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The Groundwater Quality Situation in Australia and Possible Australian Contribution to Regional Programmes

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ABSTRACT

The high salinity of many shallow groundwater systems in semi-arid and arid Australia, has been a major constraint on water supply development. Naturally occurring deleterious substances, including nitrate and fluoride, in groundwater, are additional constraints. Groundwater-related salinisation of land and water resources is a major national problem. In addition, a number of stressed aquifer systems, both inland and coastal, have deteriorating water quality. Various management strategies are being implemented to alleviate or control these problems. Monitoring bore networks are used to detect and assess these changes.

A national inventory of groundwater contamination incidents has documented 144 such incidents in Australia. A wide range of contaminant sources is involved, including industrial effluent, sewage and landfill leachate. Many cases are of local significance but several important regional aquifers are affected. These are: Quaternary sand aquifers of the Perth Basin, Western Australia; a widespread Tertiary limestone in South Australia and Victoria; Quaternary volcanic rocks and Tertiary sand aquifers in Melbourne, Victoria; and fractured Silurian sedimentary rocks at Canberra. These are all shallow unconfined aquifers that underlie regions of intensive urban, industrial or agricultural development. Remedial measures, including groundwater recovery and treatment, have been successful in some cases. Surveillance, documentation and monitoring of the reported contamination incidents is incomplete.

Regional bore monitoring networks are being reviewed and rationalised in some states, in response to emerging groundwater issues. Australian researchers have contributed to new monitoring technology applicable to groundwater pollution. Vulnerability mapping of aquifers is being carried out in two large regions.

A range of state (as opposed to federal) government legislation is applicable to the control and management of groundwater contamination, but controls are unevenly implemented. The need for a more consistent approach to the protection of aquifers from pollution has been recognised and is presently being addressed by the formulation of guidelines for groundwater protection. The guidelines will assist the development of regional policies and controls, and will form one part of a proposed national water quality management strategy. The Australian government is committed to

ecologically sustainable development both in national resource development projects and in international development co-operation programmes. Specific Australian expertise in groundwater quality assessment could be applied to co-operative regional programmes.

INTRODUCTION

Australia has a land area of more than 7 million km^2. About two-thirds is arid and totally dependent on groundwater . Several hundred small towns and communities use groundwater for drinking water in arid and semi-arid Australia, and groundwater is also used as a supplementary water source in several cities. The total amount of groundwater extracted is about 2500 million m^3 annually, and this is about 15% of the total water used in the country.

The main hydrogeological regions of Australia are shown in Figure 1. Groundwater occurs in multi-aquifer systems in several large sedimentary basins, including the Perth Basin which provides important water supplies for Western Australia; the Murray Basin, which underlies an important agricultural region of southeast Australia; and the Amadeus Basin, a vital water source for groundwater-dependent central Australia. Extensive regions of fractured-rock terrain contain important local and sub-regional aquifers. Large amounts of groundwater are extracted from surficial aquifers in Cainozoic alluvial, deltaic and aeolian deposits.

Groundwater has been abstracted in Australia for more than a century with minimal environmental controls. Little attention has been paid to the impacts on groundwater quality of different land use, mainly industrial,urban and agricultural. Increasing public concern about deleterious changes in, and pollution of, aquifers has led to the formulation of national guidelines for groundwater protection. However, groundwater is a hidden resource and the protection of groundwater supplies, and the management and remediation of polluted aquifers, lags behind that of the more visible environmental degradation of surface water and soils.

In this paper we describe briefly the current status of groundwater 'health' in Australia, discernible trends in groundwater quality change, and recent advances in monitoring capability, aquifer vulnerability assessment and groundwater protection.

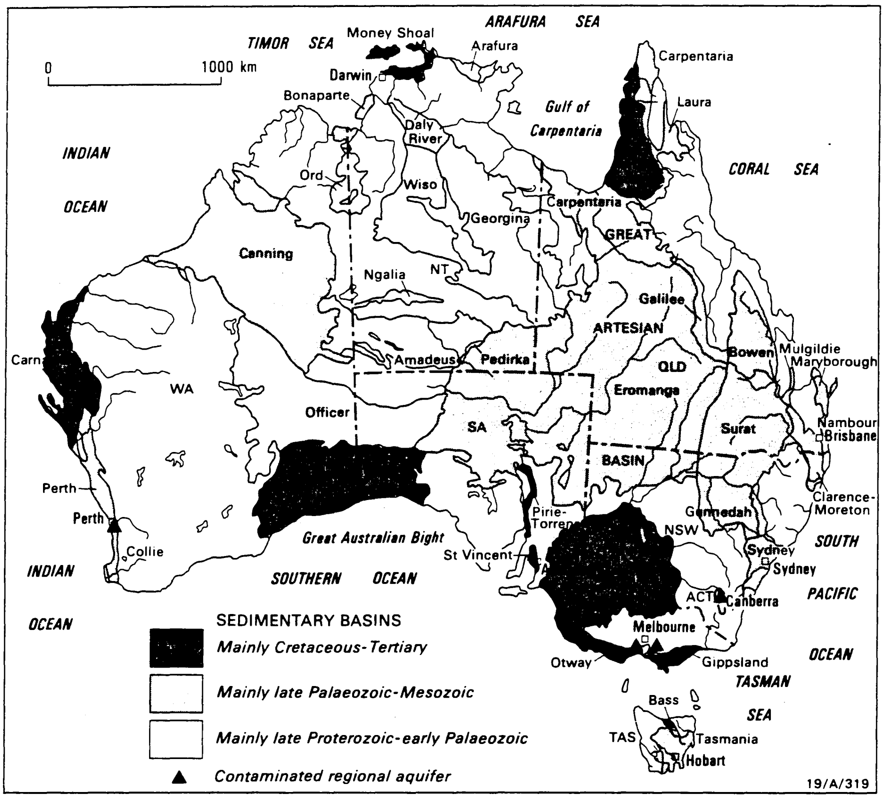


Fig 1. Hydrogeology of Australia, and location of contaminated regional aquifers

NATURAL GROUNDWATER QUALITY (SALINITY)

Natural groundwater quality has always been a major constraint on water supply development in Australia. Poor quality and variable quality groundwaters are common in shallow aquifers in the arid and semi-arid zones.

The boundary between fresh and brackish groundwater is generally taken as 1500 mg/L Total Dissolved Solids (TDS) to coincide with the World Health Organisation's maximum desirable limit for drinking water. This 'Drinking Water Line' has been plotted on the Hydrogeological Map of Australia (Lau & others, 1987), with reference to the 'principal aquifer' at a particular location. Figure 2 shows the approximate extent of fresh, brackish and saline groundwater in Australia.

Groundwaters of varying quality are extensively used in Australia. Fresh waters, up to 1000 mg/L TDS, are used for irrigation. Brackish groundwaters are widely used for livestock water supplies, with recognised limits of 10 000 mg/L TDS for cattle and 14 000 mg/L TDS for sheep. Saline groundwaters, up to 100 000 mg/L TDS, are used for industrial purposes in gold mining regions of Western Australia, where fresher water is unavailable (Boyes & Hall, in press). Hypersaline brines, above 100 000 mg/L TDS, occurring in groundwater discharge zones, may have economic value as a source of evaporites.

Desalination is undertaken in some small arid-zone communities where there is a sufficient economic base, such as tourism or mining. Brackish groundwaters form the feedstock for most of these desalination plants.

NATURAL DELETERIOUS SUBSTANCES

Natural deleterious substances in groundwater are constraints to development of water supplies in many parts of Australia. These substances include nitrate, fluoride, radioactive elements and heavy metals. Figure 3 illustrates the average concentrations of TDS, nitrate and fluoride in specific aquifers of the Amadeus Basin, a multilayered system in arid central Australia. The average salinity of bores in most Amadeus Basin aquifers is close to, or above, drinking water limits; average fluoride concentrations are high; and nitrate concentrations are high in many aquifers (Lau & Jacobson, 1991).

