The history of hydrogeology in Australia

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ABSTRACT

Australia is a land of extremes subject to an adverse and unreliable climate. The original inhabitants lived mainly in coastal zones without permanent settlements. European settlers, who arrived from 1788, founded towns from which they penetrated into the drier interior following rivers or sinking wells. There was pressure for Government to provide guidance in obtaining water supplies. The various States began to establish Geological Surveys in the 1850s and, although their prime objective was to advise on minerals they also advised on groundwater. Artesian water was discovered in 1878 and the boundaries of the Great Artesian Basin were established by around 1900. Declining yields and the long-term reliability of supply resulted in numerous conferences and committees. Following World War II geologists were appointed by organizations outside the Geological Survey. From the mid-1960s to 1980 intensive groundwater exploration took place and hydrogeology became accepted as a discipline in its own right.

INTRODUCTION

With the exception of Antarctica, Australia is by far the world's driest continent. It is sometimes referred to as the world's oldest continent – not because of its geological formations but rather because of its predominantly ancient landscape. This enormous continental island of some 7.7 million km^2 has very low relief. About half has an altitude of less than 300 m above sea level; only about 5% exceeds 600 m, practically all of which is concentrated in a zone along the eastern margin. Its highest point, Mt Kosciusko, in the far south-east, is only 2230 m in height.

Australia is a land of extremes. Climatic zones range from tropical in the north, arid in the interior, to temperate in the south. Its general aridity is evident in that 30% of it has a median annual rainfall of less than 200 mm, and half less than 300 mm. Less than 12% receives more than 800 mm, and these areas are restricted to the extreme north, east, south-east, and far south-west (Figure 1). The climatic picture is compounded by the great majority of the continent being subjected to rainfall variability ranging from moderate to extreme. High temperatures and heat waves can also cause difficulties. Evaporation too can be extreme, with average annual Class A pan rates ranging up to over 4000 mm in central Western Australia. The net result of these factors is a land subject to adverse and generally unreliable climatic conditions – a land particularly susceptible to prolonged and devastating droughts, as well as to bushfires and, almost incongruously, to floods. The tropical north is also subject to destructive cyclones.

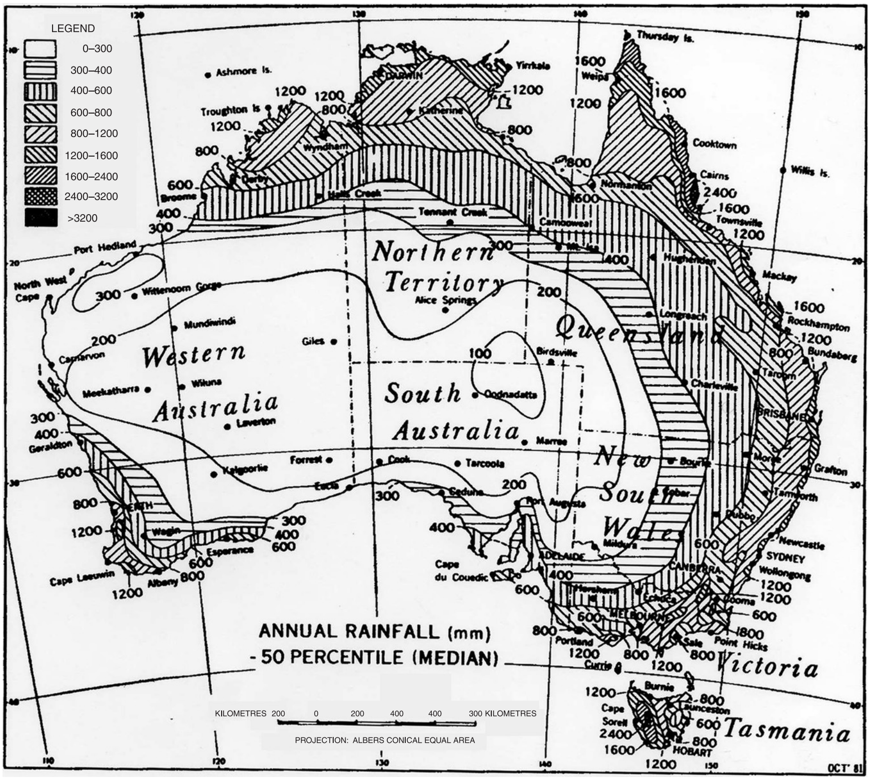

Figure 1 Annual rainfall in Australia. Taken from: *The Climate of Australia*, Commonwealth Bureau of Meteorology, AGPS, 1989. Commonwealth of Australia copyright reproduced by permission.

In such an environment, where the importance of groundwater resources is obviously enhanced, one might expect a rapid development in the application of hydrogeology. While this indeed happened, it took place predominantly from about 1960.

The development of hydrogeology in any country requires, normally, that there is first substantial use of groundwater. In this latter regard, a number of factors put Australia in a very retarded position compared with most major countries in the early 1800s. At that time, not only had the settlement of Europeans in Australia just started, its purpose was to serve as a penal colony for the British! European settlement commenced at Sydney with the arrival of the First Fleet, and its cargo of convicts, in 1788.

There was, of course, an indigenous population, the Australian aborigines, who were later shamefully treated. They lived mostly in the relatively well-watered coastal zones, but they also sparsely populated arid areas. Being astute observers, they were able to survive in such areas, where Europeans would have perished. They are known to have used wells, for example between some sand ridges and in dry creek beds, as well as springs, soaks and rock holes. But they were essentially food gatherers and hunters, moving in small groups. They did not have permanent settlements, nor did they cultivate crops or engage in animal husbandry.

The new colony of New South Wales (NSW) experienced considerable privation over the early years, including coping with the harshness of the new environment and limited availability of good quality land and water. Population gradually increased, mostly from continuing transportation of convicts, but settlement also expanded as land grants were made to military personnel and time-expired convicts. However, expansion was constrained by the Blue Mountains, which run parallel to, and within about 70 km of, the coast. It was not until 1813 that explorers found a way across them, and the young colony was able to burst its bonds and gain access to the hinterland. In the meantime, the then Van Diemen's Land, now Tasmania, had been claimed by the British in 1803 and a penal colony established there. Today, Australia comprises seven States (Figure 1). Of these, South Australia is the only one to have had free settlers from the outset, commencing in 1837.

