

Groundwater

Explanatory notes to the Groundwater Map
of the Northern Territory **June 2008**



Bibliographic Reference

Tickell, S., (2008), Explanatory notes to the Groundwater Map of the Northern Territory.
Northern Territory Government Department of Natural Resources the Environment The Arts and Sport,
Technical Report No. 12/2008D

ISBN: 1 920772 95 2

For further information contact:

Department of Natural Resources the Environment, The Arts and Sport
PO Box 496, Palmerston, NT, 0831
Australia

Units used in the report

L	litre
sec	second
mm	millimetre
m	metre
km	kilometre
mg	milligram

Copyright and Disclaimer

© 2008 Northern Territory Government

Copyright resides with the Northern Territory Government, 2006. Information contained in this publication may be copied or reproduced for study, research, information, or educational purposes, subject to inclusion of an acknowledgment of the source.

Cover photo: Water drilling, Howard East area, David Hancock



Contents

Summary	2
Introduction	3
Climate	3
Geology	4
Hydrogeological Mapping	4
Aquifers	6
Aquifer Types	8
Unconsolidated sediments with intergranular porosity	8
Sedimentary rocks with intergranular porosity	9
Fractured and weathered rocks	10
Fractured and weathered rocks with minor groundwater resources	11
Fractured and weathered rocks with some intergranular porosity	12
Fractured and karstic rocks, with local aquifers	12
Fractured and karstic rocks, with extensive aquifers	14
Recharge	15
Discharge	17
Springs and stream bed seepages	17
Evapotranspiration	18
Variation of discharge with time	19
Discharge features across the Territory	20
Impacts of long term rainfall variations	21
Water quality	23
Sources of dissolved salts	23
Salinity	24
Water quality and usage	24
Pollution and groundwater	25
Use and management of groundwater	26
Nature and groundwater	26
People and groundwater	27
History of Groundwater Use	27
Groundwater Monitoring	28
Regulations	30
Water bores	30
Water Extraction Licences	30
Water Control Districts	30
Water Allocation Plans	30
Climate Change	30
Where to get Groundwater Information	31
Glossary	32
Acknowledgements	35
References	36
Appendix 1	38
Water quality guidelines	



Summary

The Groundwater Map of the Northern Territory presents the broad scale distribution of aquifers. Aquifers comprise the network of small spaces in rocks through which groundwater moves. They are classified according to the nature of the spaces. Seven aquifer types are shown on the map. The relatively “old” geology of the Northern Territory means that most rocks are hard and fractured with little primary porosity. Consequently fractured and weathered aquifers are the most widespread followed by fractured and karstic aquifers. Aquifers containing significant primary porosity are restricted to a few of the younger sedimentary basins.

An indication of the distance that groundwater travels between where it enters the aquifer to where it is discharged back to the surface is given on the map for each aquifer type. This has been classified as either local (less than 5 km), intermediate (5 to 50 km) or regional (more than 50 km) in scale.

Other groundwater related features are depicted on larger scale side maps. These include typical bore yields, groundwater salinity, springs and groundwater fed streams. A relict drainage system in Central Australia referred to as “palaeovalleys” is also depicted. Although the associated deposits are largely untested they have potential as useful aquifers over a considerable area.

Groundwater is an important part of the natural environment across the Northern Territory. Discharge areas support diverse water dependant ecosystems in what is otherwise an arid environment. Even in the higher rainfall areas of the north, no significant rain falls for eight months of the year. Springs, groundwater fed streams and swamps often form islands of lush vegetation surrounded by vast expanses of savannah or grassland. Such features are scattered throughout the Territory, even in the arid zone.

Human activities are especially reliant on groundwater. All towns and communities use groundwater for their water supplies.

With the exception of Darwin and Katherine, groundwater is the major water source.

The cattle, horticultural and mining industries also use groundwater as a dominant water source.

Groundwater use is managed by the Northern Territory Government. To date, seven Water Control Districts have been declared in areas where increasing usage has necessitated the need for closer management. A process of consultation with existing water users and other stakeholders is used to make “Water Allocation Plans”. These allocation plans create rules for the distribution of water between the different users. The environment is given priority as a “water user”. Sustainable water use and maintenance of the natural environment are two of the main goals of allocation plans. With the increasing pressure for development of the resource and recent changes in rainfall patterns, good management of groundwater is critical.



Introduction

This report is a summary of the current knowledge about groundwater in the Northern Territory and was written to accompany the map *Groundwater of the Northern Territory*.

Climate

The Northern Territory (referred to from here on as the “Territory”) covers a vast area (1,346,200 km²) and extends from Australia’s northern coastline some 1,600 km south to the centre of the continent. Consequently there is a marked north to south climatic zonation. This influences many aspects of the groundwater, including recharge, discharge and water quality. For practical purposes the Territory can be divided into two broad climatic zones, the “humid” zone in the north and the “arid” zone in the south. There is no sharp divide between the zones but it is commonly depicted at around the 600mm rainfall isohyet (Figure 1).

The humid zone comes under the influence of monsoon while the arid zone has a continental climate. The humid zone experiences two distinct seasons: the wet season from October to April and the dry season from May to September. Rainfall during the wet season is associated with the monsoon or with local thunderstorms. Widespread and heavy rains can occur during the monsoon. Cyclones occur each wet season and if they move inland they can develop into rain depressions which produce widespread heavy rains. Little if any rain falls during the dry season. The climate is hot and humid throughout the year in this zone.

In the arid zone the contrast between wet and dry seasons is not generally as marked as in the north. It is dry for much of the year, and has an erratic rainfall pattern, with a slight summer maximum. While no rainfall can be experienced in all calendar months, significant totals are also possible in all months, but are more likely in summer. Winters (June to August) are cool and summers (December to February) hot.

Average annual rainfall is more than 1,600 mm at the northernmost coast and progressively decreases inland to a low of less than 200 mm in the Simpson Desert in the south. The reliability of rainfall also decreases southwards from the coast. Evaporation is high throughout the Territory. Average annual pan evaporation ranges from more than 3,200 mm in the arid zone to between 3,200 and 2,400 mm in the humid zone. It mostly exceeds rainfall except during the Wet season in the northern part of the humid zone.

In the harsh climate of the Northern Territory surfacewater is often scarce. For a few months during the wet season in the north, the landscape experiences flooding but for the remainder of the year most rivers stop flowing. In the arid zone, rivers only flow for short periods after big rainfall events that can be years apart. Groundwater on the other hand is widespread and provides a reliable water source. It accounts for some 90 per cent of all water supplies.

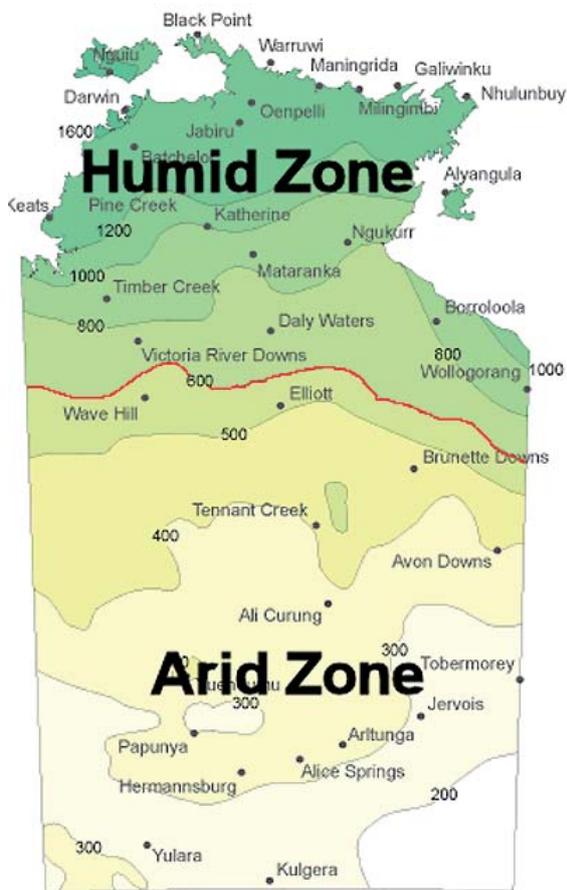


Figure 1 Mean annual rainfall and climatic zones (adapted from Bureau of Meteorology web graphic)

Geology

The distribution of aquifers and their properties are closely related to geology. The Territory's rocks are relatively old, mostly spanning the Proterozoic eon and the Palaeozoic era (Figure 2). Some were deposited during the Mesozoic era but younger formations are relatively rare. The broad geological regions are described in terms of sedimentary basins and areas which have been deformed and metamorphosed (Figure 3).