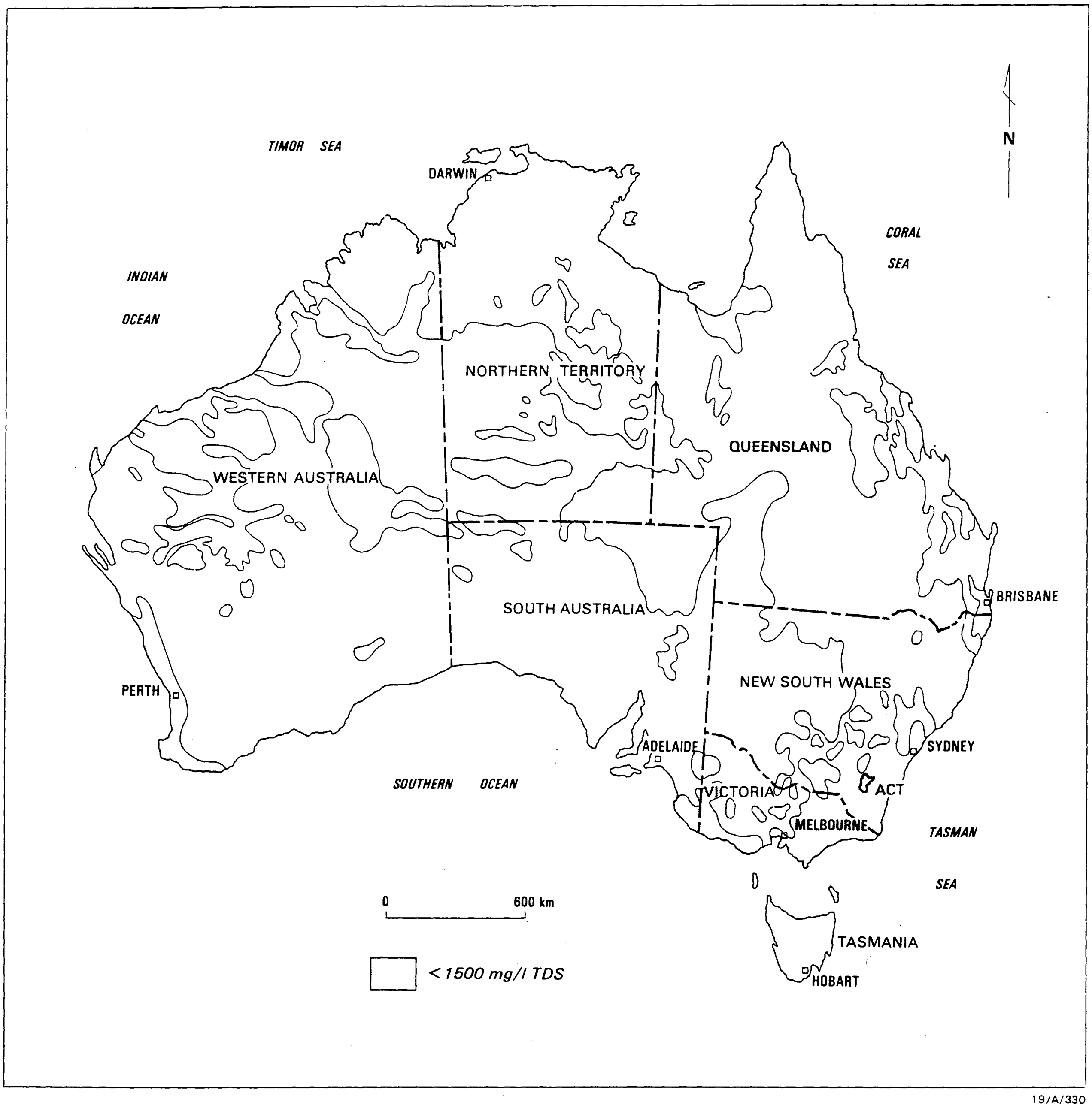


Fig 2. Groundwater salinity in Australian principal aquifers

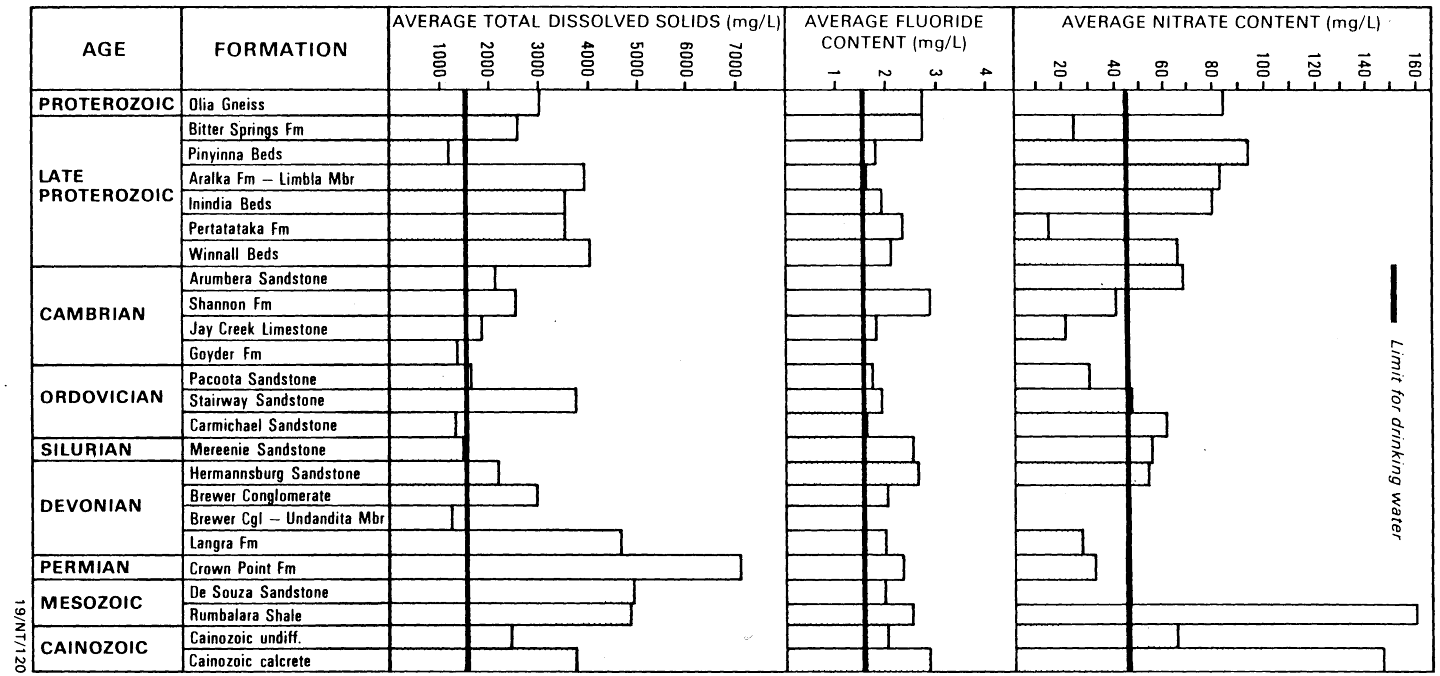


Fig 3. Average nitrate, fluoride and total dissolved solids concentrations in central Australian aquifers (Lau & Jacobson, 1991)

High-nitrate groundwaters are common in shallow aquifers of the Australian arid zone. This is a natural, not an anthropogenic, phenomenon; human population is sparse in this region and economic development is limited. The occurrence of the high-nitrate groundwaters poses a difficult problem for the development of water supplies for small settlements. The nitrate-rich groundwaters are often potable in terms of salinity, in the range 1000-1500 mg/L TDS. However nitrate concentrations greater than 45 mg/L preclude their use for drinking water, and in fact nitrate concentrations range up to several hundred mg/L. The origin of the nitrate is ascribed to biological fixation of nitrogen in the soil by bacteria associated with termites (Jacobson & others, in press).

Research into possible denitrification technology has led to the design of a biological reactor using immobilised bacteria, that may be appropriate for small settlement water supplies. The bioreactor involves the immobilisation of denitrifying bacteria on an inert support. The desired bacteria are contained in a reaction chamber so that nitrate-rich water can be passed through the reactor to remove nitrate and yield a suitable drinking water supply. The bacteria are immobilised on a polyurethane support and maintained on a low concentration of methanol, which is their carbon and energy source. The system has worked well in field trials (Jacobson & others,in press).

Fluoride concentrations greater than the drinking water standards are common in Australian groundwaters. For example, during a regional hydrogeological study in arid central Australia, we found that 40% of water bores had fluoride concentrations greater than 1.5 mg/L, the desirable limit for drinking water in this climatic zone. Some of these bores had saline groundwater but about one-third contained fresh and otherwise potable water (Jacobson & others, 1989). High fluoride concentrations are associated with particular rock units, and sometimes with structural features, as in the Carpentaria Basin in tropical northern Australia (Lait, in press).

High concentrations of heavy metals and radioactive elements in groundwaters are known in several mining provinces in Australia. For instance, at the Coronation Hill orebody, in tropical northern Australia, about half the water bores contain unacceptably high levels of lead, zinc or radioactive elements (Jacobson, 1991). This region was known as the Sickness Country in Aboriginal mythology dating back several millennia, and the appellation is now justified by measured high levels of toxic substances in the soils and groundwaters. At the Koongarra orebody, in the same region, an international project team is monitoring naturally occurring radioelements in groundwater and soils around the uranium orebody as a natural analogue for radioactive waste disposal.

NATURAL GROUNDWATER MICROBIOLOGY

Aquifers harbour indigenous microbial populations, even in the absence of contamination. These microorganisms play an important part in the biogeochemical cycling of non-conservative elements (C,S,N,P,H,O) and metals (Fe,Mn). Natural groundwater quality is to some extent determined by the activity of microbes that are attached to sediment particles. The abundance of unattached bacteria increases in the presence of organic contamination. The populations and activities of microorganisms in Australian groundwater systems are poorly known (Bauld & others,1991). Investigations are presently under way to explore the range of groundwater salinity affecting microbial activity; the capacity of aquifer microbial populations to degrade pesticides and other contaminants; and bacterial sulphide generation and metal precipitation. The corrosion and fouling of water bores by iron bacteria is a problem in many Australian aquifers.

GROUNDWATER-RELATED SALINISATION

Salinisation as a result of land clearing and irrigation practices has emerged as the most pressing problem of land and water resource management in Australia. At least 5000 km^2 of formerly productive agricultural land has been salinised, in two main regions: southwest Western Australia, and the Murray Basin in southeast Australia. A major concern is the increasing salinity of groundwater-fed rivers, including Australia's largest river, the Murray River in southeast Australia.

The salinity problems are groundwater-related. In the Murray Basin, land clearing over 150 years of European settlement has disturbed the hydrological equilibrium (Evans & Kellett, 1989). A gradual rise in the regional water table (Fig. 4) has resulted in remobilisation of salts and evaporative concentration of groundwater near the land surface. The time scale for salinisation is several decades, and the problem is severe in natural groundwater discharge zones. Monitoring indicates that the water-table rise in regional aquifers of the southern part of the Basin is 0.1 - 0.2 m/y (Macumber, 1987). Even with the present development of management strategies, large areas are expected to become salinised in the next few decades.