By the 1850s, European settlement of Australia was still essentially in its infancy. The main centres of population were the few towns which are now the capitals of their respective States, and then, to a lesser extent, along the coastal zones which were relatively well-watered. As is normally the case, the initial spread of settlement inland mainly followed reliable surface water supplies, but as settlers penetrated into the drier inland grazing country, or if they did not have riparian access, recourse was soon made to tapping groundwater with wells.

With a rapidly expanding wool industry, and the need for more pasture land, settlers eagerly followed up the discoveries of early explorers and quickly spread inland. Further impetus was given by the announcement of payable gold in NSW in 1851, and by 1856 the population had more than doubled to 929 000. Enterprise quickened in every direction, but concern was also developing about water resources and the need for conservation measures. It was groundwater that attracted the first Government expenditure on rural water-conservation works. In 1866, £2900 was allocated to the sinking of wells to render practical a stock route from the Darling to the Lachlan and Warrego Rivers in NSW.

BUILDING THE FOUNDATIONS

In NSW, although there had been some earlier activities, including visits of various scientific expeditions, the Rev. W.B. Clarke, known as "the father of Australian geology", was prominent in geological activities prior to meaningful Government appointments. Soon after his arrival in 1839, he combined geologising with his duties as a cleric and mapped relatively large tracts of country (Vallance & Branagan, 1968). His geological expertise was also recognised from a groundwater viewpoint. In 1850, the Governor directed that an Artesian Well Board be formed "for the purpose of considering and reporting as to the best means of conducting an undertaking for endeavouring to obtain an abundant supply of pure water for the City of Sydney, by boring on the Artesian principle within the walls of Darlinghurst Gaol," and Clarke was appointed Chairman of the Board (Clarke, 1850). The attractions of Darlinghurst Gaol were that it was in a reasonably elevated position from which water could be distributed by gravity, and that the hard-labour convicts could be used on a tread-wheel as the motive power for the boring plant. Clarke was not optimistic of success, and estimated it would take three years to bore to 150 m. The bore was commenced in November 1851, but had an ignominious ending, being abandoned at 23 m as a result of sabotage (perhaps not surprisingly as it must have been purgatory on a tread-wheel in Sydney's summer temperatures!). However, Clarke's initial report (Clarke, 1850) would appear to be Australia's first groundwater report.

With population expanding, and settlers venturing further inland, inevitably there was pressure for Government to provide guidance and assistance in obtaining water supplies, including groundwater. Of major importance was the establishment of Geological Surveys in the various States, for they gradually provided geological maps, a basic requirement for hydrogeologists. The first such Survey was formed in Victoria in 1856, though it had a Geological Surveyor from 1852. However, in all cases they were part of Departments of Mines, and the prime object in setting them up was in relation to minerals such as gold and coal, rather than water. Nevertheless, most of the early Government Geologists had a special interest in groundwater, notably A. R. Selwyn in Victoria, C. S. Wilkinson in NSW, R. Logan Jack in Queensland, H. Y. L. Brown in South Australia, and A. Gibb Maitland in Western Australia. With time, as Surveys were able to carry out more intensive mapping, the locations of bores and wells were included on maps, and available details incorporated in reports. Eventually, prior to World War II, some reports specific to the groundwater resources of various mapped areas were being published. Johns (1976) gives a valuable outline of the history and role of the various Surveys, as well as descriptions of the activities and personal traits of their early leaders.

The apparent plethora of Geological Surveys in Australia arose from the Australian Constitution, adopted in 1901, under which the States are responsible for their own resources, such as forests, soils and minerals, including water. With the exception of Northern Territory (NT) and the Commonwealth, all the Surveys were in operation before the Constitution, so it was only formalising what was already in practice. In any event, considering the enormous area of most of the States, the remoteness of the main settlements from each other, and that in the early 1800s the geology of Australia was virtually unknown, there was justification for the individual State Surveys.

The early activities of the various Surveys were oriented mainly towards mineral prospects and mining, but in some cases, particularly in relation to alluvial gold in shallow or deep leads, they had significant relevance to hydrogeology. Examples in Victoria are given by Smythe (1869) and in NSW by Andrews (1910), Jones (1940), and Rayner (1940).

DISCOVERY OF THE GREAT ARTESIAN BASIN

A tremendous boost was given to the search for adequate water supplies by the discovery of artesian water in 1878 (in Australia, the term "artesian" implies that a bore will flow naturally). It was probably this discovery, more than anything else, which triggered the movement towards hydrogeology becoming a discipline in its own right in Australia, even though this happened over many decades.

Scientists of the day had already been pondering on the fate of the water disappearing from the Murray-Darling Rivers system. Rawlinson (1878) had appealed for an enquiry "into the cause of the disappearance of the vast bodies of river water which collect on the inner water-shed of the coast ranges of Australia" and considered that the interior of Australia would "ultimately be proved to be the storage reservoir where are conserved the rain and river waters which other theories fail to account for". The Government Astronomer claimed that less than 1.5% of the rain falling in the upper Darling River catchment flowed past Bourke, whereas for a corresponding point on the Murray, the discharge appeared to be of the order of 25% of the catchment rainfall Russell (1879). In the same year, Professor Tate examined mound springs near Lake Eyre in South Australia, pronouncing them to be natural artesian wells and predicting that boring for artesian water would be successful.

In fact, Professor Tate's prediction had already been proven, for in 1878 a flowing supply had been obtained on the remote Kallara Station in New South Wales. Finding the supply obtained by reconditioning a 33 m deep well to be inadequate, the manager had an auger hole drilled on from the bottom. At 43 m a flowing supply was obtained – the first flowing bore in what was to prove to be one of the world's largest artesian basins. Its site was about 170 km WSW of Bourke, and 30 km from the Darling River. Also it was about 120 m W of Wee Wattah mud springs, which were doubtless the result of shallow artesian conditions in the area.

The recognition of the bore and mud springs indicating artesian conditions led to further boring and within a few years small flows had been obtained from shallow bores near such springs in Queensland, NSW, and South Australia. These results encouraged deeper exploration in areas remote from any springs and, within a decade of the Kallara bore, large artesian flows were being obtained from depths of over 300 m. The first of these in NSW was in 1887 on Kerribree Station, about 80 km WNW of Bourke.