EON	ERA	PERIOD	Millions of years before present
Phanerozoic	Cainozoic	Quaternary	0
		Tertiary	2
			65
	Mesozoic	Cretaceous	141
			490
	Palaeozoic		545
		Cambrian	545
	Proterozoic		2500
		Archean	2500

Figure 2 Geological Timescale (terms referred to in the text)



Figure 3 Geological Regions (simplified from Ahmad and Scrimgeour (2006))

Hydrogeological Mapping

The 1987 map "Hydrogeology of Australia" at 1:5,000,000 scale was the first published groundwater map covering the Northern Territory (Lau and others, 1987). It depicted aquifer type (fractured or porous), aquifer scale (local or extensive) and productivity (low, moderate or high). Regional groundwater salinity and the major sedimentary basins / fractured rock provinces were also shown.

The first published hydrogeological map of an area within the Territory was "Hydrogeology of the Lake Amadeus - Ayers Rock region" at a scale of 1:500,000 (Jacobson and others, 1989). More detailed inset maps at 1:100,000 scale covered the areas around Ayers Rock, Curtain Springs and Kings Canyon. The map depicted aquifer type, yield and groundwater salinity. Springs, discharge zones and potentiometric surfaces were also shown.

A program of systematic hydrogeological mapping was started by the Northern Territory Government in 1989 with the publication of the 1:250,000 scale map of the Pine Creek Mining Region (McGowan, 1989). Since then a large proportion of the Territory has been mapped at scales ranging from 1:1,000,000 to 1:50,000, depending on the amount of information available (Figure 4). The areas covered include standard 1:250,000 mapsheets, individual cattle stations or regional scale project areas. Mapping in the arid zone generally depicts yield, salinity and aquifer type. In the humid zone groundwater salinity is low and is mostly not an issue for users. Maps in northern areas have concentrated on yield and aquifer type.

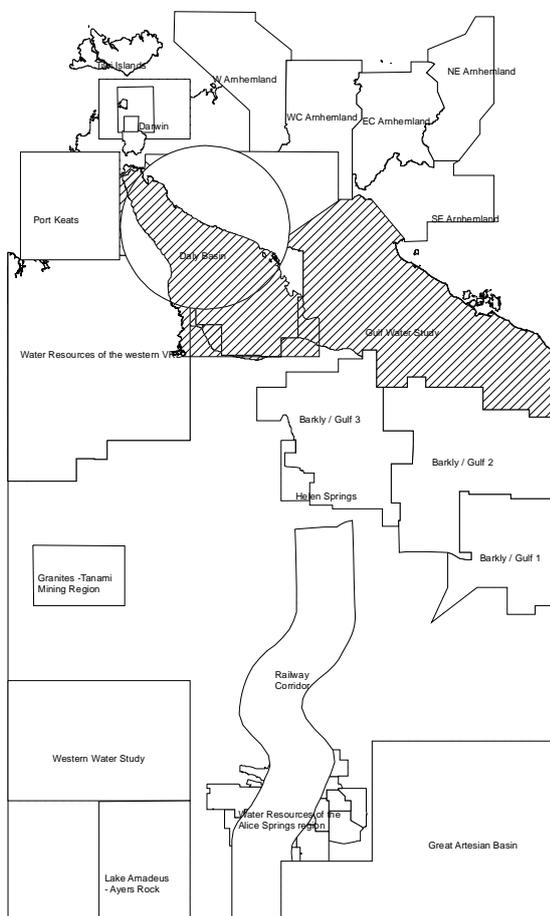


Figure 4 Water Resources mapping
 (Refer to <http://www.nt.gov.au/nreta/nretamaps/> for details of individual maps)

A new type of “Water Resource” map has been produced for pastoral areas such as the Barkly Tablelands, Victoria River District and the Alice Springs Region. These maps combine three types of information; standard hydrogeological maps, maps showing suitability for dams or excavated tanks (derived from soil maps) and topographic data.

The resulting map gives options for the most suitable type of water source for a particular area. Another recent innovation is the mapping of end of dry season stream flows, a reflection of groundwater discharge. Streams with permanent flow are divided into zones of the lowest recorded end of dry season flows. When combined with traditional yield/aquifer type maps they provide a more informative view of the hydrogeology.

In Arnhem Land, the Tiwi Islands and the Wadeye region, hydrogeological mapping has involved traditional Aboriginal landowners. They have assisted with local knowledge about stream flow characteristics, springs and names of water related features. Some of the Arnhem Land maps have been produced in the local languages as well as in English.

A Northern Territory map was compiled for the National Land and Water Resources Audit (2001), an Australia-wide assessment of water resources. This showed “groundwater management units” which are essentially the major aquifers. The map together with information about the characteristics of each aquifer, the available groundwater resource, usage and current management was published as a web site (www.environment.gov.au/atlas). The assessment was repeated by the National Water Commission (2005) with most data also available online (www.water.gov.au).



Aquifers

An aquifer is defined as a body of rocks or sediments that stores, conducts, and yields water in usable quantities. The main feature depicted on the accompanying map is aquifer type. It is determined by the nature of the spaces in the rock or sediment in which groundwater occurs. The properties of these spaces determines how extensive the aquifer is, how easily water moves through it and how much water can be stored in it.

The three basic aquifer types include rocks that are fractured, those in which fractures have been enlarged by dissolution of carbonate rock, and those with pore spaces between sand grains in sand and sandstone. Various combinations of these have resulted in seven categories of aquifer type mapped across the Territory.

Fractured rock aquifers are the most common type. All rock formations are broken up to varying degrees by networks of cracks (fractures) (Plate 1). These can be formed by tectonic forces, cooling and shrinkage of igneous rocks or from the stress relief when overlying rocks are stripped away by erosion. Although fractures are normally very narrow openings (sub-millimetre), if there are enough of them they can constitute an aquifer.

Fractures tend to narrow with increasing depth due to the weight of the overlying rock. Weathering of rock also influences the hydraulic properties of fractures.

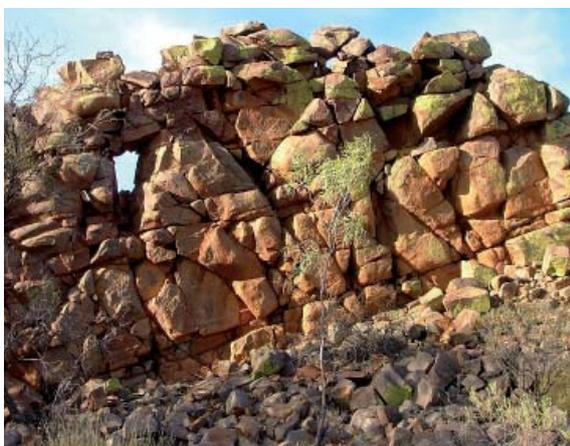


Plate 1 A sandstone outcrop showing fractures (cracks). Photo S. Tickell

Chemical changes to rocks during weathering can involve changes in the volume of the rock. That can lead to either opening or narrowing of existing fractures or to the formation of new ones. In fractured rocks the most productive aquifers are found in the weathered zone, typically shallower than 80 m.