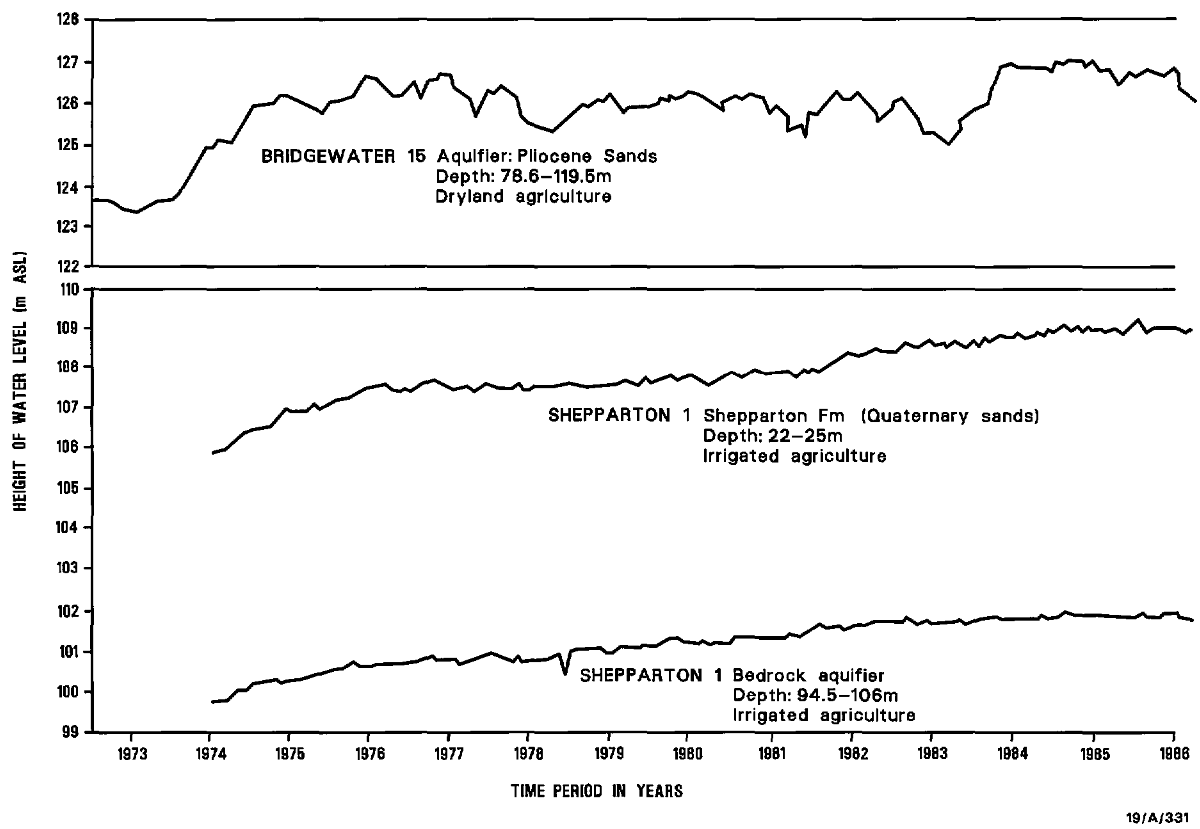


Fig 4. Bore hydrographs for Murray Basin aquifers (after Evans & others, 1988)

Current research in this large (300 000 km_2) sedimentary basin is directed at developing management and remediation strategies. A series of hydrogeological maps is being compiled and linked to numerical models of the complex layered regional aquifer system. Geographic Information Systems (GIS) are used to facilitate data processing for the maps and models (Brodie, in press).

SALINITY CHANGES IN INLAND AQUIFERS

A number of important inland aquifers have become stressed through overpumping for irrigation. An example is the Padthaway Formation, a Pleistocene limestone in southeast South Australia. About 22 million m^3 of groundwater is abstracted annually from this aquifer for the irrigation of vineyards, vegetables and other crops. This is approximately balanced by natural recharge (Harris & Stadter, 1987). However monitoring has shown a gradual increase in groundwater salinity in the irrigated area over a 15-year period. This is considered to be due to the reduction of groundwater flow through the area; some of the irrigation water is lost through evaporation and plant transpiration. The dissolved salts are recycled to the aquifer by the seepage of irrigation water and by rainfall. In order to avoid more serious water quality degradation, irrigation development is now restricted to current levels.

SALINITY CHANGES IN COASTAL AQUIFERS

In several Australian coastal aquifers, water levels have declined through heavy abstraction, and this has led to saline intrusion, or to management action being taken to prevent saline intrusion. An example is the Westernport Basin in Victoria, which contains several aquifers in Cainozoic sediments up to 300 m thick. Intensive pumping for irrigation of vegetables in the 1970's led to a rapid decline in water levels, to well below sea level. Water level and water quality are monitored in a network of 50 regional observation bores (Lakey & Tickell, 1981). The current management strategy is to reduce irrigation entitlements, and for this reason all the irrigation bores are metered (Baker & others, 1987).

At Bundaberg, on the central Queensland coast, irrigated agriculture depends on groundwater from Cainozoic sand aquifers which extend beneath the sea (Hillier, 1987). Excessive overdraft of groundwater has led to water levels below sea level in parts of the region. Monitoring results are used to calibrate the model used for predictions which form the basis for managing the system. The management strategy now involves the conjunctive use of surface water.

A significant problem in several Australian coastal aquifers is the change in groundwater quality caused by dewatering of buried coastal swamp sediments (Walker, 1972). Chemical and microbial reactions lead to the oxidation of sulphides and other minerals, and this causes the groundwater to become more acidic and saline, and sulphate- and iron-rich. This process has been documented for coastal aquifers at Sydney and Newcastle affected by pumping or sand mining (Johnson, 1981; Viswanathan, 1989). High aluminium concentrations have also been ascribed to this phenomenon (Noller & Cusbert, 1985).

The predicted rises in sea level due to global warming could have complex effects on these and other coastal aquifer systems. Groundwater recharge might increase in parts of eastern Australia, but there might also be an increased possibility of saline intrusion.

POLLUTION OF REGIONAL AQUIFERS

A preliminary assessment of groundwater pollution in Australia has been carried out by means of a national inventory of groundwater contamination incidents (Jacobson & Lau, 1988). Information was obtained from questionnaires distributed within water agencies, supplemented by a literature search. Details of the incidents were entered into a microcomputer data base and this has recently been updated. To date, 144 groundwater contamination incidents have been documented in the inventory. The inventory is not exhaustive, and there are undoubtedly other undocumented or undiscovered incidents. Nevertheless it has provided a starting point for investigating the extent and seriousness of groundwater pollution in Australia, and for assessing national needs for aquifer protection strategies.

The major regional aquifers affected by pollution are:

Aquifer	*Number of incidents*
Superficial formations, Perth Basin	27
Gambier Limestone and equivalents, Otway Basin	21
Fyansford Formation and Brighton Group, Port Phillip Basin	11
Cainozoic volcanics, Melbourne	10
Fractured Silurian rocks, Canberra	5

The locations of these aquifers are shown in Figure 1. The remaining 70 incidents are distributed among several other aquifers. The main problem aquifers, and the increasingly vulnerable aquifers, are shallow and unconfined and underlie regions of intensive urban, industrial or agricultural development.

A total of 26 cases in the inventory are described as having serious effects on water use. In general these cases affect drinking water supplies, or have intractable pollutants, or have deleterious effects on surface waters. Another 60 cases are described as having limited effects on water use; 25 cases apparently have no effects on water use; and the effect on water use is unknown in 33 cases (Fig. 6). Many of the cases described as having little or no effect on water use are of concern for other reasons, such as degradation of surface waters, or alienation of potential resources.

Of the documented incidents 38 are described as diffuse and 106 as point-source. Most of the diffuse contamination is defined by plumes of high nitrate concentration. The largest of these is in a Tertiary limestone aquifer in southeast South Australia (Fig. 5). In this region nitrate concentrations in groundwater exceed 45 mg/L over 270 km^2 of pastoral land (Waterhouse, 1977; Dillon, 1988). Much of this nitrate can be considered as diffuse pollution, resulting from a century of grazing cattle. The main source is atmospheric nitrogen fixed by clover grasses (Dillon, 1988). The cattle redistribute nitrogen unevenly over the pastures, enhancing leaching of