In Queensland, following one of the then-familiar droughts in the west, in 1881 the Government created a Water Supply Department, under J. B. Henderson as Hydraulic Engineer, with the aim of providing more adequate water supplies for inland towns and on main coach roads and stock routes. However, the drilling plant then available was suitable only for shallow depths, and the groundwater encountered was mostly too saline for human consumption. Also in 1881, the then Government Geologist, R. Logan Jack, had speculated on the possibility of encountering artesian water in inland Queensland. So in 1885, following yet another drought, when he and Henderson were asked to advise on the prospects of obtaining artesian water in the western interior, he reported favourably, and Henderson recommended the importation of plant and operators for deep drilling.

The first of the deep bores to be completed was on Thurralgoonia Holding, near Cunnamulla, a flow of 363 m^3/d being obtained at 393 m. This discovery had great impact in Queensland and there was rapid expansion of drilling. By 1889, 34 artesian bores had been completed, with 524 by 1899. In 1888, the drilling of 13 more bores for town water supply was approved, and their waters markedly improved the living conditions and health of the western communities. By 1900, artesian bores for 24 inland towns had been completed or commenced (Dept. Coordinator-General of Public Works, 1954).

It is significant that, in a collaborative report to the Government in 1893, Henderson and Jack expressed considerable concern about the number of bores, in which the flows were inadequately or not controlled, with consequent wastage of water, and the difficulty in obtaining adequate information on the bores. Their recommendations included that (a) the Crown assume control of artesian supplies in Queensland; (b) control of drilling activities be exercised; (c) the waste of water be combated; and (d) the State asset be conserved. The commendable foresight of this report resulted in legislation being passed in the Assembly to control artesian water, but frustratingly this was nullified by the Legislative Council, said at the time to be because of “vested interests”. Clearly, the pastoralists did not want the constraints of controls, and they had the political power to offset such attempts. The matter was not rectified until the passing of the Water Act of 1910, but this was after the artesian water situation had deteriorated much further.

In the meantime, in NSW, with the introduction of the Public Watering-places Act in 1884, the Government invited tenders for the construction of artesian bores on some of the far-western stock routes. The successful completion of many of these provided safe and permanent water supplies on stock routes which in some cases had previously been little used. Development was further promoted by the Artesian Wells Act in 1897, which enabled groups of settlers to obtain Government assistance to construct an artesian bore to serve their collective properties, the water being distributed to them by open drains.

During these early years of development in the Great Artesian Basin, geologists of the various State Geological Surveys were mapping large areas, assessing the new information coming to light from bores, and advising on the prospects of boring in various areas. It is a tribute to the geologists of the day that, in spite of the enormous size of the Basin (some 1.7 million km^2, or 22% of the Australian mainland) its limits were broadly established by about 1900 (Figure 2). It is indeed fortunate that geological conditions have provided this water-source in regions in which rainfall is often so low and unreliable that otherwise much of the pastoral industry would be impracticable.

In NSW, a Royal Commission was appointed in 1884 “to make a diligent and full enquiry into the best method of conserving the rainfall, and of searching for and developing the underground reservoirs supposed to exist in the interior of the Colony, and also into the practicability, by a general system of water conservation and distribution, of averting the disastrous consequences of the periodical droughts to which the Colony is from time to time subject.” The Commission was extant for four years and its lengthy hearings were published in three reports, in 1885, 1886 and 1887, respectively, but it failed to achieve much direct action.

The most tangible outcome of the Royal Commission was the establishment of a Water Conservation and Irrigation Branch, attached to the Department of Mines and Agriculture, but later, in 1896, transferred to the Public Works Department. Initially, this Branch was concerned with stream gauging and related activities, and assessing the potential for irrigation developments. However, in 1913 it became a Commission in its own right. In relation to artesian bores, it continued with the previous practice of having Government bores constructed under private contract, but in its first year it purchased two “Combination Cable Rig and Hydraulic Rotary Boring Plants” for drilling bores to a maximum depth of 900 m. The intention was to operate these plants with “day labour” under the supervision of officers of the Commission. For its shallow boring (maximum 150 m) activities, it then had only one plant, and insufficient funds to acquire others that year (Water Conservation and Irrigation Commission Annual Report, 1913). This was the humble beginning to activities of that Commission which were later to play a significant role in the development of hydrogeology in Australia.

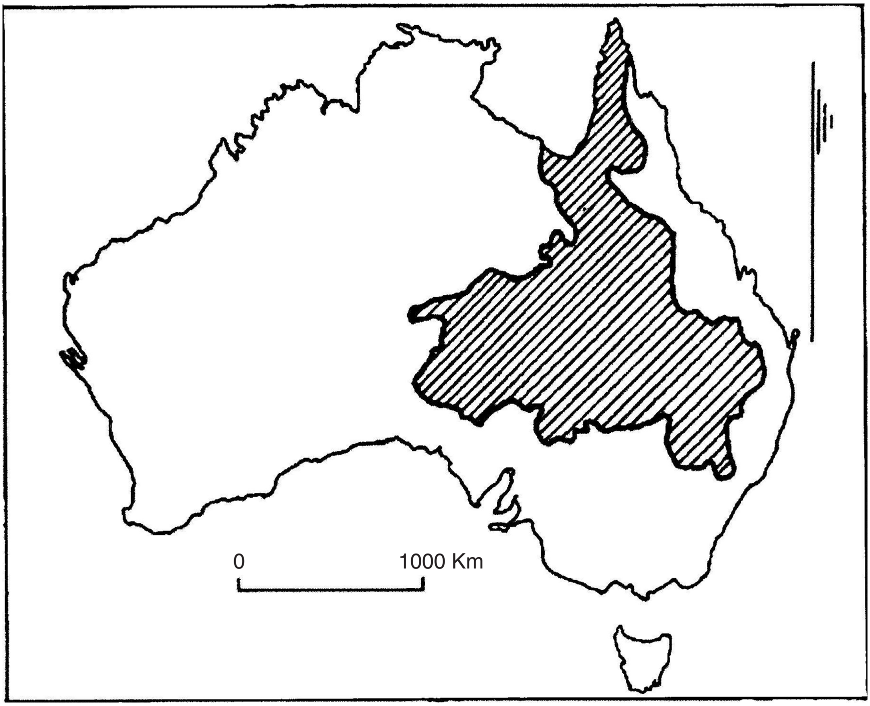

Figure 2 The Great Artesian Basin. Adapted from: *Review of Australia's Water Resources*, Australian Water Resources Council, AGPS, 1975. Commonwealth of Australia copyright reproduced by permission.