In some areas fractures can occur throughout the mass of rock, forming an interconnected network of fractures. This results in a single widespread aquifer. At the other extreme, fractures may be sparsely developed or very localised. Aquifers in that situation are usually not very productive and can be restricted to the immediate vicinity of fault/fracture zones. In that case individual aquifers may not be connected to each other. The extent and degree of interconnection of fractures can range anywhere between these two extremes.

Fractured and karstic aquifers form in carbonate rocks (limestone or dolomite). Over geological time scales these rocks are soluble in water. Water moving through fractures gradually enlarges them as the rock is slowly dissolved. This process can result in openings up to the size of caverns but more commonly up to a millimetre or centimetre scale. As with fractured rock aquifers the openings tend to narrow with depth.

Porous rock aquifers develop in sand and sandstone. The open pore spaces between the sand grains constitute the aquifer. Not all sand and sandstone have sufficient intergranular porosity to form this type of aquifer. A variety of minerals, including clay, may fill or partially fill the pore spaces. In the case of sandstone, the younger the geological age of the formation, the more likely that the intergranular porosity will be preserved. Such aquifers are found in rocks of Cainozoic and Mesozoic age but are rarer in older formations.

On a regional scale, geology is the major factor which delineates areas of similar aquifer type. For example carbonate rock often hosts “Fractured and Karstic rock aquifers”

and shale and granite often host “Fractured and weathered rock aquifers with minor groundwater resources”.

Many of the aquifer boundaries therefore correspond to boundaries taken from geological maps, either from scanned 1:250,000 scale maps or from the 1:2,500,000 scale digital coverage of the Territory. Drilling information was used to confirm the interpretation of aquifer type and to modify boundaries where necessary. Records of some 36,000 water bores have been used to compile the aquifer map (Figure 5).

Note that the map does not show areas where no aquifers are present. Such areas exist, particularly in rocks like shale or granite which may be only sparsely fractured or where the fractures are too tight to transmit water. They are typically too restricted in area to be depicted at the scale of the map. Areas of this type mostly occur in the “Fractured and weathered rocks with minor groundwater resources” aquifer type.

In some places two or more major aquifers may be present at different depths.



Figure 5 Water bores in the NT

Only the shallowest aquifer has been shown on the map because of the difficulty of showing more than one layer. For example the Daly Basin contains two extensive fractured and karstic rock aquifers.

In the centre of the basin only the uppermost aquifer is shown even though the lower aquifer is present.

An aquifer type not shown on the map occurs in shallow laterite profiles. Such aquifers are individually small in area but are distributed widely near the northern coast and islands. Cretaceous aged claystone is the most common formation that such aquifers are developed in.

The formation of laterite is superficially similar to solution in carbonate rocks but involves the redistribution of iron, silica and clay minerals. It creates abundant pore spaces that can be up to centimetre scale (Plate 2). Root holes and fractures also contribute to the porosity and permeability of the aquifers. Laterite aquifers can give short term yields of up to 5 L/sec but long term sustainable yields are usually much lower. This is mainly because the aquifers are shallow, at less than 10 m deep. They often fill to overflowing in the wet season but they can run dry before the next wet season because of rapid lateral drainage.

Warruwi on Goulburn Island obtains its water from a shallow laterite aquifer and has had difficulties maintaining the supply when water levels drop late in the dry season.



Plate 2 A laterite profile developed on Cretaceous claystone (at base). Note the holes in the cliff face. Inset shows water streaming out of a pore during the wet season. Photo S. Tickell

A trial was carried out there to artificially recharge a deep sandstone aquifer with water pumped from the laterite aquifer during the wet season (Pavelic and others, 2002) and then to withdraw it for use in the dry season.

Most groundwater moves through aquifers from where it enters the ground (recharge areas) to where it returns to the surface (discharge areas). The distance it flows is dependant on the extent of the aquifer. In the case of large sedimentary basins this can be up to hundreds of kilometres, while at the other extreme in aquifers formed in local fractures, flow distances can be less than a kilometre. The term “groundwater flow system” is used to describe the scale of groundwater flow in an aquifer.

Coram and others (2000) classified aquifers across Australia into groundwater flow systems. Three categories; local, intermediate and regional were used based on the distance between recharge and discharge areas. Distances of less than 5 km, 5 to 50 km and more than 50 km defined the respective categories. The same terminology has been used on the accompanying Northern Territory Groundwater Map.

Aquifer Types

The seven aquifer types shown on the map are:



Unconsolidated sediments with intergranular porosity



Sedimentary rocks with intergranular porosity



Fractured and weathered rocks



Fractured and weathered rocks with minor groundwater resources



Fractured and weathered rocks with some intergranular porosity



Fractured and karstic rocks, with local aquifers



Fractured and karstic rocks, with extensive aquifers

The occurrence and characteristics of each of these aquifer types will now be described.

Unconsolidated sediments with intergranular porosity

These occur in sand and gravel deposits. Groundwater moves through and is stored in the pore spaces between the sand grains. The spaces need to be connected with each other to form an aquifer. They are mainly associated with Cainozoic aged alluvial sediments that occur within palaeovalleys and small sedimentary basins, mainly in the south western quarter of the Territory.

Only two occurrences are shown on the main map, the Ti-Tree Basin near the township of Ti-Tree and a palaeovalley deposit beneath the Keep River floodplain. Both of these have been extensively drilled and their extents and properties are well known (Read and Tickell, 2008 and Humphreys and others, 1995). Both have intermediate scale flow systems. The remainder of the palaeovalleys and Cainozoic sedimentary basins are only depicted on the “Palaeovalleys” side map because their locations and aquifer properties are poorly defined or even speculative.

Senior and others (1995) identified the main Cainozoic basins in Central Australia. Using their map as a starting point the “Palaeovalleys” map was made with the aid of borehole information and satellite imagery.

Other aquifers that fall into this type but which have only small area extent are not shown on the map. These include aquifers developed in coastal sand dunes and in shallow Quaternary aged alluvial sands and gravels.

Coastal dune / beach deposits are widespread particularly along the Arnhem Land coastline. They commonly extend inland for up to several hundred metres but can run for many kilometres along the coast. In the past Aboriginal people obtained water from them from seeps or shallow hand dug wells.

Several small communities currently obtain water supplies from coastal dunes. Sand spears and infiltration galleries have been used to tap the groundwater in the loose sand aquifers. It is unlikely that the deposits are very thick so they are probably only capable of yielding small supplies.

The community of Wurryi near the base of the Coburg Peninsula is supplied with water from an infiltration gallery dug into dune sands (Plate 3).

Shallow alluvial deposits are relatively uncommon in the northern half of the Territory. Isolated deposits occur along the major rivers. The communities of Yarralin, 100 km south east of Timber Creek and Gunbalunya, 43 km north east of Jabiru obtain water supplies from alluvial aquifers. Such supplies are often only small due to the limited thickness and extent of the deposits.

Alluvial activity has occurred from the Tertiary to the present day so there is not a clear cut distinction between the Tertiary palaeovalleys described above and Quaternary alluvium. Alluvium deposited by the Todd River at Alice Springs hosts a minor aquifer locally referred to as the Town Basin. It is up to 20 m thick and covers an area of about 10 km². Bores obtain yields of up to 20 L/sec but average 5 L/sec. There are presumably many similar but as yet unmapped alluvial aquifers in Central Australia.