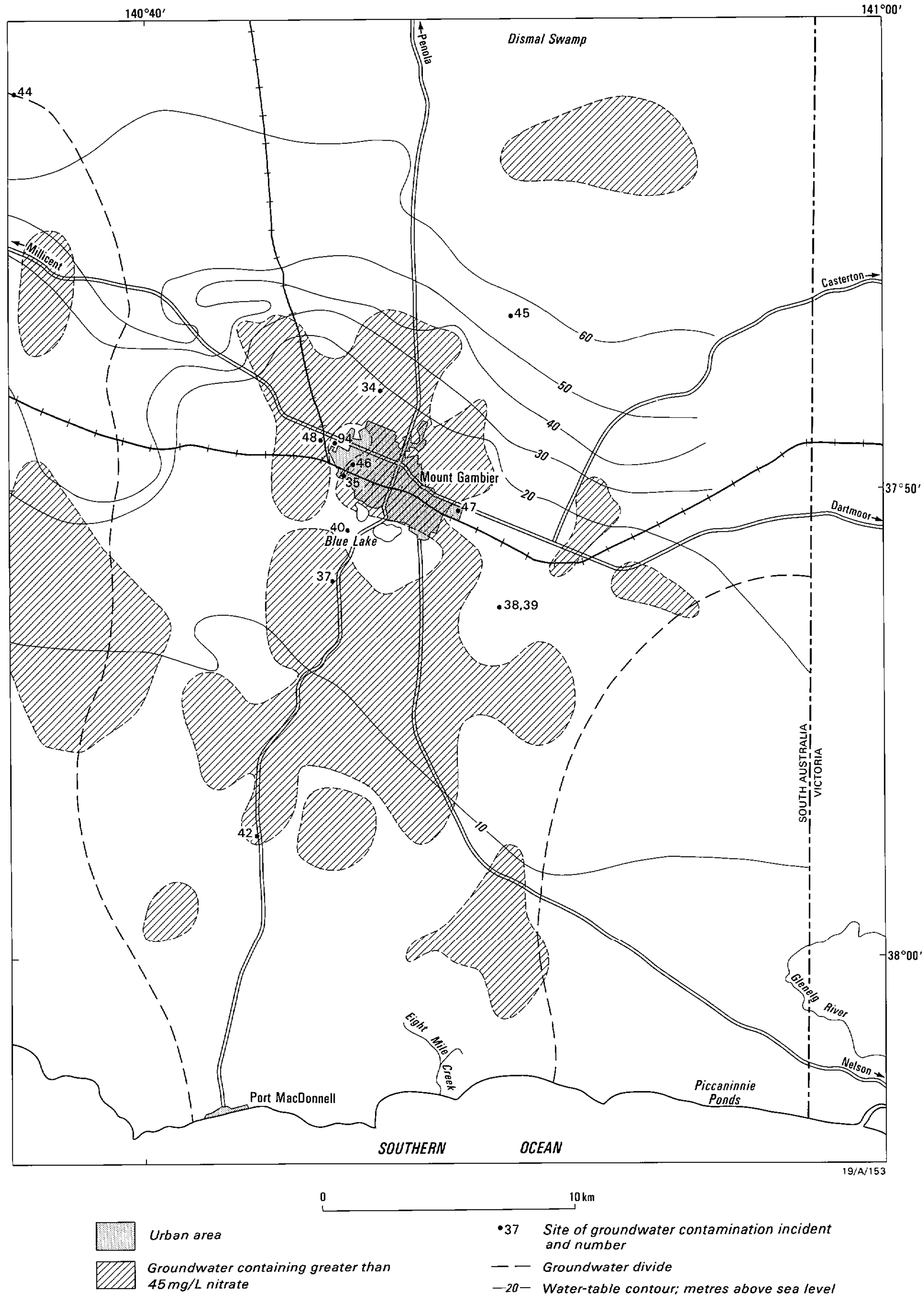


Fig 5. Nitrate concentrations in the Gambier Limestone aquifer, southeast South Australia (after Waterhouse, 1977)

nitrate. Infiltration time through the unsaturated zone, which averages 15 m deep, is 20-30 years .

An analysis of contaminant sources for all incidents shows the following distribution:

Contaminant source	*Number of incidents*
Industrial effluent	46
Sewage	26
Landfill leachate	16
Petroleum products	16
Food processing waste	11
Mining	15
Agriculture	14

This distribution is illustrated graphically in Figure 6. Several of the industrial effluent incidents are directly related to the chemical industry. Figure 7 shows the extent of groundwater pollution plumes in the industrial area of Kwinana on the Swan coastal plain in Western Australia. The main pollution plumes in this area are described as being in the 'high risk' category (Hirschberg, 1989). This is defined as high risk to the environment or population because of toxicity, volume of effluent or location. Pollutants in this category include heavy metals, cyanide, arsenic, pesticides, organochlorides and hydrocarbons. High risk groundwater pollution plumes require careful management, regulation and rehabilitation. In fact, the known plumes in this area are monitored , and contaminated groundwater is being recovered from several of them. According to Hirschberg's classification, the 'moderate risk' category includes plumes with high ammonia, nitrate, sulphate, and phosphorus concentrations, and surfactants. These plumes require regular monitoring and assessment. 'Low risk' pollution plumes are those with moderately elevated values for BOD, ammonia and nitrate, and increased salinity; these are recognised and recorded, but no control is required.

Contamination from sewage is generally from unsewered areas with a large number of septic tanks. Nearly half of the Perth urban area, with one million people, is unsewered, and relies on septic tanks. High nitrate concentrations in groundwater are causing algal blooms in wetlands (Appleyard & Bawden, 1987). The nitrogen input to groundwater in the

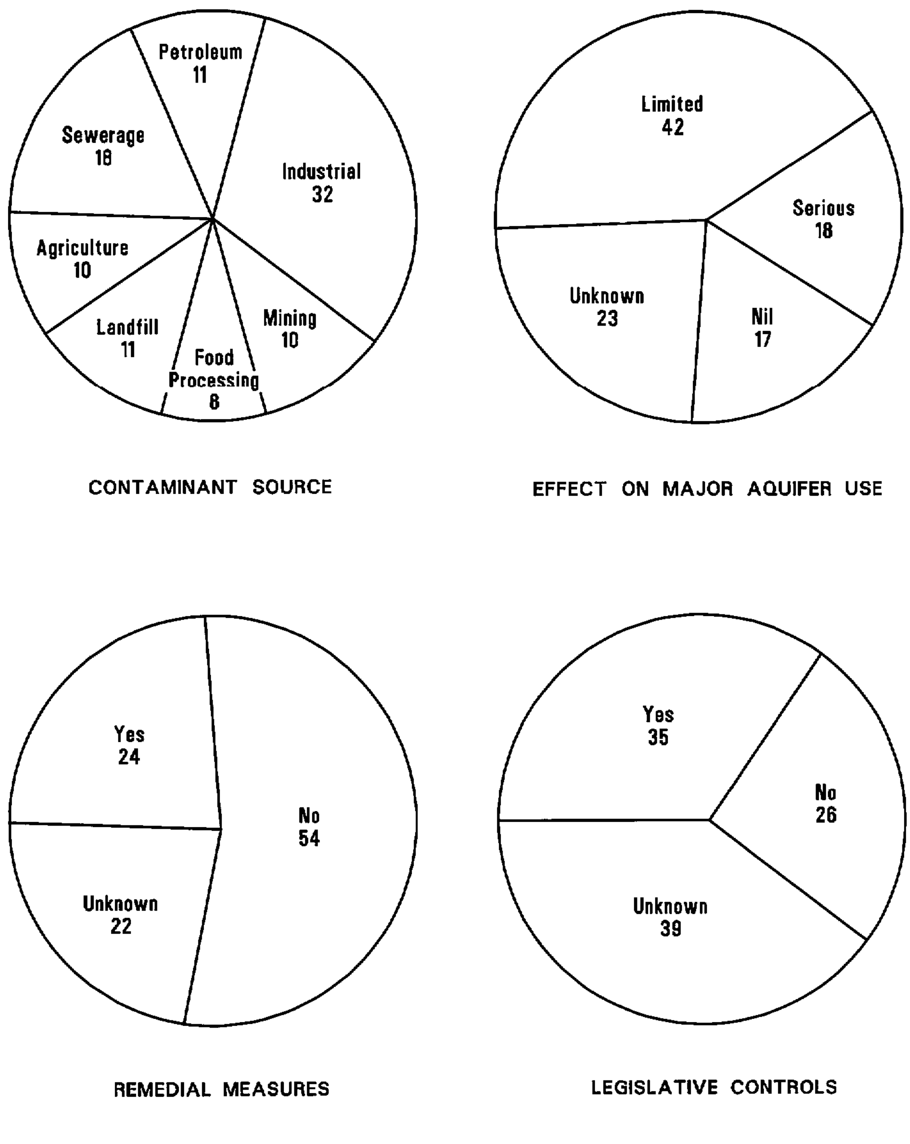


Fig 6. Groundwater contamination incidents in Australia; contaminant source, effect on major aquifer use, remedial measures and legislative controls