PROBLEMS DEVELOP IN THE GREAT ARTESIAN BASIN

With an apparently inexhaustible supply issuing from artesian bores, attention was also given to utilising the water for small scale irrigation projects, starting in 1891, near Bourke, NSW. It was not long before difficulties were experienced. An irrigation expert reported "as the soil cakes on the surface after irrigation, and the water from this and all other bores contains alkali, the necessity for keeping the surface broken up and for using the water sparingly is obvious" (Home, 1897). So here, another aspect of water chemistry was coming into the picture, the apparently unexpected residual alkali problem, which proved to be the undoing of this irrigation scheme. Over most of the Great Artesian Basin, the waters of the main artesian aquifers are essentially sodium bicarbonate waters and for this reason, although not unduly high in total salts, the waters are generally unsuitable for irrigation. The unfavourably high ratio of sodium to calcium plus magnesium ions has an adverse effect on soil structure, ultimately rendering the soil impervious. Even so, Cox (1906) considered that it was possible to cope with the alkali problem, and advocated extensive use of the artesian waters for irrigation, and of the artesian head for the production of mechanical and electrical power. Symmonds (1912) details considerable experimentation with materials such as gypsum and nitric acid to try to offset the ill effects of the alkali, but an economic and practicable solution was not forthcoming. Surprisingly, it was fourteen years before the irrigation scheme was finally abandoned.

In spite of this setback, here was a major water resource underlying an enormous area of semi-arid and arid lands. It was potable, being successfully used for town water supply, and served the pastoral industry. Apart from the irrigation aspect, it appeared to be the panacea of water supply problems for some 22% of Australia. But was it?

Soon other problems started to develop. With bores tapping aquifers at depths of 300 to 1200 m, construction and completion techniques were generally inadequate for proper control of the high-pressure water. It was found that the flows, although often initially large (flows in excess of 9000 m^3/d were not uncommon), soon showed a marked reduction, some bores even ceasing to flow. Various theories were advocated to explain this, e.g. leakage into upper formations, caving of the aquifer, choking of the bore, loss of gas pressure, and regional loss of head because of droughts; but none was sufficient to be of general application. In some areas, too, difficulties were being experienced because of severe corrosion, steel casing in the bores sometimes being eaten through in a matter of months. Furthermore, with regard to the potential of the Basin's water resources and their appropriate development, many conflicting views were raised. Even opinions as to the source of the water were not unanimous, a matter which raised an interesting controversy.

Well before 1900, the origin of water in artesian basins, or, for that matter, virtually all groundwater, was recognised as being of meteoric origin, i.e. from rainfall. However, J. W. Gregory, then Professor of Geology at Melbourne University (and later Glasgow University) caused a scientific stir by advocating a plutonic origin, from deep-seated igneous rocks. His views were first aired in a lecture in 1901, and were refuted by Knibbs (1903). Gregory developed his theories further in his book "The Dead Heart of Australia" (1906), basing his case mainly on the anomalies in temperature and pressure and the chemical composition of the water. He claimed that the rise of the artesian water was due to the combined effects of the temperature of the igneous rocks from whence the waters originated, and the pressure of the overlying rocks. Pittman (1907), then NSW Government Geologist and active in the study of the Basin for many years, attacked Gregory's theories. However, not to be outdone, Gregory criticised Pittman's arguments and maintained his views. The final broadside by Pittman (1914) replied in considerable detail, but Gregory remained unconvinced. At that time, no one fully understood the hydraulics of such a large artesian system. Even Pittman (1901), in trying to explain the diminishing flow of one of the bores, stated "... seeing that the drought has lasted between 3 and 4 years when the diminishing flow was observed, there cannot be much doubt as to the cause of the deficiency".

This controversy had ramifications beyond simply being a scientific argument. If Gregory was right, there were serious implications as to the continuity of the water resource. But even apart from this controversy, the marked reductions and cessations of flow caused considerable alarm, particularly among pastoralists, as it was feared that this invaluable resource might have a relatively short life. It was evident that the whole matter required careful investigation and review, and to this end, in 1908 the NSW Government invited other States to form a consultative Board. Unfortunately, only South Australia was willing, and the matter lapsed. It was revived again in 1911, this time successfully, and the First Interstate Conference on Artesian Water was held in Sydney in 1912. There were five such conferences, the last in Sydney in 1928. At the latter, the need to extend the activities of the conference to cover all groundwater in Australia was included, and it was resolved that "the whole body of underground water, whether under pressure or not" should come within the scope of the conference. Unfortunately, although it was proposed that the next meeting be in 1930, this proved to be the last of this series of Conferences on Artesian Water. Even so, they had been of enormous benefit. They clarified many problems, allayed many fears, instigated the systematic collection and interpretation of data on Australian artesian basins, and stressed the need for controlled development of artesian water resources.

Although there were no further Artesian Water Conferences, the movement towards having a national forum for the consideration of all groundwater was not forgotten. At a Brisbane meeting of the Australian Agricultural Council in 1937, the national aspects of water conservation and irrigation schemes were stressed and a joint Commonwealth and State enquiry was recommended. An Interstate Conference on Water Conservation and Irrigation was subsequently convened in Sydney in 1939, but the Commonwealth was not represented. The matters considered by this conference were of very wide scope but it is significant that the first resolution in its report recommended that the States and the Commonwealth participate in "a national investigation into the question of underground water supplies and the matters relating thereto".

The conference also resolved that "a permanent advisory committee or council, consisting of representatives from each State and from the Commonwealth, should be formed to consider and advise on those problems relating to the conservation and utilisation of water, which are of national or interstate interest and importance". It was recommended that this matter be referred to a proposed further conference "for recommendations as to the constitution, powers and duties of such committee or council". Unfortunately, World War II burst onto the scene, and it was to be many years before these proposals were implemented.