The main drilling method used in the past for unconsolidated sand aquifers was cable tool but the air rotary method is now used. The soft sand can lead to problems with hole stability and mud rotary can achieve better results. In order to keep sand out of the bore they are best constructed with stainless steel screens rather than with slotted casing.



Plate 3 Digging an infiltration gallery in beach sand at Wurryi. Groundwater filters into the stainless steel screen in the base of the pit. Photo U.Zaar

Sedimentary rocks with intergranular porosity

In this type of aquifer the sand grains are cemented together to form sandstone. There are however sufficient interconnected pore spaces to form an aquifer. Cretaceous aged sandstones are the most common formation to host this aquifer type, particularly in Arnhem Land where fluvial sandstone fills palaeovalleys up to 90 m deep. The flow systems are of intermediate scale. The aquifers provide baseflow for many streams, often throughout the year. Some of these include the Durabudboi, Latram and Cato Rivers and Wonga, Jungle and Yirrkala Creeks. End of dry season flows of up to 100 L/sec have been measured in some of these streams.

The water supply for Nhulunbuy and the nearby bauxite mine is obtained from such an aquifer. The production bores are about 80 m deep and are constructed with stainless steel screens to exclude loose sand.

In other areas of the Top End, Cretaceous sandstones are thinner and aquifers are not so well developed. In the Barunga area, 65 km east of Katherine for example thin sandstone aquifers cap several plateaus. Numerous springs surrounding the plateaus form the drainage points of the aquifer.

Sandstone aquifers occur at the base of Cretaceous marine sedimentary sequences on the Coburg Peninsula, Tiwi Islands and near the coast adjacent to the Queensland border. The sandstone is typically only a few metres thick and can be absent in some areas. Yields obtained from bores are generally low due to high clay content of the sandstone but can be up to 8 L/sec where the sandstone is clean.

On the Tiwi Islands the Tertiary aged VanDiemen Sandstone is an important aquifer (Haigh and others, 2003). The formation is marine in origin and comprises fine to coarse grained sandstone and clayey sandstone. It varies up to 60 m in thickness and in the thicker portions is capable of yielding up to 10 L/sec. The aquifer is widespread across the islands and discharge from it supports many permanent and ephemeral spring fed streams.

The communities of Nguiu, Milikapiti and Pirlangimpi obtain their water mostly from this aquifer as well as locally from a deeper aquifer, the Moonkinu Member. The latter unit is also a sandstone aquifer with intergranular porosity but is Cretaceous in age.

A small portion of the Great Artesian Basin is present in the south eastern corner of the Territory. The basal formation in that area is the Algebuckina Sandstone, an extensive, porous rock aquifer. It is up to 400 m thick and consists of fine to coarse grained fluvial sandstone with minor clay and siltstone inter-beds. In its outcrop area on the basin margin the aquifer is unconfined but over most of its extent it is confined by thick shale beds. Yields of up to 10 L/sec have been obtained in the outcrop area for the Finke township production bores, 200 km south east of Alice Springs.

Further into the basin the aquifer is deep and water levels are above ground level. A former oil exploration bore McDills 1 (RN5028) free-flowed at 125 L/sec until it was capped in 2002. The aquifer is little used apart from a few stock bores and the Finke township water supply.

The flow systems in this aquifer type are mainly intermediate to local scale, except for the Great Artesian Basin aquifer which is on a regional scale. In that aquifer groundwater flows to the south eventually discharging to mound springs in South Australia, such as Dalhousie Springs.

The sandstones in this class of aquifer are generally competent enough for the use of air rotary drilling for investigation bores. Mud rotary drilling is often preferable for production bores however to ensure that the hole diameter is not enlarged excessively adjacent to the aquifer. Stainless steel screens are preferred for town water supply and other high yielding bores to exclude fine sand. Slotted casing is normally adequate for lower yielding stock bores.

Fractured and weathered rocks

Aquifers of this type are formed in the network of fine cracks (fractures) that are present in most hard rocks. In general fractures tend to be more open in the weathered zone and thus form better aquifers.

The depth of weathering varies from place to place but typically ranges down to a maximum depth of 80 m. The most productive aquifers commonly occur near the base of the weathered rock.

Sedimentary rocks ranging in age from Proterozoic to Palaeozoic are the commonest formations to host this type of aquifer in the Territory. Palaeozoic aged basalt, particularly in the Victoria River District also host aquifers of this type. All of these rocks are hard and fractured but the degree of fracturing varies considerably from place to place depending on the rock type, its age and the amount of deformation to which it has been subjected. Formations vary from being flat-lying to those that have been strongly folded and suffered low grade metamorphism. Aquifer flow systems are generally local, but a few may be of intermediate scale.

The Hermannsburg Sandstone aquifer that discharges in springs at Palm Valley, 120 km south west of Alice Springs is a fractured rock aquifer whose flow systems is intermediate in scale, of the order of 50 km (Wischusen and others, 2004).

Supplies from fractured rock aquifers are commonly small, sufficient for stock and domestic uses or locally for small scale irrigation. Some small towns and many communities source water supplies from these aquifers. For small communities a single bore pumping up to 2 L/sec may be adequate but for larger communities and small towns multiple bores are commonly required. For example Adelaide River, Pine Creek and Lajamanu have borefields in fractured rock aquifers, however obtaining sufficient water can often be difficult. Pine Creek for example has some twelve production bores with a total sustainable yield of only 8.6 L/sec (Dames and Moore, 1992). At least double that number of investigation bores were drilled in order to secure the current supply.

Rotary percussion drilling using air is the most common technique used in these aquifers. The rock formations are generally hard resulting in stable boreholes. Bores are completed with either slotted casing or stainless steel screens.

In high rainfall areas fractured rock aquifers only make minor contributions to stream baseflows. Most streams that overlie these aquifers only flow for a short time during the early dry season. Figure 6 illustrates this point, showing stream flow and rainfall from Bennetts Creek, 26 km south east of Darwin. The catchment is underlain by Burrell Creek Siltstone, a fractured and weathered rock aquifer. Note that the stream continued to flow for about two months after the last major rains in April of the year shown. In lower rainfall areas baseflows from this type of aquifer are usually non-existent.

Fractured and weathered rocks with minor groundwater resources

These aquifers are found in Cambrian and Proterozoic aged rocks that are only sparsely fractured. They include shale, siltstone, hard sandstone, quartzite, granite, dolerite, gneiss, schist and many volcanic rocks. Prominent geological formations that host this type of aquifer include the Angalarri Siltstone in the Victoria Basin, the Raiwalla Shale in the Arafura

Basin, the Horn Valley Siltstone in the Amadeus Basin, the Kombolgie Sandstone in Arnhemland and the Heavitree Quartzite in the Amadeus Basin. All these aquifers have local flow systems.

Water supplies for individual households or for small communities are obtained from localised fracture zones. They can be very difficult to locate and often require considerable exploratory drilling. Up until 1999 the Amanbidji community west of Timber Creek sourced its water from the Angalarri Siltstone, a sparsely fractured rock.

Six production bores with yields between 0.2 to 0.5L/sec supplied the community of up to 80 people. At least 18 bores were drilled to obtain the six production bores, illustrating the difficulty of obtaining adequate supplies from such an aquifer.

Drilling techniques and bore construction methods are generally similar to those described above for fractured and weathered rock aquifers.