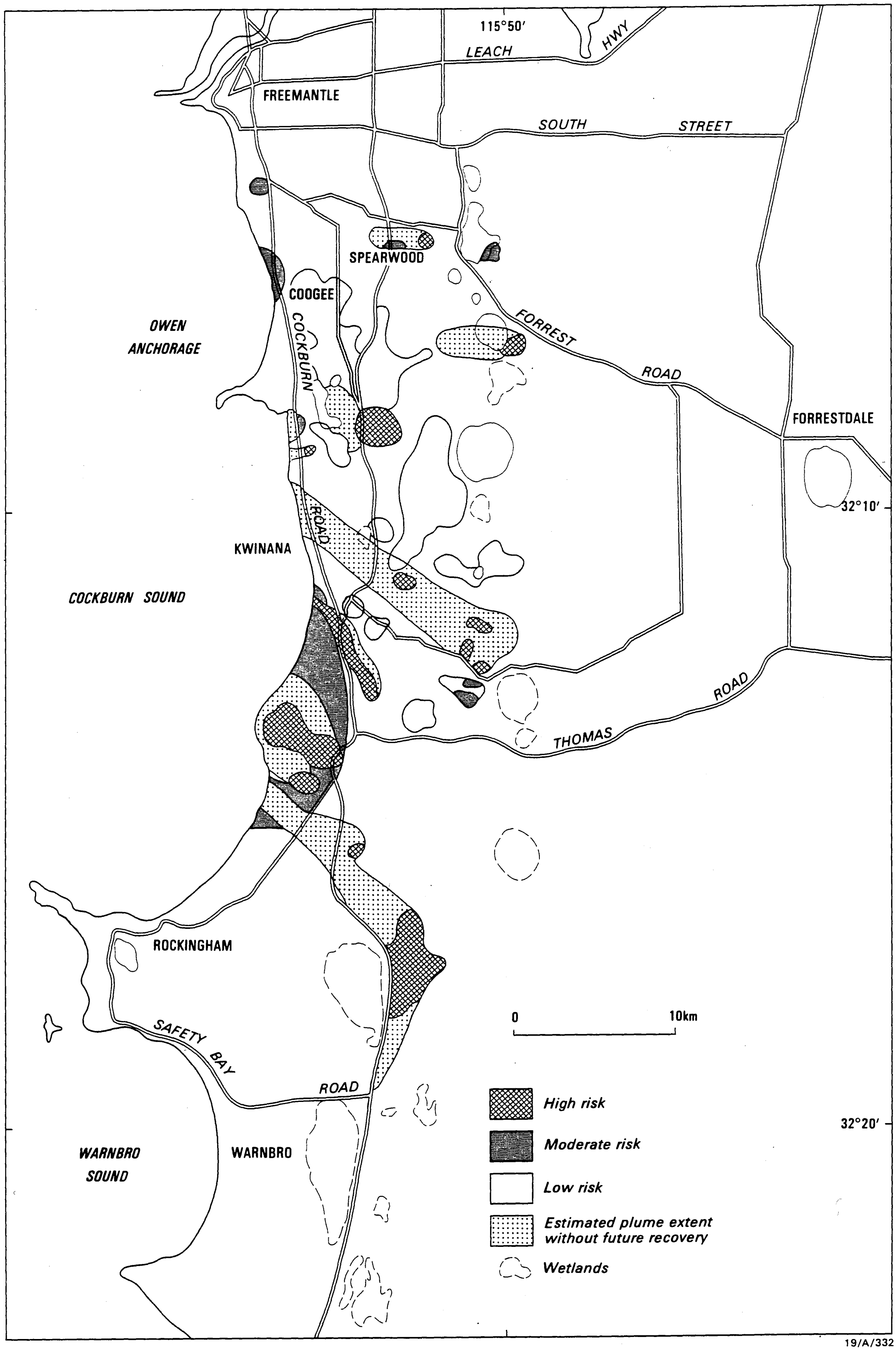


Fig 7. Groundwater pollution plumes in Quaternary sand aquifer, Perth coastal plain, Western Australia (after Hirschberg, 1989)

unsewered area is estimated as 260 kg N/ha/y, about three times that of sewered areas (Gerritse & others, 1989). The nitrate concentrations in water bores beneath the unsewered areas are 25-80 mg/L NO_3, compared with less than 14 mg/L NO_3 beneath the sewered areas. There is also a likelihood of widespread bacterial contamination of groundwater beneath the urban area (Parker & others, 1981).

Contamination from petroleum products is not commonly reported because of possible litigation, and there are probably many more incidents than are documented. An example is the case of a cinema in Canberra where a fatal explosion led to the discovery of a pollution plume containing 32000 L of petrol and underlying 0.5 ha in the heart of the city (Jacobson, 1983). This occurred in a shallow aquifer of weathered and fractured Silurian mudstone. Canberra is a planned city and the area immediately upgradient from this incident is zoned for light industry including motor vehicle service stations. These facilities contain petrol tanks set 3-4 m below ground level and bedded in sand. Remedial action was undertaken by pumping to depress the water table and then skimming off the pollutant (Fig. 8). Investigation of the fatal accident has led to the tightening of local regulations governing the installation and monitoring of underground fuel tanks.

Incidents relating to mining reflect a legacy of past uncontrolled mining which caused pollution of both surface water and groundwater, prior to the introduction of environmental impact legislation in the early 1970's. In some cases this has required massive, publicly funded, rehabilitation works, for instance at the former base metals mine at Captains Flat, New South Wales (Jacobson & Sparksman, 1988). At this site rehabilitation works have removed the risk of catastrophic collapse of tailings dumps, but have left a chronic problem of acid mine waters polluting a river, several decades after mining ceased.

In addition to the documented groundwater contamination cases there are known to be a large number of bores with high nitrate concentrations of anthropogenic origin, especially in agricultural regions (Lawrence, 1983). In New South Wales, inspection of the state monitoring data base revealed 287 such locations with nitrate concentrations greater than 45 mg/L (Jiwan & Gates, in press). Detailed investigation of these cases has not yet been undertaken.

The pollution of shallow aquifers with agricultural pesticides is a potential problem. Our recent investigations at Shepparton, an irrigated fruit-growing

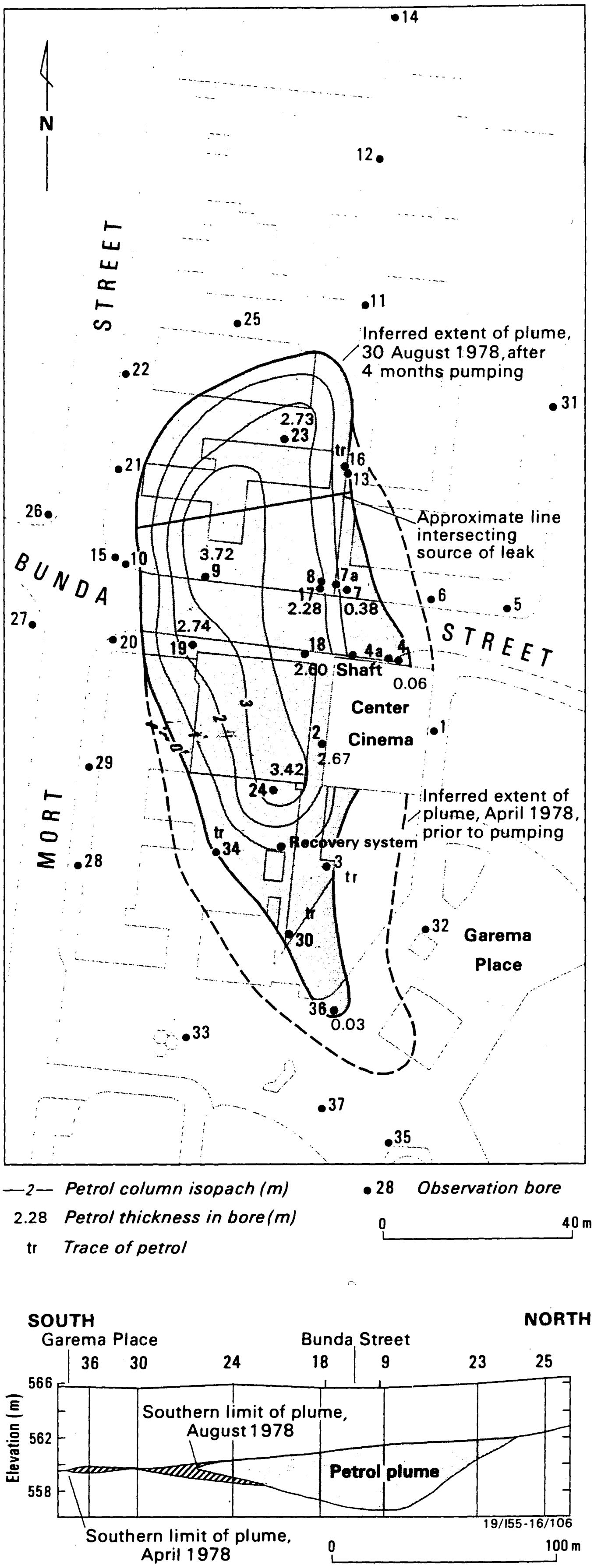


Fig 8. Petrol pollution plume in fractured Silurian mudstone, Canberra (Jacobson, 1983)

and dairying area in southeast Australia, included collection of samples from about 20 bores (Bauld, in press). A diverse range of groundwater quality parameters have been analysed, including major and minor element inorganic chemistry, trace elements, and nutrient (nitrogen and phosphorus) chemistry. Microbes indigenous to the aquifer have been examined because of their potential for degrading organic contaminants reaching the water table. Microbes that are indicators of faecal pollution and/or are opportunistic pathogens, have been analysed, as have pesticides. Preliminary results indicate the existence of polluted "hot spots" in this unconfined aquifer of Quaternary sediments. In these hot spots, nitrate concentrations and/or faecal indicator populations are significantly above background levels. In some instances, these approach or exceed widely recognised safe levels for drinking water. The most likely sources are fertilisers (nitrate) and animal wastes (faecal indicator bacteria). Pesticides were detected in about one quarter of the sampled bores: the herbicides atrazine and simazine and their degradation products were identified. Concentrations at the time of sampling were below health risk levels.

GROUNDWATER QUALITY MONITORING NETWORKS

Rationalisation of a large groundwater quality monitoring network in the state of New South Wales is presently being undertaken (Gates & Verhoeven, in press). In this state, groundwater quality information has been collected for 80 years, with 2000 bores monitored on a 5-yearly basis. However users of the information now require more accurate water quality data and a greater range of parameters. A new approach defines the users' requirement either for long term data or for issues-related data. The need for long term data is to be addressed by the state bore network, whereas the need for issues-related data is to be met by regional or project networks. Recommended key indicators for particular groundwater issues have been defined (Table 1).

The state groundwater quality network is being re-designed by Gates & Verhoeven (in press) to contain 200 bores. These will be monitored permanently for a wide range of groundwater quality parameters to determine departure from initial baseline values. Regional groundwater quality networks are to be used for specifically defined issues including pesticide contamination, salinity problems and overpumping. These networks will contain about 2000 bores, which will be monitored for several years or decades depending on regional priorities. A trial regional network has been

Table 1

Key indicators for groundwater issues
(after Gates & Verhoeven, in press)

Issue	Indicators
Salinity	EC,pH,major ions
Iron bacteria	*Gallionella*,Fe(total), Fe(soluble)
Resource evaluation & management	EC,pH,major ions,NO_3,SiO_2
Organic pollution	Hydrocarbons as appropriate
Inorganic pollution	Heavy metals,NO_3,PO_4,others as appropriate
Pesticides	As appropriate
Biological contamination	*E.coli*,faecal streptococci, bacteria,viruses,NO_3,N(total),NH_4
Bore corrosion	pH, dissolved gases (CO_2,O_2,H_2S),EC,Fe (total),Fe (soluble),major ions

established in part of central New South Wales: about 280 bores have been defined as monitoring 12 separate groundwater issues; specific parameters are being measured accordingly; and an appropriate frequency of measurement has been defined for each bore (Table 2). Project groundwater quality networks are to be used for short term scientific investigations; bores will be intensively monitored for 2-5 years and then closed.