However, there were still concerns, particularly by pastoralists, about declining yields of artesian bores, cessations of flows, and the long-term reliability of supply. In response the Queensland Government set up a Committee for its own official investigation in 1939. An enormous amount of data had accrued over the years, especially since the start of the Interstate Artesian Conferences. Furthermore, Theis's non-equilibrium equation and the theory of elasticity of aquifers had been developed since the last of those conferences in 1928. Unfortunately this Committee's work was interrupted by World War II, and not resumed until 1946. Its final report was not presented to Parliament until 1954, but it provided an important collation of the state of knowledge of the Queensland portion of the Great Artesian Basin at that time (Dept. Coordinator-General of Public Works, 1954). In relation to uncontrolled and leaking bores, it concluded (p. 49) that stringent conservation measures were not warranted, on the grounds that "the resultant benefits were insufficient to outweigh the cost and the many difficulties involved in the implementation of a programme which could be expected to meet with strenuous opposition from the majority of the owners who would be required to carry it out". This controversial conclusion prompted a scathing minority report from committee member C. E. Parkinson, which included the disturbing statistics (p. 77): "Of the flowing bores in the State, 26.4% have no control valves; 16.9% have casing that has chemically deteriorated; 10.2% have leaking casing; 4.2% run to swamps; and 28.2% run to watercourses". Perhaps the only bright note was that, in

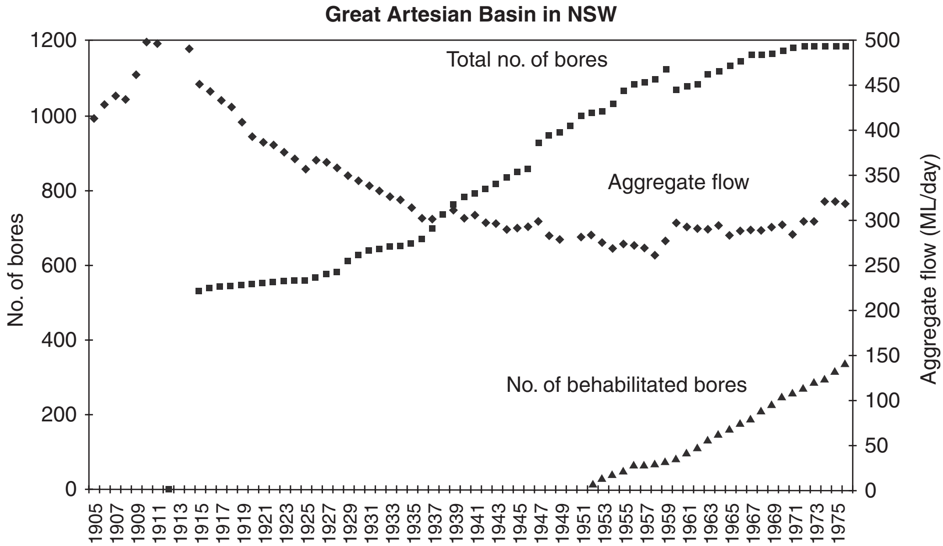

Figure 3 Effects of bore rehabilitation on the aggregate flow of artesian bores in NSW (Department of Land and Water Conservation, NSW).

1954, Queensland introduced legislation requiring that new artesian bores be properly controlled by valve and the water from them distributed only by pipeline.

In contrast, in NSW, a programme of rehabilitating uncontrolled bores had been commenced in 1952 and continued until 1976. It was not long before beneficial effects became apparent. By 1959 the aggregate available flow of artesian bores in NSW showed an upward trend for the first time since 1911 (Figure 3). In South Australia too, where there were about 300 artesian bores, rehabilitation of uncontrolled bores began in 1977.

POST WORLD WAR II TO THE 1960's

With the end of WWII there began a period of increased emphasis on water developments, including groundwater. In NSW, this was not only due to the resurgence to be expected when a nation can return to normal pursuits, but also because it had been experiencing a succession of droughts from the mid-1930s until 1947. At that stage, hydrogeological matters were dealt with by the Geological Survey and the then Water Conservation & Irrigation Commission, among other things, constructed artesian and sub-artesian bores. The Survey serviced the Commission in matters such as determining from drilling samples whether bedrock had been reached in the Great Artesian Basin, and to some extent in the selection of bore sites outside the Basin. However, only one or two geologists could be made available for this work, and then only on a part-time basis.

A significant post-war development in NSW, serving to help re-establishment, and as an anti-drought measure, was the Farm Water Supplies Act, in 1946. Under this Act, primary producers could obtain technical advice and financial assistance on matters relating to water supply, including groundwater. This scheme proved very popular, particularly in drought periods, when there was great emphasis on groundwater.

In 1950, the Commission, until then essentially an engineering organisation, decided it should have its own geological staff to specialise on groundwater. At that stage, apart from the pressures arising from the Farm Water Supplies Act, the Commission was operating twenty boring plants throughout the State, and it needed geological expertise on hand. The author was appointed to the Commission in May 1950, but immediately a problem arose. The then Government Geologist advised that if the author were classified as a geologist he would lodge an official objection on the grounds that the Geological Survey should service other government departments in geological matters. To overcome this impasse, and since he was to specialise in groundwater, the author suggested he be classified as a hydrogeologist. This was accepted, and appears to be the first usage of the designation of Hydrogeologist in Australia.

At that time there were no courses in Australia to provide training in hydrogeology, so it became a matter of gaining in-service experience and much self-education from overseas literature. Learning the capabilities of various types of boring plant, and the design of various types of bores, was gained mainly through considerable discussion and field work with the Engineer for Boring, and Boring Superintendents, as well as from literature. Later, finding that the results of test-pumping of completed bores were being treated in a rather rudimentary and pragmatic way, the author introduced time-drawdown and time-recovery measurements to allow mathematical analysis of the data. For high-yielding bores, such as for irrigation or town water supply, step-drawdown tests were also applied with the object of determining bore efficiency and to allow extrapolation for the effects of long term pumping at rates higher than those of the test-pumping.

At that time too, belief in water divining was rife in rural areas. Sometimes a land-holder would seek technical advice to check the prospects of a divined site, or conversely get a diviner to check the hydrogeologist's site. Even today, there are still some adherents to divining, especially in areas where there is no difficulty in obtaining groundwater. Perhaps the most telling evidence against divining is the statistics accrued by the then NSW Water Conservation & Irrigation Commission over the period 1918 to 1945 from its drilling of 3638 bores, shown in Table 1. About half were on divined sites, and in spite of the "advantage" of having been divined, there were twice as many failure bores on such sites than on sites not divined. Prior to the introduction of new regulations in 1947, the Commission was committed to boring on whatever site the landholder wanted, and many of the undivined sites were not favourably located. However, with the advent of hydrogeological advice, failure bores became rare.