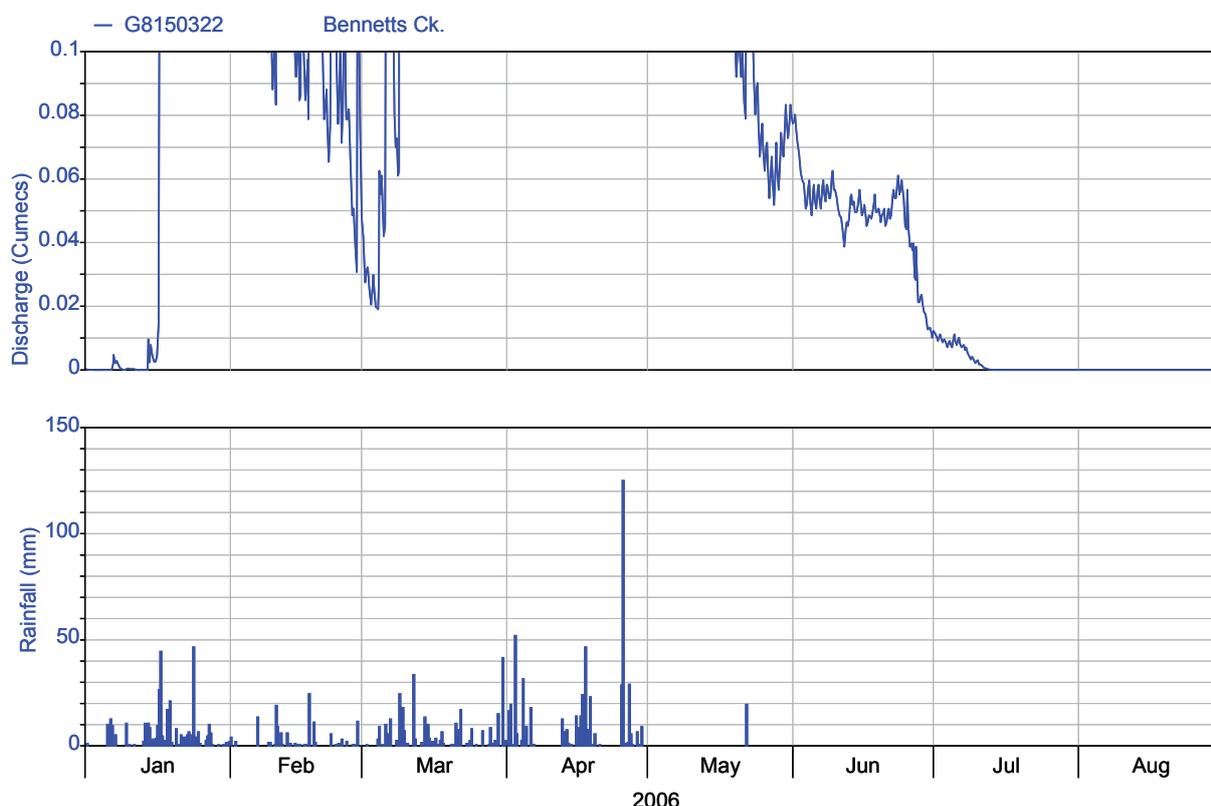


Figure 6 Stream flow and rainfall from Bennetts Creek near Noonamah

Fractured and weathered rocks with some intergranular porosity

Fractured rock aquifers that also have intergranular porosity are found in some Palaeozoic aged sandstones in the Amadeus, Wiso, Georgina and Bonaparte Basins.

The Mereenie and Pacoota Sandstones in the Amadeus Basin are two significant aquifers of this type. The water supply for Alice Springs is currently sourced from a borefield that taps these aquifers. Detailed investigations including core sampling and porosity/permeability testing have been done at the borefield (Lau, 1989 and Jolly and others, 1994). They have shown that the aquifer is both fractured and porous. The porosity can be locally as high as 30 per cent (i.e. 30 per cent of the volume of the rock is open spaces) and is both primary and secondary in origin. The sandstones have a complex history that has involved partial blocking of primary pore spaces with cements and then later partial dissolution of the cements. Some of the fractures in friable sandstone have been enlarged up to centimetre size (Seidel, 1999) and are superficially karstic in appearance. The fractures provide major pathways for groundwater movement and the porosity enhances the storage capability of the aquifer. Individual production bores are capable of pumping in excess of 100 L/sec. The enlargement of fractures, the high porosities and the high bore yields have not been encountered elsewhere in the basin to date but exploratory drilling is only sparse over most of the basin. On a regional scale these aquifers can be described as being fractured with intergranular porosity but fractures are probably the dominant features for the storage and movement of groundwater.

In the other basins mentioned above no detailed studies of the aquifers have been carried out. Certain sandstones have been assigned to this aquifer type based on their outcrop appearance and results from sparse water drilling. In particular the Dulcie Sandstone, the Lake Surprise Sandstone and the Border Creek Formation from the Georgina, Wiso and Bonaparte Basins respectively are likely to have a significant amount of intergranular porosity. These aquifers are relatively soft to drill and can yield up to 15 L/sec from individual bores. The flow systems are intermediate to regional in scale.

Discharge of groundwater to the surface from these aquifers is only known from the Mereenie and Dulcie Sandstones. They usually take the form of seepages which maintain semi-permanent waterholes. Running Waters waterhole on the Finke River is an example of such a feature (Plate 4).

Rotary percussion drilling using air is usually the best technique for these aquifers but in cases where the sandstone is too friable, mud may be more appropriate than air to ensure a stable borehole. A few boreholes in the Roe Creek borefield have encountered lost circulation problems in the zone of enlarged fractures.

Fractured and karstic rocks, with local aquifers

Aquifers of this type are developed in rocks in which limestone or dolomite is present but is either thin or is not the dominant rock type. Karstic enlargement of fractures is typically limited to thicker dolomites or limestones. The ages of these formations range from lower Palaeozoic to Proterozoic.



Plate 4 Running Waters Waterhole on the Finke River, maintained by permanent groundwater seepage. Photo S. Tickell

An example is the Jinduckin Formation in the Daly Basin where thin limestone beds are interbedded in a predominantly siltstone sequence. Moderately productive fractured and karstic aquifers are restricted to the limestone beds. The Karns Dolomite of the McArthur Basin comprises a variety of rock types. Dolomite is subordinate to dolomitic shales, dolomitic sandstone and non-dolomitic rocks. Karstic aquifers are only well developed in thicker dolomite beds. Similar dolomitic sequences occur in the Victoria and Amadeus Basins.

In the arid zone shallow fractured and karstic aquifers are associated with Cainozoic aged palaeovalleys and basins (see the "Palaeovalleys" side map). They are developed in calcrete, a chemically deposited limestone formed in the zone where the watertable fluctuates. The calcrete deposits are commonly elongated along the axis of the palaeovalleys and are mostly shallower than 20 m (Figure 7). The aquifers are both fractured and karstic and small sinkholes sometimes occur. In places the calcrete is replaced by silica but can still retain high permeabilities.

The calcrete aquifers have been studied in the Granites - Tanami mining region where they are used for water supplies (Domahidy, 1990). Bore yields of 10 L/sec. are obtained in that area and groundwater levels are from 3 to 6 m below ground level. A related type of aquifer occurs near Tennant Creek but consists of fractured and karstic silcrete (Lau, 1993). The silcrete also occurs within a palaeovalley that appears to be flowing towards the west.

A borefield that supplies the town consists of some ten bores, averaging 40 m deep and each capable of pumping 6 L/sec. A similar silcrete aquifer was encountered in the southern Victoria River District along a palaeovalley associated with the Sturt Creek.

These fractured and karstic aquifers are distinguished from fractured rock aquifers in that moderately high yields are locally available associated with the karstic sections.