Rationalisation of groundwater quality monitoring networks is also being undertaken in the state of Queensland. McNeil and others (1991) have re-designed the regional monitoring network for the Condamine valley, a region of irrigated agriculture in southeast Queensland. Statistical analysis of existing groundwater and surface water data has been used to select a network of sensitive monitoring sites, and to define the most appropriate times of sampling. The number of monitoring bores has been cut from 200 to 10. These are being sampled once for a wide range of parameters, then at 2-year intervals for specific agricultural pollution indicators, including heavy metals, pesticides and nutrients. Similar rationalisation of the surface water monitoring network has been carried out. Even with limited data, trends towards increasing salinity and nitrate concentrations have already been identified in parts of this region. Other groundwater quality networks in Queensland are to be re-designed on similar lines.

Current site-specific monitoring systems are reported for 68 out of 144 documented groundwater contamination incidents in the National Inventory. The monitoring agencies include federal, state and local government agencies and industrial concerns. The frequency of monitoring, and the number of parameters monitored, varies considerably.

Table 3 shows examples of monitoring bore networks for selected groundwater pollution sites. At the Ranger uranium mine, in the Northern Territory, groundwater is sampled from bores commissioned by the mining company and the state regulatory agency. Monitoring is overseen by a federal agency, the Office of the Supervising Scientist, which was specially created for the surveillance of uranium mining in this region, and research into its environmental effects. Groundwater in both deep and shallow aquifers is monitored in bores around the perimeter of the mine and close to the tailings dam (Fig. 9). Bores beside the tailings dam show increasing sulphate concentrations and slightly increased uranium concentrations over several years (Supervising Scientist, 1990). Although these concentrations are not of immediate concern, they demonstrate a pathway from the tailings dam to the environment which will be a future concern.

Table 2

Groundwater quality regional network in central New South Wales (after Gates & Verhoeven, in press)

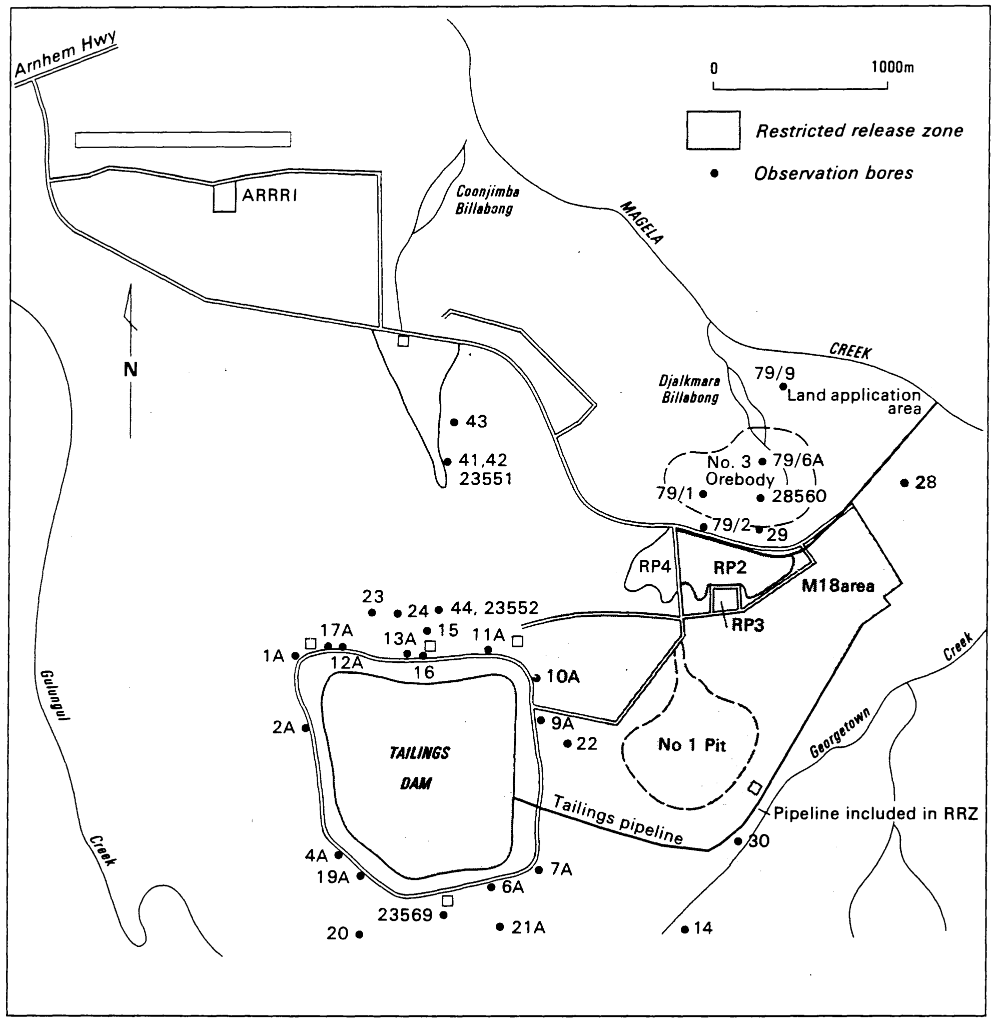
Issue	Monitoring bores	Parameters	Frequency
High groundwater use	43	1,2*	3 times/year
Major storages/ high river levels	31	1,2*,9	Twice/year
Agricultural chemicals	27	site specific	Annual
Intensive rural industry	27	1,2*,9,6*	Annual
Dryland salinity	26	1,2*	Annual
Irrigation salinity	26	1,2*	Annual
Urban contamination	26	1,9	Annual
Nutrients in groundwater	24	1,2*,9	Annual
Industrial/ mining	19	1,2,5*	Annual
Wildlife areas	17	1,5*	Annual
Iron bacteria	7	1,3,8*	Three yearly
Bore corrosion	0	1,2*,8	Five yearly

Parameter key

* = Possibly initial sampling only
1 = Field EC, pH, T
2 = Major ions, NO_3, SiO_2, Fe, pH, EC
3 = Iron bacteria (*Gallionella, Crenothrix, Leptothrix*), Fe, Fe(soluble), Eh, pH, T
4 = TOC, specific hydrocarbons
5 = Heavy metals, specific nutrients, Fe, Fe(soluble), pH, Eh, EC
6 = TOC, specific pesticides (from gas chromatograph scan)
7 = E. coli, faecal streptococci, bacteria, viruses, N(k)
8 = pH, Eh, dissolved gases (CO_2,O_2,H_2S)
9 = Nitrogen(k), nitrate, nitrite, ammonia, phosphate

Table 3
Examples of observation bore networks

Network	Problem	Number of bores	Frequency of sampling	Key indicators	Reference
Tullamarine Vic	Industrial waste disposal	9	Six monthly	Zn, TDS	Shugg, 1981
Allansford Vic	Dairy factory effluent	5	Three monthly	As, NO_3, methane, TDS	Shugg, 1984
Porepunkah Vic	Landfill	4	Three monthly	NO_3	Shugg, 1980
Springvale	Landfill	3	Three monthly	Mn, TDS	Leonard, 1979
South Oakleigh Vic	Landfill	8	Three monthly	phenols, TDS	Leonard, 1983
Canberra ACT	Below ground storage of petrol	30	Monthly	petrol	Jacobson. 1983
Rum Jungle NT	Waste rock leachate and tailings burial	30	Various	SO_4, pH, Ra, heavy metals	NT Dept Mines & Energy, 1986
Ranger uranium mine NT	Tailings dam seepage	30	Various	SO_4, Ra	Super-vising Scientist, 1990



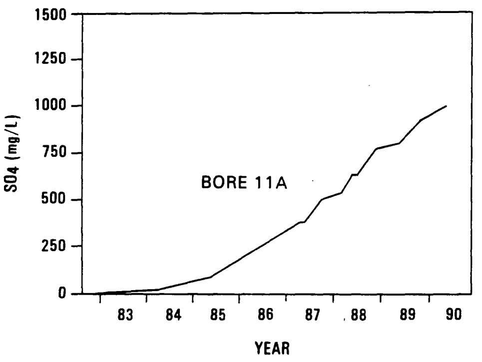


Fig 9. Observation bore network at the Ranger uranium mine, Northern Territory (after Supervising Scientist, 1990)

MONITORING TECHNOLOGY

Advances in monitoring technology have been made recently by Australian researchers. These include: extension of the use of electromagnetic survey techniques to monitoring groundwater salinity and pollution problems; and improved sampling and analytical procedures for determination of organic compounds in groundwater.

Electromagnetic induction techniques have been applied to mapping and monitoring soil and shallow aquifer salinity in southeast Australia (Williams, 1987). Airborne electromagnetic techniques could be used for broad scale problem identification and monitoring (Lee & Ignetik, in press). Experimental work has also been carried out to determine the effectiveness of transient electromagnetic sounding techniques in monitoring changes in groundwater pollution plumes. At a polluted site in Western Australia, Barber, Davis & others (in press) have successfully tested a range of interpretation techniques for electromagnetic soundings. They concluded that there is scope for improvement in field operation and interpretation, which will lead to more cost-effective assessment of groundwater pollution, by reducing the need for extensive networks of monitoring bores.