During the 1950s, NSW, Queensland and South Australia started to undertake regional exploratory drilling programs for groundwater supplies. In NSW, the first of these programmes commenced in 1953 in the Hunter Valley (Williamson 1958). In 1957, attention turned to the much more extensive inland drainage systems, initially the Lachlan (Williamson 1964), and later, in 1963, the Namoi (Williamson 1970). The investigations in these inland systems revealed a far higher groundwater potential than was formerly known, and led to a major increase in the use of groundwater for

Table 1 Comparative results of water divining. Water Conservation and Irrigation Commission NSW. Annual Report for 1945, p. 21.

	Divined		Not divined	
	Number sunk	Per cent	Number sunk	Per cent
Bores in which supplies of serviceable water estimated at 100 gallons per hour or over were obtained	1291	70.4	1516	83.9
Bores in which supplies of serviceable water estimated at less than 100 gallons per hour were obtained	185	10.1	96	5.3
Bores in which supplies of unserviceable water were obtained	87	4.8	61	3.4
Bores – absolute failures, no water of any kind obtained	269	14.7	133	7.4
Total	1832	100	1806	100

irrigation and town water supply. Queensland started an exploratory programme in the Dumaresq Valley in 1958 (Queensland Irrigation and Water Supply Commission 1965), while South Australia carried out such drilling in an area south of Adelaide in 1950 and 1955–56 (O'Driscoll & Shepherd 1960), and in the Willochra Basin in the mid-1950s (O'Driscoll 1956). The Victorian Department of Mines had a long history of stratigraphic drilling, particularly in the Otway Basin. This was continued in that Basin in the 1950s (Wopfner & Douglas 1971) and also in the Murray Basin (Johns & Lawrence 1964). Western Australia, Northern Territory, and Tasmania were not able to undertake regional groundwater exploration programmes in this post-World War II period, and had to await developments in the 1960s in order to have the necessary funds and resources. Indeed, these factors were severely handicapping all of the States in their groundwater investigations.

POST – 1960 DEVELOPMENTS

Events moved swiftly in the 1960's. An Underground Water Conference of Australia was formed, and had its first meeting in Canberra in 1961. More importantly, an Australian Water Resources Council (AWRC) was formed soon afterwards, and held its first meeting in March 1963. The Council was a Ministerial body, serviced by a Standing Committee comprising heads of relevant authorities, and this in turn was serviced by Technical Committees. In 1964, the Underground Water Conference was reconstituted as the Technical Committee on Underground Water (TCUW). An initial task was to have each State prepare a review of its surface water and groundwater resources as in 1963, and these were collated and published as "*Review of Australia's Water Resources, 1963*" (AWRC, 1965). A major contribution in the Review was the first meaningful map of Australia's groundwater resources.

The Review showed there were glaring deficiencies in information on both surface water and groundwater resources. To assist in achieving more complete knowledge in these regards, the Commonwealth passed the State Grants (Water Resources) Act, 1964. This had the object of encouraging the States to implement accelerated programmes of research and investigation into surface water and groundwater resources, and finance was made available by subsidy, initially for a three-year period. This was a major step in the development of hydrogeology in Australia. At last it had become politically acceptable for finance to be made available to increase hydrogeological staff numbers in the under-resourced relevant State authorities, and to embark on systematic exploration and investigation programmes. There was, of course, an immediate problem – the recruitment and training of requisite staff. There were still no appropriate training courses in tertiary educational institutions in Australia. Hence, to augment in-service training, TCUW organised a series of Groundwater Schools; intensive courses of two weeks duration. The first was held in Adelaide in 1965. Apart from the lectures and workshop content, the Schools provided an important forum for discussion and exchange of experience, adding markedly to their value. The Schools also brought out the multi-disciplinary nature of hydrogeology, attracting both geologists and engineers. However, there was a severe shortage of geologists, and this difficulty was compounded by a synchronous boom in mining, starting in the mid-1960s. Not only were additional geologists needed in relation to mining, but also hydrogeologists in relation to associated groundwater matters.

Probably the major transitional factor to elevate hydrogeology to a discipline in its own right at this time was that it had become quantitative. Prior to this, groundwater reports were almost entirely qualitative insofar as the resource was concerned. Usually there were neither sufficient data nor staff to do otherwise. This change came at an opportune time, for in every State there were already areas in which there was concern either about over-development of groundwater resources or urgent need for additional resources.

Although there were initial problems in obtaining requisite staff and equipment, the mid-1960s heralded the start of greatly accelerated progress in the investigation and assessment of the nation's groundwater resources. An indication of the progress is given by two landmark publications: *Groundwater Resources of Australia* (AWRC, 1975); and *Review of Australia's Water Resources* (AWRC, 1976). The latter provides the first quantitative assessment of Australia's water resources, both surface water and groundwater. Even so, much remained to be done, and the State Grants Act to provide Commonwealth subsidies to the States was extended for a number of three-year periods.

The mid-1960s to about 1980 was the period of the most intensive groundwater exploration. As groundwater resources were proven and developed, there was a gradual transition in emphasis from exploration to management. Thus, as investigations proceeded, the need for quantitative assessments became paramount, particularly with regard to how the systems would respond to development. It was clear that the closed mathematical or analytical solutions used in relation to the behaviour of an individual bore or well would not lend themselves to considering the response of a whole aquifer system to multiple extractions, so recourse must be made to other approaches. Fortunately, there had been important advances overseas in these regards during the 1960s. Various analogue models had been developed, initially physical and then electrical. From the outset, it was evident that physical models would have very limited application, but electrical analogue models appeared to offer more scope. Lawson and Turner (1970) built a resistance network and McPharlin (1970) reported on the use of the more sophisticated resistance-capacitance network models on two projects. With the introduction of computers Pilgrim (1970) reviewed the use of digital models, based on both finite difference and finite element methods, and correctly foresaw their advantages would increase as the technology and capacity of computers improved. At last, here was a management tool that lent itself to assessing the long-term effects of various development strategies and which was also more amenable both to setting up the model and adjusting hydrologic parameters during the process of calibration. The first reported Australian study of a computer-based simulation of a substantial aquifer system appears to be that by Kalf and Woolley (1977) in relation to an investigation started in 1971 in the Murrumbidgee Valley, NSW.

