW where groundwater schools were held in 1989 and 1991, convened by Prof M Knight. In 1995 the responsibility for running the Schools was assigned to the Centre for Groundwater Studies. Trevor Pillar has been business manager of the Centre for Groundwater Studies since its inception.

The duration of the Schools was reduced from 2 weeks to 1 week with the content changing to reflect the increasing awareness of the environment and increased participation from the mining industry. Furthermore it accommodated advances in groundwater chemistry, isotopes and groundwater modelling. Reflecting the changes in our society and its environmental concerns the backgrounds of the participants changed from predominantly geology, engineering and hydrology in the 1960s-1980s to more than 50% environmental scientists and resource managers in recent Schools.

Twelve Schools were held between 1965 and 1995. From 1995 to 2007 inclusive twenty two Schools had been conducted during that period and over 100 experts lectured, notably: I Acworth, D Armstrong, C Barber, P Commander, G Davis, R Ellis, Ray Evans, Richard Evans, C Hazel, A Herczeg, T Laws, C Lawrence, A Love, S Toze and M Williams.

Based on the contributions of the numerous presenters at the Schools a handbook [39] has been compiled by an editorial panel of C Hazel, T Laws, I Acworth and C Lawrence.

Since that time there have been several organizations running equivalent courses to that of the Australian Groundwater School, often specializing courses on groundwater modelling and groundwater management

Many universities run courses on groundwater now and undertake post graduate courses and research. Based on the AMIRA Australian geosciences thesis data base compiled in 2008 from 10500 theses there were several hundred categorized as hydrology and hydrogeology, with the most prominent universities being the University of New South Wales and the University of Melbourne

11.2 Australian Drilling Industry Training Course

With water well drillers such an integral part of groundwater investigations and development and changes in regulatory requirements , rig type and drill technology the AWRC Technical Committee on Underground Water found it was important that there be training for water well drillers, both private and government. The committee agencies contributed financially for 5 years for the establishment of the Australian Drilling Industry Training Course. It has run many courses including those on screen installation, gravel packing, mud technology, and water well licensing and safety. It has published a Drilling Manual, which is regularly updated. This ADITC training is complimented by the national "Minimum construction requirements of water bores [124].

The water well drillers established a professional association in 1970, known as the National Water Well Association of Australia

12. Hydrogeology: Past to Future

The steps of the past have led to the current hydrogeological knowledge base and more recently a reformed water resource management system, with its drive for economic efficiency, yet accommodating the environment. Whilst endeavouring to manage water resources in a holistic way there is still the need to accommodate the differences between surface water and groundwater: surface water has relatively small storage compared with groundwater and the infrastructure for surface water has been constructed and owned by government, and that for groundwater has been constructed and owned by the private sector. Further much of the deeper groundwater storage unlike shallow groundwater and surface water is not renewable in the shorter term and requires a different rationale for its management in the sustainable development context.

In addition there will be other variables to accommodate, such as other water sources from sea water desalination, etc; and changes in community values on society and the environment.

In terms of future scientific studies; to compliment management of groundwater there will be a need to:

- continue to maintain information bases in a way accessible to all, and including temporal data from regular physical and chemical monitoring from a reliable networks of observation bores.
- investigate groundwater flow systems in a holistic way, accommodating recharge areas and discharge areas and their environments.
- further define the relationships between groundwater and ecology
- predict the impact of coal seam gas extraction on groundwater and the environment
- predict climate change and droughts and their impact on groundwater and the environment
- predict the impact of onshore and offshore extraction of petroleum on groundwater systems
- investigate, as required, groundwater contamination
- investigate, as required, stressed groundwater systems to refine optimal extraction and any correction measures
- investigate, as required, tasks associated with salinity and drainage strategies
- regularly review the status of groundwater in all jurisdictions using an appropriate mix of skills
- search for new groundwater resources

13. Professional Associations

There are a number of professional associations catering for groundwater in Australia. They include:

- International Association of Hydrogeologists (IAH) (Australian Chapter). (Prof M J Knight appointed World President of IAH in 1996 -2000)
- Australasian Land and Groundwater Association
- Geological Society of Australia, Environmental Engineering and Hydrogeology Specialist Group
- Institute of Engineers, Australia
- Australian Drilling Industry Association
- Waste Management Association of Australia

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