Water supplies are generally only sufficient for stock and domestic purposes but can be locally large enough for small townships, communities or for limited irrigation. Timber Creek for example with a population of 260, taps the Timber Creek Formation, a Proterozoic aged unit consisting of siltstone, dolomitic siltstone and dolomite. Bores that intersect fractures have been enlarged by dissolution of dolomite and can pump up to 12 L/sec (Pearson, 1985).

Flow systems in this type of aquifer are typically local to intermediate in scale.

As with fractured rock aquifers these normally only make minor contributions to stream baseflows and only in high rainfall areas. Baseflows are only maintained on average until the early to mid dry season. The Robinson River for example drains an aquifer in the Karns Dolomite. In an average rainfall period the river at Robinson River community ceases to flow by August.

Rotary percussion drilling using air is best technique for these aquifers as the formations are generally hard resulting in a stable borehole.

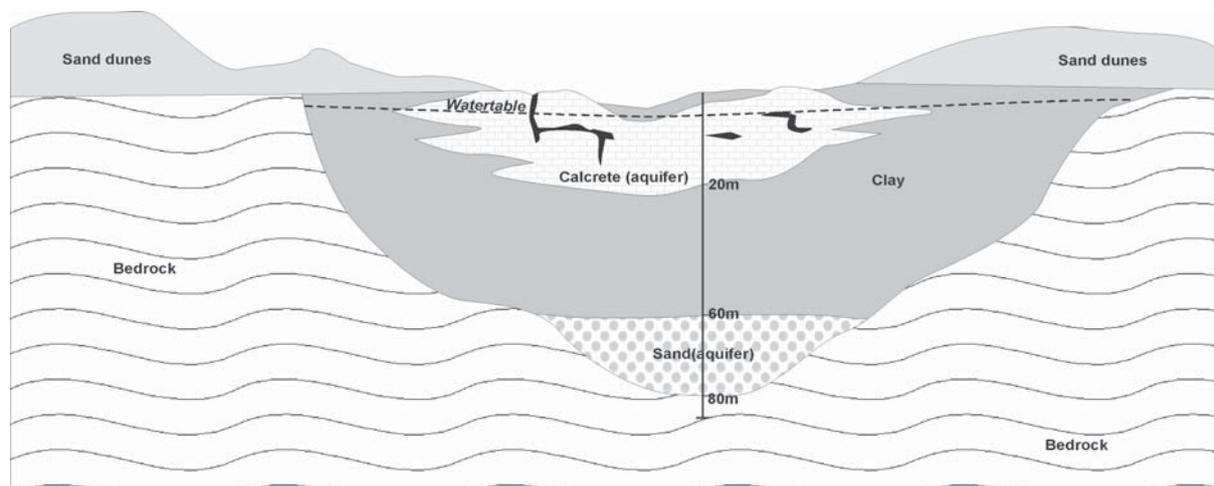


Figure 7 Diagrammatic section through a palaeovalley

Losing circulation of the drilling fluids into cavernous formations can sometimes be encountered.

Fractured and karstic rocks, with extensive aquifers

Aquifers of this type occur in Lower Palaeozoic and Proterozoic aged limestones and dolomites. Their greatest extents occur in the Daly, Wiso and Georgina Basins. Significant aquifers also occur in the Koolpinyah Dolomite near Darwin, an unnamed dolomite unit at Berry Springs, the Dook Creek Formation (dolomite) in the Goyder River area and the Karns Dolomite on Pungalina Station, 125 km south east of Borroloola. In many areas these aquifers are overlain by Cretaceous aged sedimentary rocks which form a semi-confining layer. This is the case for all of the Koolpinyah Dolomite and for a broad area extending from the Sturt Plateau to the northern Georgina Basin.

The limestone and dolomite formations are hard and fractured. Fractures are commonly enlarged by solution of carbonate rock often to the extent that cave systems are locally present. A more pervasive secondary porosity can be formed by selective dissolution of dolomite crystals. This is the case with the Koolpinyah Dolomite near Darwin. Crystalline dolomite is partially silicified by weathering, crystals that have not been replaced by silica are then dissolved by acidic recharge waters, leaving a porous rock that resembles “sugary” sandstone. This can form a sheet like aquifer which overlies and is in hydraulic connection with fractured and cavernous rock below. Solution cavities are most abundant at depths of less than 80 m but can be present at great depths, well beyond the zone of weathered rock. In the Daly Basin for example, stratigraphic drill holes have encountered limestone with solution cavities at depths of the order of 600 m. An irrigation bore west of Katherine yields 90 L/sec from cavernous Tindall Limestone at a depth of 300 m.

These karstic aquifers are capable of yielding quantities of water, sufficient for town supplies and major irrigation. About 10 per cent of Darwin’s water is sourced from the Koolpinyah Dolomite while 40 per cent of Katherine’s is extracted from the Tindall Limestone.

Irrigation developments near Darwin, Katherine, Mataranka and the Douglas / Daly Region all rely on groundwater from major karstic aquifers.

The flow systems in these aquifers are of regional to intermediate scale (Figure 8). At one extreme is the Georgina Basin with groundwater flow paths of the order of several hundred kilometres. These aquifers discharge via karstic springs commonly with individual flow rates up to several hundreds of litres per second. Prominent examples include Katherine Hot Spring, Rainbow and Bitter Springs at Mataranka, Flora River Spring, Howard and Berry Spring near Darwin, Top Spring in the Mainoru River area and Bubbling Sands Spring in the Calvert River area. Such springs and stream bed diffuse seepages, provide baseflows to rivers, often throughout the Dry season. The Daly, Flora, Katherine, Douglas, Roper, Goyder and Calvert Rivers are the main streams that currently maintain year round baseflow from karstic aquifers.

Rotary percussion drilling using air is normally used in these aquifers because formations are generally hard and the holes stable. Problems are often encountered when cavities are intersected and drilling circulation is lost. Cuttings and groundwater may not be returned to the surface, so information about the formations and water intersections is lost. Running casing as drilling progresses is a technique used to avoid this problem.

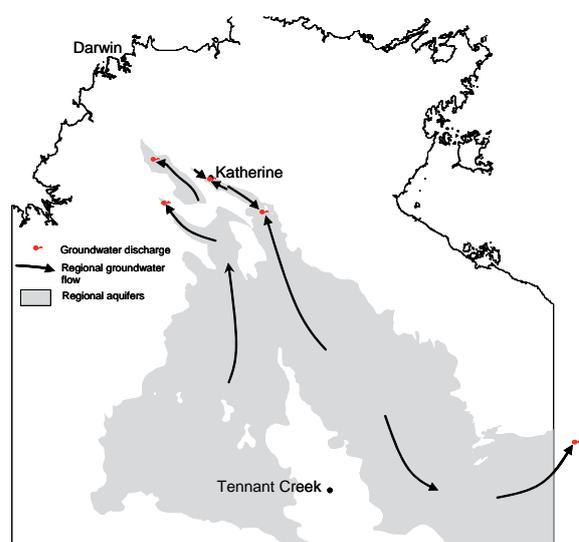


Figure 8 Flow paths in some major fractured and karstic aquifers



Recharge is the process whereby water is added to an aquifer. It can occur by three main mechanisms; diffuse, stream bed and point source (Figure 9). Diffuse recharge is the widespread downward seepage of rainwater through the soil and then into the aquifer. Stream bed recharge occurs where the soil and rock beneath a stream is permeable enough to allow leakage down to an aquifer. The watertable must be lower than the riverbed otherwise leakage cannot occur. Point source recharge occurs where large conduits such as sinkholes or caves allow direct drainage of runoff into the aquifer (Plate 5).