A particularly ambitious project was carried out by the then Bureau of Mineral Resources (BMR) over 1971 to 1979 to model the Great Artesian Basin. This was at the instigation of the then TCUW, and involved not only an overview of the geology and hydrogeology of the Basin, but also modelling to simulate its hydrodynamics. The comprehensive overview was prepared by Habermehl (1980), and the model GABHYD developed by Seidel (1980) over 1975 to 1978. To deal with 3-D transient groundwater flow, a finite difference model was chosen. The geometry and hydrogeology of the Basin was drastically simplified, both horizontally and vertically, in order not to exceed the capacity of the computer used. The multiple aquifer system was reduced to only two groups, with each group represented by one layer of grid nodes in the model. Horizontally, a square grid of 25 km spacing was used. Naturally, the model lends itself only to regional predictions. To complement the project, in 1974, a major study of the isotopic hydrology of the Great Artesian Basin was jointly commenced by six relevant organizations (including three from the USA), in conjunction with the then BMR.

Green (1965) had carried out earlier isotopic studies, commencing in 1962, using Carbon-14 dating in the NSW part of the GAB, but the age limit of about 35 000 years before present restricted its application to marginal zones. However, the ages determined were in accord with those derived by Hind and Helby (1969) from hydraulic data – a rate of water movement of about 1.6 m/year. Hind and Helby (1969) also presented basement contours in the NSW part of the Basin, as well as thermal gradients and their relationship to basement lithology. Later, Polak and Horsfall (1979) dealt with geothermal gradients over the whole Basin.

Other substantial developments occurred during the 1960–1980 period. One of these was the formation of the first Australian consultant group specifically for hydrogeological activities. Although there were a few consultant engineering groups carrying out some groundwater projects, such projects were generally subordinate to their main interests. Hence the formation of Australian Groundwater Consultants in 1966 by two hydrogeologists from the author's staff was a significant move. The contemporaneous rapid expansion of groundwater investigations by State departments and the onset of a mining boom after the mid-1960s provided an ideal opportunity for consultancies. Both required hydrogeological expertise, but the economic bias in favour of mining developments led to the movement of some experienced departmental staff into the consulting field.

A second specialist consultancy, Stephen Hancock and Associates, formed in Victoria in 1967, and both of these were drawn into mining developments in Western

Australia, working as partners on some projects. They amalgamated as Australian Groundwater Consultants Pty. Ltd. in 1969. In the early 1970s, several other consulting or contracting companies formed and/or entered the field of specialised hydrogeological services, and others came from overseas.

Further scope for hydrogeological consultants came in the 1970s because of the emphasis that had finally developed on environmental issues. Most States had legislation in this regard in place by the early 1970s, e.g., Clean Waters Acts in NSW in 1970, Western Australia in 1971, and in Tasmania in 1973; and the Underground Water Preservation Act in South Australia in 1969. Contamination of groundwater systems poses a particular problem because of its long-term effects, and although State departments became heavily involved, the demand for hydrogeological input became such that it also increased the demand for consultants. The spectre of radioactive contamination around uranium mines and their associated plant and tailings ponds roused much early concern. Soon, the principles of contaminant containment, fixation, management and monitoring were being applied with greater intensity to all coal and metalliferous mining and mine waste management, as well as potentially contaminating industries, including power stations, petroleum refineries, and metallurgical and chemical works.

In mining projects, conflicts of interest are not uncommon. In an important example in NSW, for many years the Sydney Water Board had resisted proposals by four coal-mining companies to allow mining to extend under five major water storage reservoirs owned and operated by the Board. Matters were finally brought to a head when a Public Inquiry was instituted in 1974, and in the course of this the author was made available to the Department of Mines in relation to hydrogeological aspects. The Inquiry sittings were held in 1976, and it was concluded that, subject to certain conditions, mining should be permitted under the reservoirs but not under the dam structures (Williamson, 1978).

Another prominent example is the open-cut mining of major brown coal deposits of the Latrobe Valley in the Gippsland Basin, Victoria. Winning of the coal requires the lowering of artesian pressures in sand aquifers beneath the coal to prevent heaving of the open cut floor and to aid batter stability. Dewatering commenced at Morwell Open Cut in 1960 and has resulted in lowering of the potentiometric surface by up to 130 m, the effects being evident within a large area and at distances up to 50 km. The water is used in power generation and for industrial purposes, and the dewatering has resulted in surface subsidence of up to 2 m. The water being extracted is at about 50°C, and the thermal gradient is as high as 5 m per degree through the thick brown coal seams. Thompson (1978) showed that the high groundwater temperature is essentially due to the insulating effect of the coal beds on local areas of high geothermal flux, with the presence of artesian aquifer systems within the coal sequence modifying the simple thermal conductivity relationships.

Most major groundwater investigations in Australia have been directed towards unconsolidated sediments, or, to a lesser extent, sedimentary rocks. Although fractured rock systems have received relatively little attention, this is not to say that they are not important, for they provide the only groundwater source over about half the continent. Prior to the 1960s, bores were used to obtain water for stock and/or domestic purposes. Such supplies normally put limited demand on the system, so there was little need for quantitative investigations. Also, general principles and the suite of data from the many thousands of landholder's bores gave a broad picture of groundwater availability in regions of fractured rocks.

In many areas, particularly in those of low rainfall, the groundwater is brackish or salty, or the yields are low. An example of the outcome of an exploratory drilling programme in such an area is given by Lord (1971). In a period of severe drought in SW Western Australia in 1969, the Government instituted a drought relief programme, with bore sites selected by geologists of the Geological Survey. The area is underlain by Precambrian granite and gneiss, and was known to have poor groundwater potential. In a crash programme, of 2639 bores drilled, only 10% were classed as successful. However, the criteria of "success" were a yield of only 4.5 Kl/day, with salinity less than 11 000 mg/l!

Although the yield of most bores in fractured rock tended to be less than 2.5 l/s, in some areas much higher yields were available. This is expected in calcareous rocks, where solution channelling is common, but rocks normally less favourable were also involved. Hillwood (1967), in reviewing the problems and results of bores in hard rock areas in South Australia, gives many examples of yields of the order of 12.5 l/s. Down-hole hammer drilling was then coming into vogue in Australia, and it was significant that the yields being obtained from hard rock bores drilled by this method were consistently higher than those drilled by cable-tool. This is believed to be due to the clean hole being maintained by the hammer method.

Considerable interest was taken in groundwater in fractured rocks after a mining boom commenced in the mid-1960s, particularly in relation to mines in arid and semi-arid areas. Of concern were the dewatering of mine workings, the supply of water to the mines for needs such as ore processing, dust suppression, or general water supply, and commonly to meet water supply requirements of small townships set up to service mines. These townships often had to be located at a substantial distance from their respective mines because the salinity criteria for their water supplies were more stringent than for the mine. O'Driscoll (1979) reviewed the significance of groundwater to mining developments in Western Australia from the late 1800s to the 1970s, and the majority of mines were in fractured rock environments.