Integrated sampling and analytical procedures have been developed for the determination of volatile and non-volatile organic compounds in groundwater (Barber, Briegel & others, in press). The sampling procedures involve purge-pumping and sampling in situ using syringe samplers . In a study at a Western Australian landfill site, volatile organics were determined by purge and trap GC techniques; non-volatile organic compounds were characterised by a fractionation technique using exchange resins. Further research studies used diffusion cells buried in boreholes and connected to the surface by small diameter nylon tubes, to determine concentrations of dissolved methane and dissolved oxygen in groundwater (Barber & Briegel, 1987; Barber & others, 1990). These techniques, developed for research studies, could be adapted for routine monitoring.

Australia's vast distances and the high cost of data collection have led to the development of remote-area data acquisition platforms for groundwater and other hydrological and climatic data. At a remote locality in central Australia we monitored piezometric levels for several years using a computer-controlled and solar-powered system (Johns & Jacobson, 1988). Sensors are linked by cable or radio to a platform where data are recorded on tape and/or transmitted by satellite. This system is now being developed for a range of water quality parameters. New 'intelligent interface' technology has been developed by CSIRO Australia to link existing data loggers or remote location sensors with the INMARSAT-C satellite communications system (Fig.10).

AQUIFER REMEDIATION

Remedial measures have been undertaken in 35 of the 144 documented groundwater pollution incidents (Fig. 6). These measures can be categorized as follows:-

Remedial measures	*Number of incidents*
Groundwater recovery and treatment, disposal or re-use	16
Closure of site or changed effluent disposal practice	10
Elimination of source	5
Bioremediation	2
Removal of contaminated ground	2

The success of the remedial measures is categorised as 'great' in 7 cases, 'moderate' in 10 cases and 'limited' in 3 cases. In 15 other cases the effectiveness of remedial measures is unknown. In the majority of documented incidents (109), no remedial measures have been undertaken and this includes several cases described as having serious effects on water use.

Table 4 lists selected examples of remediated aquifers. One example is the Quaternary sand aquifer at the Australind mineral processing plant in the southern Perth basin, Western Australia. At this site, iron staining was observed in a nearby estuary and high sulphate levels were monitored in nearby bores in the 1980's. An exploratory drilling programme identified a plume of polluted groundwater beneath, and adjacent to the factory (Whincup & others, 1987). Pollution originated from leakage of sulphuric acid from storage facilities, and was manifest as high sulphate and iron

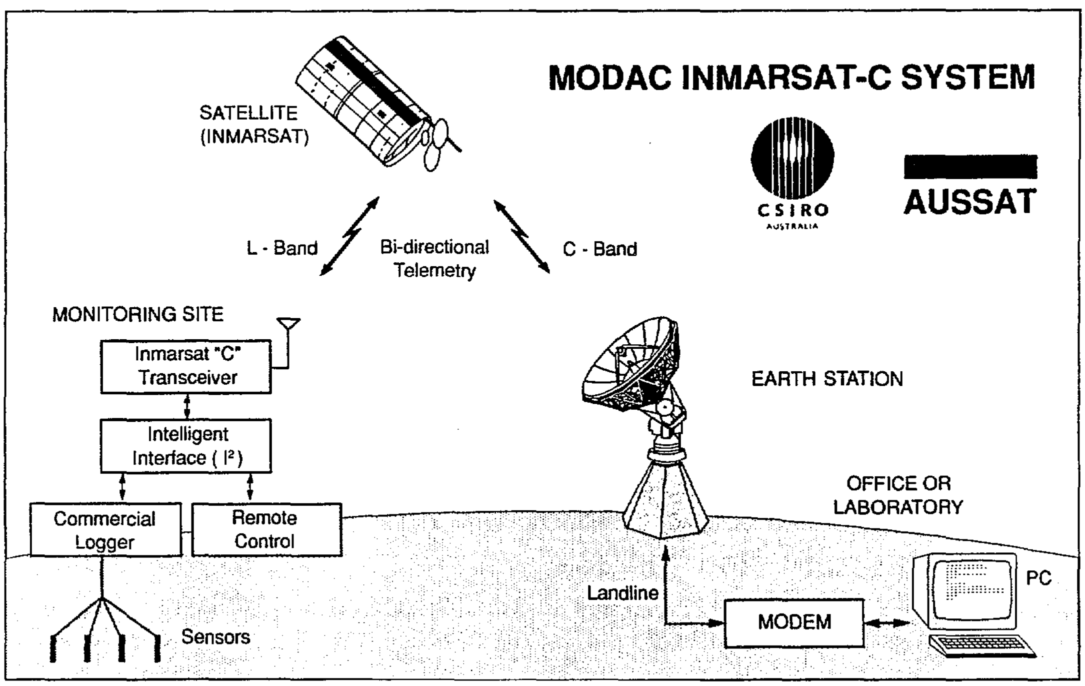


Fig 10. Satellite communications and remote monitoring system recently developed by CSIRO Australia

Table 4
Examples of aquifer remediation

Site	Area (ha)	Aquifer	Pollutant source	Remediation	Reference
Bayswater WA	1	Sand	Chemical waste pile	Processing into new product	
Australind WA	32	Sand	Tailings seepage	Recovery & reuse	Whincup & others, 1987
Kwinana WA	200	Sand	Tailings seepage	Recovery & reuse, grouting	Alcoa, 1990
Canberra City ACT	1	Fractured mudstone	Below ground petrol tank	Recovery by skimming bores	Jacobson, 1983
Millel SA	100	Limestone	Cheese factory effluent	Recovery, dilution, land-spreading	Smith & Schrale, 1982
Rum Jungle NT	400	Fractured schist	Waste rock leachate & buried tailings	Sealing of waste rock heaps	NT Dept Mines & Energy, 1986

concentrations and low pH. The contaminated area covered 32 ha, representing about 600 000 m^3 of groundwater, contaminated by about 2300 t of acid. Production bores were commissioned to recover contaminated groundwater, and at the rate of 2000 m^3/d the contaminated groundwater should be recovered within 10 years. Disposal of this water is partly to the factory process water stream; partly by discharge to calcareous sand dunes; and partly by chemical neutralisation before reinfiltration to the aquifer. Contaminated domestic bores in the surficial aquifer were replaced with deeper bores from a confined aquifer.

At Rum Jungle, in the Northern Territory, a major project has been undertaken to rehabilitate an abandoned uranium and base metals mine. This has involved capping and re-vegetating waste rock dumps rich in sulphides so that heavy metal pollution of a nearby river has been significantly reduced. However, polluted groundwater remains beneath the site and requires additional monitoring (Northern Territory Department of Mines and Energy, 1986).

Bioremediation technology has been applied to several sites polluted by chemicals including hydrocarbons (Knight, 1991).

AQUIFER VULNERABILITY MAPPING

The mapping of aquifer vulnerability may be undertaken for general planning and groundwater protection purpose or to evaluate the impact of particular land uses.

A current project is under way to map the vulnerability of the shallow aquifers of the Perth Basin to contamination (Appleyard, in press). The map uses a modified form of the US Environmental Protection Agency's DRASTIC vulnerability index system (Aller & others, 1985). DRASTIC is an acronym expressing ranking factors for Depth to water table, Recharge, Aquifer media, Soil media, Topography, Impact of unsaturated zone, and hydraulic Conductivity. The Perth map will depict five classes of different vulnerability, using red for highly vulnerable areas, and green for areas of low vunerability. The map is being compiled at a scale of 1:500 000, and two sheets cover the basin. The map also contains topographic information, and location of waste disposal, industrial and mining sites. There are about 700 possible sources of groundwater pollution in this basin (Hirschberg, 1989). Symbols for these sites are colour-coded on the basis of their perceived hazard. The map is intended as a tool for planning the siting of industrial development and for assessing the need for groundwater protection.

A second major project is being undertaken in the state of New South Wales, where there is a substantial increase in intensive cattle farming. Cattle feedlots are sources of pollution of shallow aquifers, and are consequently difficult to site. In this study, Gates & others (in press) are zoning the whole state (800 000 km^2) for vulnerability of shallow aquifers, and are preparing a feedlot site-selection map. Six broad zones of suitability have been identified.

The increasing availability of GIS is expected to facilitate the vulnerability mapping of important aquifers or regions. GIS combine computerised mapping and data base management functions. They enable users to combine and analyse layers of different spatial data. Information can be studied interactively or can be presented as maps.

GROUNDWATER PROTECTION GUIDELINES

The legislative and institutional framework for groundwater quality management varies in Australia, between and within states. This has led to a diversity of approach and philosophy on groundwater quality management. Growing awareness of these issues within a number of national policy-setting fora has in turn led to the present development of groundwater protection guidelines by the Australian Water Resources Council (in press, a). These are intended to provide a broad national framework within which state and local agencies can develop their own specific resource protection measures.

The goal of groundwater protection is stated as "*... to protect the groundwater resources of the state ...to... support their identified beneficial uses in an economically, socially and environmentally sustainable and acceptable manner*". This goal relies on an hierarchical framework of existing or potential beneficial uses for the water in an aquifer. These beneficial uses are particular values or uses of the environment that are conducive to public benefit, welfare, safety or health, and determine the level of protection afforded to each groundwater body. The identified beneficial uses of groundwater are defined as: human consumption and food production; agricultural, industrial and mining uses; ecosystem support; and no definable beneficial use, with possibly controlled degradation of the aquifer. These beneficial uses have also been referred to as protected environmental values.

Generally, the designated beneficial use classification should be that of the most valuable potential use of that water. Once the beneficial use determination has been assigned, the obligation for protection of groundwater under this framework lies with the industry or activity which has the potential to contaminate the groundwater resource. This is consistent with the 'polluter-pays' principle.

Implicit in the beneficial use concept is the requirement for sufficient hydrogeological knowledge regarding the groundwater systems so that each system can be assigned to an appropriate beneficial use category. This information may be extremely costly to obtain.