The recharge mechanism and the amount and frequency of recharge vary across the Territory. They are all influenced by climate, soils and geology. Rainfall is probably the most obvious controlling factor. As rainfall progressively decreases southwards from the coast so the potential for recharge also decreases. In the humid zone rainfall is high, often widespread and falls regularly each wet season. This is conducive to regular seasonal recharge. Diffuse recharge is generally the dominant recharge mechanism in the humid zone. Cook and others (1998) estimated that recharge to the Koolpinyah Dolomite aquifer near Darwin to be 200 mm/year. The majority of that is thought to be via diffuse recharge.

At the other extreme in the arid zone, rainfall is low, geographically sporadic and only falls at irregular periods. As a consequence the amount of recharge is much less, occurs episodically and is not evenly spread across the landscape. With the lack of widespread rains, stream beds concentrate water and stream bed recharge can be the dominant recharge mechanism. In a study of recharge in the Ti-Tree Basin, 200 km north of Alice Springs, Harrington and others (1999) found that the long term mean recharge is approximately 1.9 mm/year. More than half of that occurs via stream bed recharge following the heavy and sustained rainfall events that occur every 5 to 10 years.



Plate 5 Runoff draining into a small sinkhole after a storm, Daly River area. Photo D. Karp

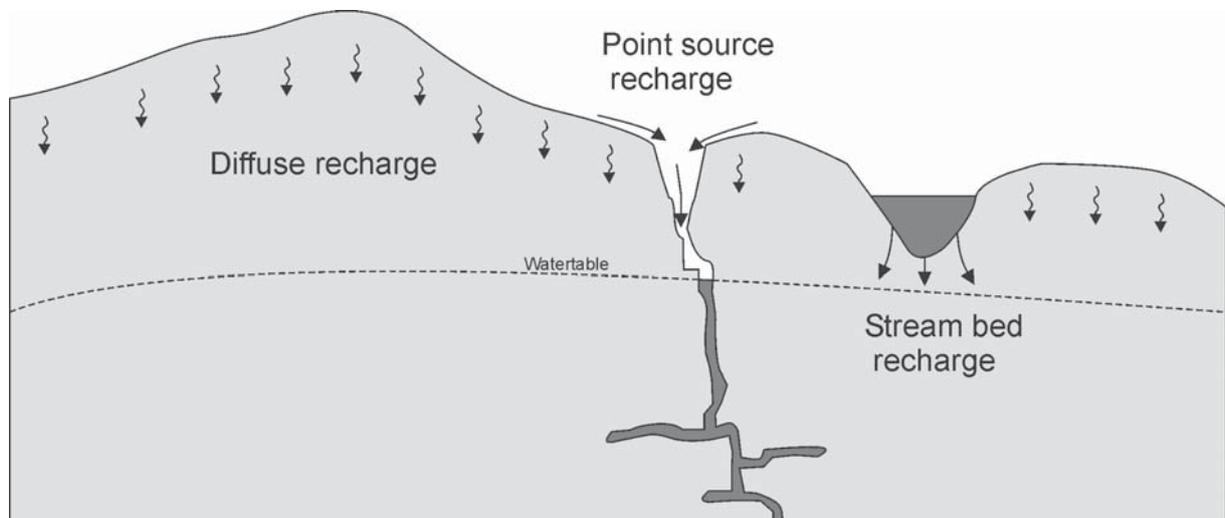


Figure 9 Recharge mechanisms

There is naturally a gradation in recharge properties between the northern humid zone and the southern arid zone. Local variations in geology and soils can also have a big influence on recharge. In the case of karstic aquifers, point source recharge can occur if the rock is cavernous. That recharge is in addition to any diffuse or stream bed recharge that may also occur. A study of recharge to the Ooloo Dolostone aquifer in the Daly Basin found that 70 per cent of the recharge was from point sources (Wilson and others, 2006). Open sinkholes are uncommon in that formation but the nearby Tindall Limestone has many sinkholes (Karp, 2004).

Actual inflows to a cave have been measured at one site. An acoustic doppler flow meter sited at the entrance of Sculpture Cave near Katherine has recorded instantaneous flows up to 8000 L/sec during flash floods. A dye tracing experiment in a cave system near Katherine showed that the dye took two days to travel 2.5 km (Karp, 2005). These examples illustrate that point source recharge can involve large volumes of water and can take place rapidly.

Another common geological influence on recharge is when an aquifer is overlain by a formation that is less permeable. In the Great Artesian Basin for example recharge is only possible at the margin of the basin where the basal sandstone aquifer outcrops. Towards the centre of the basin it is overlain by shale beds that stop water leaking down to the aquifer.

In parts of the Daly, Wiso and Georgina Basins, clayey Cretaceous aged formations overly the major karstic aquifers. They are not completely impervious however, but they reduce the amount of recharge. Jolly (2002) estimated the recharge to the Ooloo Dolostone aquifer is 150 mm/year where it is unconfined and 40 mm/year where it is confined by Cretaceous formations.

Soil type can also limit or enhance recharge. Clay soils tend to reduce the potential for recharge while sandy soils increase it. On the cracking clay soils of the Keep River Plain, Tickell and others (2006) estimated that recharge to the underlying sand aquifer is negligible (0.1 mm/year). By comparison recharge to a sandstone aquifer which adjoins the plains and which has only thin sandy soils is 40 mm/year.



Discharge

In nature there are two main ways that groundwater can discharge from an aquifer. The most obvious is to directly drain out via a spring or through a stream bed. The other avenue for discharge is through transpiration or evaporation. An uncommon variation involving evaporation occurs when the watertable is directly exposed to the atmosphere in an open sinkhole (Plate 6) or on a larger scale in a lake.

Recharge generally occurs over a greater area than does discharge, particularly with diffuse recharge. In other words it seems easier for water to get into an aquifer than for it to get out. On the other hand recharge usually only occurs over a relatively short period during the year but discharge can potentially occur throughout the year if watertables are high enough.

Resistance to flow in the narrow spaces that constitute aquifers means that the water does not discharge instantaneously. It takes longer for the water to discharge from an aquifer than it does to recharge it. Equilibrium is reached between recharge, discharge and a range of heights that the watertable fluctuates between each year.

Springs and stream bed seepages

Springs are localised discharge points whose locations are governed by topography, watertable elevation and or geological features. The most common location of springs is in parts of the aquifer that are lowest in the landscape, typically along a stream.

Many springs are marked by lush vegetation than that of the surrounding area due to the availability of water (Plate 7).

In homogeneous aquifers such as “sedimentary rocks with intergranular porosity” discharge will be governed largely by topography. Aquifers in which permeable zones can be localised such as fracture or karstic rocks, discharge may be governed by the location of cave systems or fault zones. In the case of confined aquifers a conduit such as a fault is required for the water to reach the surface.



Plate 7 The Wickham River in Gregory National Park, flow is maintained by stream bed seepage and springs. Photo D. Karp



Plate 6 A sinkhole on Marrakai Station with the watertable exposed. Photo R. Farrow

Shallow groundwaters range in temperature from 24 to 36°C. There is a broad north to south gradation from higher to lower temperatures. Several springs are locally referred to as hot or thermal springs. Although there is no universally accepted definition of a hot/thermal spring there are only a handful of springs with temperatures that are considerably higher than the ambient temperature of the local shallow groundwater.

These include Douglas Hot Springs (51°C), an unnamed spring on McArthur River Station (60°C), Sybil Springs (41°C) and Nathan River Spring (45°C) (Figure 10). These are all sited on faults which are conduits that bring the water from depth. Normal geothermal gradients suggest that depths of up to a kilometre would account for the observed temperatures.