At the other end of the spectrum, a particular problem was where groundwater yields from fractured rocks were so low that bores did not warrant developing even for stock and domestic supplies. This had been of concern to the author for many years in NSW, and in 1978–79 he led an AWRC-funded research project involving the use of hydraulic techniques to stimulate the yields of such bores. At that time, the NSW Water Resources Commission was using combination rotary and down-hole hammer plants for these bores, and the project approach was to use the mud-pump of the plant, in conjunction with a booster auxiliary pump, to pressurise the aquifer zone isolated by packers. Up to six-fold increases in yield were obtained, thus converting what had formerly been taken as failure bores to viable stock and domestic water supply bores. An important finding was that sufficient inter-block propping was achieved by injecting only water, and no advantage was gained with viscosity-inducing additives and propping agents as used in oilfield technology (Williamson & Woolley 1980).

In the 1960s to 1980s, there were also some important Australian developments in the application of geophysical techniques to hydrogeological work. Earlier applications had been almost entirely derived from overseas methods. Some of the earliest geophysical reports relevant to groundwater were by staff of the then Bureau of Geology, Geophysics and Mineral resources (BMR), established in 1946. Examples are resistivity investigations in five areas in WA (with special attention to the granite country) by Wiebenga (1955), and Dyson and Wiebenga (1957) in relation to an investigation in 1956 regarding the Alice Springs water supply. Seismic refraction, resistivity traverses and depth soundings were used in this latter investigation, but the results proved unsatisfactory. An important advance in using seismic refraction techniques was developed by Hawkins, with Wiebenga and Dyson. It was used as a standard procedure in the Canberra area in 1956, and termed the Reciprocal Method (Hawkins, 1961). It was this method that the then NSW Water Conservation & Irrigation Commission adopted when, in 1965, it incorporated a program of seismic refraction surveys to track the buried "valley-in-valley" in its investigations of the extensive Lachlan Valley, and subsequently in other major inland valleys in that State. Additional developments of the method were made by the Commission's geophysicists in the course of that work, including the incorporation of blind zones (Merrick *et al.*, 1978).

A further significant enhancement to seismic refraction surveying and interpretation was the Generalised Reciprocal Method developed by Palmer (1980) during the 1970s. This combined many of the better features of previous methods, including the standard reciprocal method. It added the concept of an "optimal offset" to accommodate significant irregularity in the subsurface refractor being mapped. The method has gained wide acceptance internationally as the most effective available for seismic refraction interpretation.

Following the establishment in 1964 of the Technical Committee on Underground Water, in the Australian Water Resources Council, an early concern was the problem of obtaining reliable quantitative interpretations of the various geophysical methods. Later, when funds became available for approved research projects, one such project, carried out during 1969 to 1971, was on geophysical well logs in water bores in unconsolidated sediments. The report highlighted the difficulties involved in gaining quantitative interpretations, and made recommendations for further research (Emerson & Haines, 1974).

In the Great Artesian Basin, a difficulty in effecting stratigraphic correlations was that only driller's logs were available for the great majority of bores. To obtain more specific data, the BMR conducted a geophysical well logging programme in the Basin from 1960 to 1975. In all, wire-line logs were run in 1250 wells. Many could not be accessed because of complicated headworks or internal obstructions. Other operational difficulties included high water temperatures, commonly in the range of 30°C to 50°C, but in some areas in Queensland up to 100°C at the well head. Since the wells were cased, the logging was mainly restricted to nuclear logs. Natural gamma logs were run in all wells and in some cases also neutron-gamma logs. From many wells, temperature, differential temperature, and casing collar locator logs were acquired, and from some flowing wells, flow-meter logs were also obtained. Where more than 100 m were uncased, spontaneous potential, resistivity, and calliper logs were run in those sections. This programme provided a valuable suite of complementary data for subsequent studies of the Basin.

Of surface methods, electrical resistivity, either by traversing or depth sounding, had long had problems. Unfortunately, reports were commonly being made without benefit of ground-truth data, and subsequent drilling had often found them to be misleading. In NSW, geophysicists N. Merrick and D. O'Neill, in the author's Hydrogeological Section, contributed important developments in this field. One of the difficulties in Schlumberger depth sounding was the data shifts that often occurred when potential electrode spacing had to be expanded. An advance was made in this regard by Merrick (1974) with his Pole-Multidipole Method. This acquired simultaneous sounding data for a multi-electrode array, and also offset the ambiguities created by data shifts. It was a forerunner to the multi-electrode soundings and imaging arrays now in popular use.

In spite of the number of electrical resistivity surveys carried out, it would be fair to say that until 1971 the interpretation of the data was a tedious process and of dubious reliability. A major constraint was the difficulty of modelling the theoretical response of the fundamental model consisting of known layer thicknesses and resistivities. Overseas, Ghosh (1971) produced a major breakthrough by applying linear filter theory to the problem, providing a basis for simple, rapid and inexpensive modelling. However, Ghosh's "digital filter" was rudimentary and limited. In Australia, O'Neill (1975) refined Ghosh's technique by developing a more generally applicable filter for the widely used Schlumberger electrode array. Subsequently, the filter became a widely adopted standard for resistivity modelling that largely eliminated the constraints of Ghosh's original filter. O'Neill's filter was a catalyst for the subsequent development of resistivity "inversion" (Merrick, 1977) that finally paved the way for more reliable resistivity interpretation. Later, additional filters were developed by O'Neill and these were incorporated by O'Neill and Merrick into a methodology for resistivity modelling for a generalised (four electrode) array, eliminating the need to adhere to conventional arrays and providing a mechanism for efficient and flexible resistivity surveying. In 1973–74, these staff also developed the first automatic inversion method of interpretation that ran on a micro-computer (Merrick, 1977).

CONCLUSION

From the foregoing review, it will be evident that the 1960–1980 period was particularly important in the development and application of hydrogeology in Australia. 1980 has been taken as the as the cut-off point, but it is clear that by then hydrogeology had been accepted in Australia as a discipline in its own right. In this dry continent, groundwater inevitably played an increasingly important role, so that the future augured well for the hydrogeologist. Hydrogeology had really arrived!

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