The concept of beneficial use can be used further to define 'pollution' as occurring when the water quality has deteriorated to a point where the existing or potential beneficial uses are diminished.

The main components of the groundwater protection strategy are : particular forms of government intervention, including consideration of the 'polluter pays' principle; and legislation, which is grouped under the broad objectives of groundwater management, land-use planning, and environmental protection legislation.

Groundwater management strategies can include: the planning framework; vulnerability and vulnerability mapping; aquifer classification systems; levels of action for classified groundwaters; and well-head protection plans. Land use planning and environment protection strategies may also be developed under various legislative powers. Development of a regional groundwater protection plan requires public involvement, strategic assessment of groundwater resources, and definition of beneficial uses.

It is likely that groundwater protection in Australia will, in the long term, move away from its reliance on groundwater management strategies towards land use and environmental protection strategies.

Options for groundwater protection include the degree of degradation allowable; water quality standards; and land use and environment protection considerations. Market incentives may be necessary; monitoring and review procedures need to be established; and contingency plans developed.

The guidelines have been framed by the Australian Water Resources Council so that they can be adapted to different regulatory situations in the states. Implementation will require coordination between agencies with different functions. The national goal for the coming decade is to protect those groundwater resources that are either used for drinking water or support important ecosystems; and to provide a beneficial use classification for all other aquifers. The effectiveness of national groundwater management and protection strategies will depend on their enforcement. This in turn will rely heavily on good monitoring and adequate enforcement procedures.

NATIONAL WATER QUALITY MANAGEMENT STRATEGY

Sustainable water quality management is as an important issue in Australia, and the Australian Water Resources Council (in press, b) is developing a national management strategy. This is intended as a framework within which state agencies can institute complementary policies and programmes for water quality management. The groundwater protection guidelines (see above) form one component of this strategy.

The key outcome of the national water quality management strategy is sustainability. This includes aspects of water resources protection, and anthropogenic and natural change, as well as social, economic and financial issues. The main components of the water quality management strategy are: a model administrative framework; national drinking water guidelines; guidelines for sewerage systems; and guidelines for water quality management in the rural environment.

Other strategic management concerns are to be addressed by: water quality guidelines; groundwater protection guidelines; guidelines for urban stormwater systems; guidelines for specific industries; guidelines for integrated urban waste management; community awareness; and consideration of the economic and financial aspects of water quality management.

The Australian federal and state governments are currently negotiating an Intergovernmental Agreement on the Environment. It is expected that national standards for water quality,assessment of contaminated sites, and hazardous waste management will be developed under this Agreement.

POSSIBLE AUSTRALIAN CONTRIBUTION TO REGIONAL PROGRAMMES

The Australian government is committed to ecologically sustainable development. This is manifest in the draft Australian submission prepared for the UN Environment and Development Conference in 1992. This supports, amongst other things, steps to ensure that the intellectual and technological resources necessary to achieve sustainable development are available and are applied to meet the needs of all countries.

The principles of ecologically sustainable development have been incorporated in guidelines for international development cooperation programmes and activities (Australian International Development Assistance Bureau, 1990). Among the key principles of ecologically sustainable development are: intergenerational equity; constant natural capital; an anticipatory and precautionary policy approach; limits on natural resource use; and global and regional perspectives. The listed priorities for international development assistance programmes include improved methods of environmental appraisal, a better understanding of the state of the environment, and the implementation of conservation strategies.

Many of these principles and priorities underpin the need for assessment and conservation of the quality of groundwater resources. Specific Australian expertise in groundwater quality assessment could be applied to co-operative regional programmes. This includes:

1. *Holistic surveys of contaminated, vulnerable or particularly important aquifers, covering a wide range of possible contaminants* (Fig 11). Such surveys are exemplified by the investigation at Shepparton, in southeast Australia, described above, and result in an appreciation of the 'health' of the aquifer. This enables assessment of cost-effective monitoring, management and protection needs for these aquifers.

2. *Vulnerability mapping of regional aquifers.* This can be done to assess the impact of particular land uses, as in the New South Wales feedlot study referred to above, or for planning and protection purposes as in the Perth study. Geographic Information Systems allow the ready integration and analysis of complex overlays of relevant spatial data. Use of this technology facilitates the vulnerability assessment and map production.

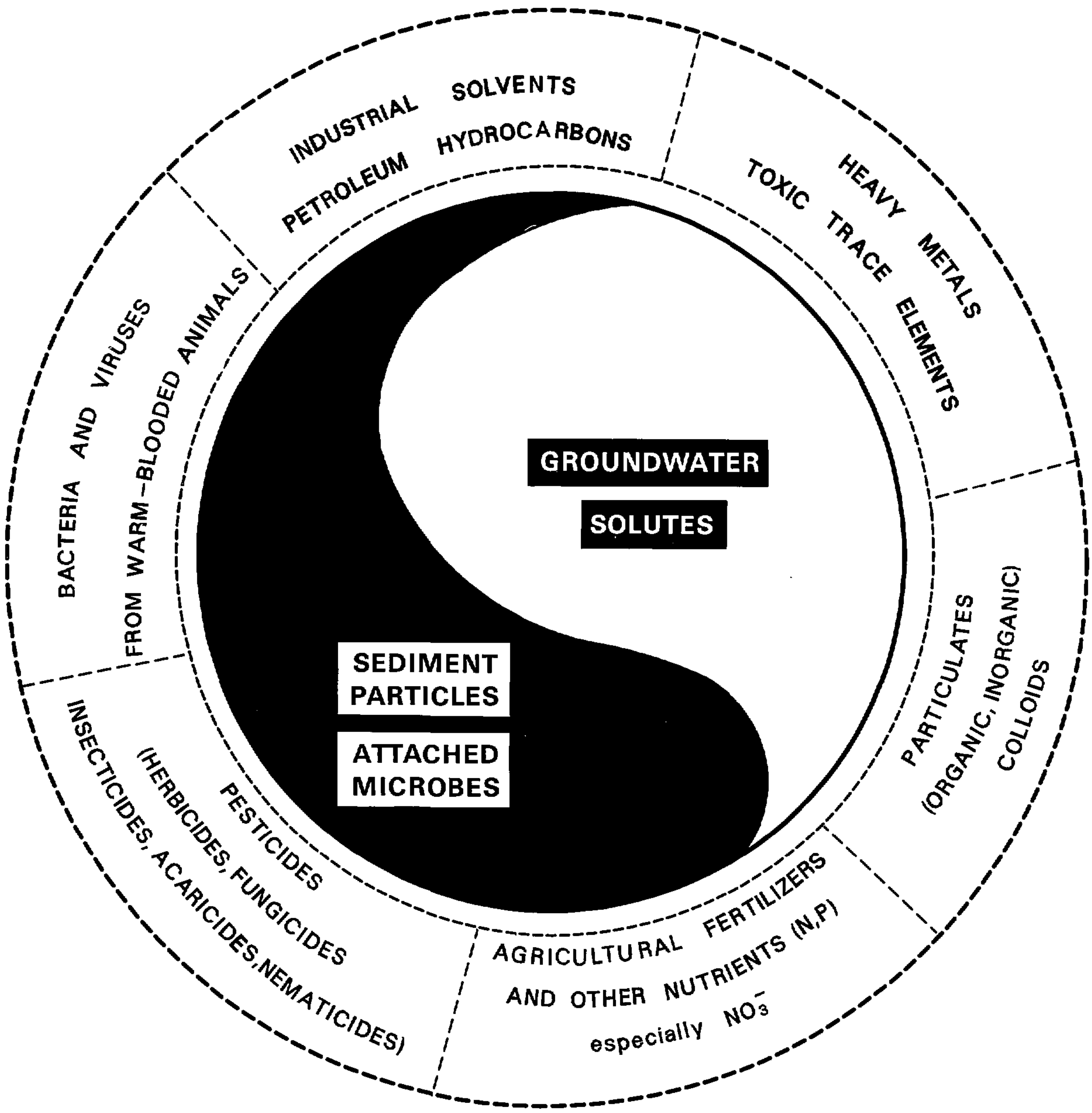


Fig 11. Holistic representation of a pristine aquifer under threat from natural and anthropogenic contamination

3. *Design and rationalisation of monitoring bore networks.* Examples of the rationalisation of groundwater quality monitoring networks in New South Wales and Queensland are given above. This rationalisation is undertaken for cost-effectiveness, and to make the monitoring networks more responsive to emerging groundwater quality issues.

4. *Monitoring technology.* The Australian problems of large distances and high costs have led to the research and development of advanced technology for groundwater and other environmental monitoring.

5. *Training.* Australia has training institutes at various levels, and specialist courses can be arranged.

CONCLUSIONS

1. Groundwater quality is a serious constraint on the development of Australia's water resources. Shallow aquifers in much of the continent are naturally saline or contain deleterious elements.

2. Groundwater-related salinisation of agricultural areas is a major national problem in Australia.

3. Increasing salinity is a serious problem in several stressed inland and coastal aquifers.

4. Pollution of regional aquifers is an emerging problem in several regions of intensive urban and agricultural development.

5. Groundwater quality monitoring networks are in place in several states and regions, and are being rationalised in order to increase cost effectiveness.

6. Advances in monitoring technology have been recently made by Australian researchers.

7. Increasing public awareness of groundwater pollution has led to the vulnerability mapping of important aquifers.

8. National groundwater protection guidelines are being formulated as part of a national water quality management strategy.

9. The Australian government is committed to principles of ecologically sustainable development in international development cooperation programmes.

10. Specific Australian expertise that could be applied to regional programmes includes holistic contaminant surveys of important aquifers, vulnerability mapping, design of monitoring networks, monitoring technology, and training.

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