Stream bed seepages are also low points in the landscape and so potential places for groundwater discharge. For that to occur the stream bed and the formation beneath must be permeable and the watertable has to be above the stream level. The distinction between a spring and a stream bed seepage is not always clear especially when a series of springs merge into a zone along a stream.

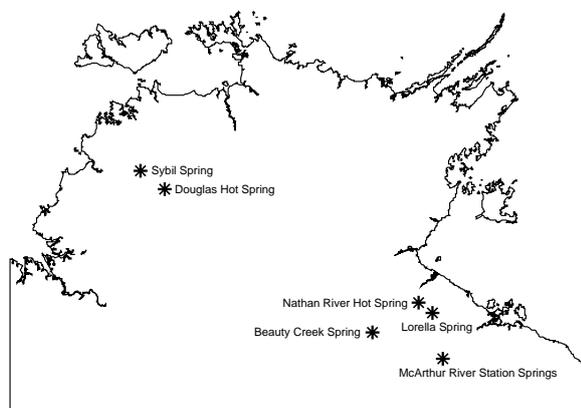


Figure 10 Hot springs

Evapotranspiration

A less obvious but an important form of groundwater discharge is transpiration and evaporation. Plant water use is termed evapotranspiration. For plants to easily utilise groundwater the watertable need only be shallow enough for plant roots to tap it. Evapotranspiration has been measured at several sites across the Territory and in general it decreases southwards with decreasing rainfall. Determining the amount of groundwater, if any, that is included in the evapotranspiration can be problematic. The studies to date have confirmed that some vegetation utilises groundwater but this has not been quantified. It is unlikely that there are many vegetation communities that utilise groundwater 100 % of the time.

In the humid zone monsoon vine forests around springs and some riparian vegetation communities (O’Grady and others, 2002) are known to utilise groundwater. Cook and others, (1998) concluded that the eucalypt savanna in the Darwin region is not dependent on groundwater for dry season transpiration. In the arid zone the river red gums that flank many streams are thought to tap groundwater. Recent work in the Ti-Tree Basin (Howe and others, 2007) estimated evapotranspiration to be in the range 40 – 100 mm / year at a site with a shallow watertable (5.6 m) but to be less than 15 mm / year at a site where the watertable was deeper than 20 m. That suggests that the vegetation are largely groundwater dependent. Springs at Palm Valley west of Alice Springs support an unusual community of plants including red cabbage palms, remnants of once more widespread vegetation during a wetter climate (Wischusen and others, 2004).

Where the watertable is within about two metres of the surface it can be drawn upwards by capillary action and be lost to the atmosphere by direct evaporation. In the humid zone that type of discharge takes place in some swamps.



Plate 8 Lake Lewis, Central Australia, a salt lake and a groundwater discharge zone. Photo P. English

At Mataranka for example an extensive swampy area is underlain by shallow watertables. It supports a Melaleuca woodland with Pandanus and palms that depend on groundwater. Groundwater is also being discharged by evaporation through the soil as evidenced by abundant salt efflorescence during the dry season. Similarly in the arid zone salt lakes are underlain by shallow watertables and are sites of active groundwater discharge. Capillary action brings saline groundwaters to the surface. The water evaporates but the salts remain (Plate 8).

Variation of discharge with time

Groundwater discharge can change with time and location. It is dependant on the elevation of the watertable in relation to ground level. Seasonal and longer term fluctuations of the watertable result in changes in the amount of discharge. As watertables fall after the wet season, discharge also decreases. In the case of stream bed seepage the seepage zone can progressively shorten downstream. Discharge can stop altogether if the watertable falls below the stream bed (Figure 11).

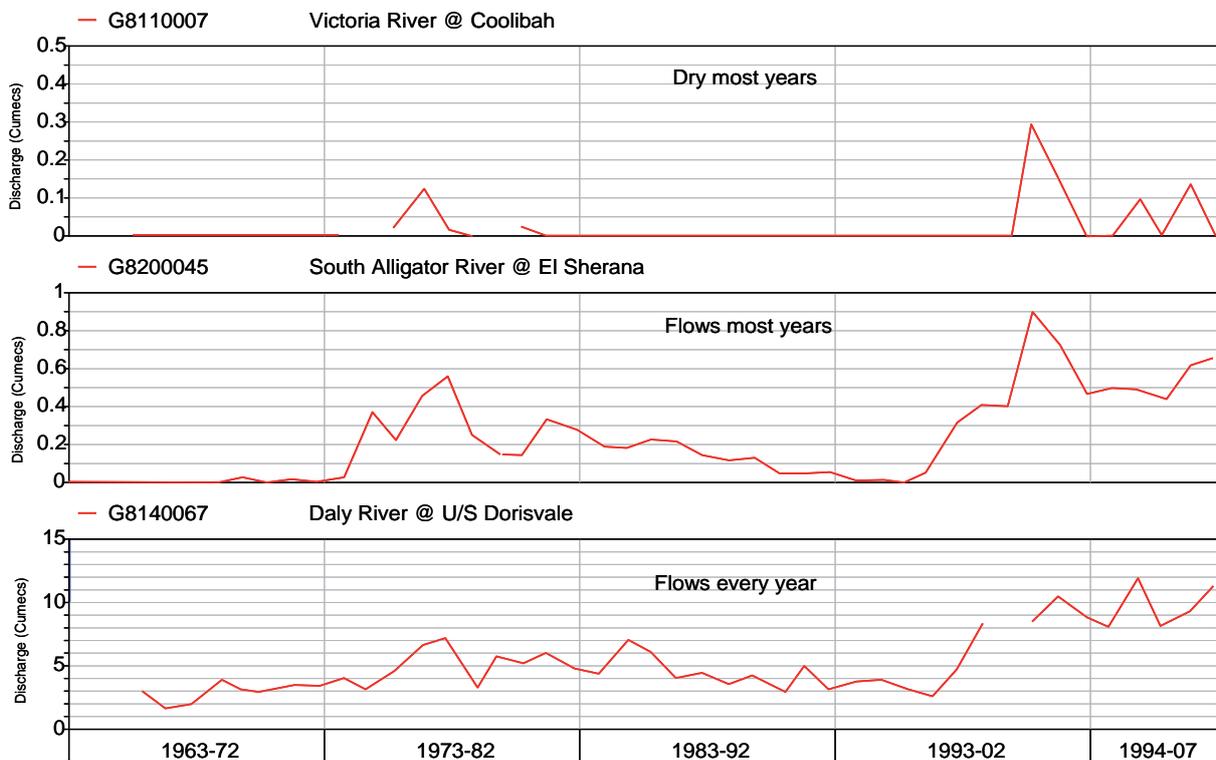


Figure 11 Minimum end of Dry season flows for three Top End streams (note the different discharge scales)



Plate 9 Trees killed by prolonged inundation due to groundwater discharge, Douglas / Daly area. Photo S. Tickell

If this occurs and the stream still has flow from upstream sources the discharge zone can become a recharge zone. Long term changes in rainfall can affect discharge. For example since the mid-1970's rainfall has been above the long term average in the humid zone. Discharges have been higher and new discharge features have appeared (Plate 9)

Discharge features across the Territory

The side map "Groundwater Discharge" shows major groundwater discharge features across the Territory.

These include known springs, significant groundwater fed streams and salt lakes. Several factors influence the distribution of discharge features. In higher rainfall areas, recharge is on average higher. What goes in must come out, so discharge is correspondingly greater in both quantity and in the number of discharge points. Direct outflow via springs and seepage into stream beds is the dominant form of discharge in the humid zone.

With decreasing rainfall stream bed seepage decreases and eventually either does not occur or is limited to short stretches of a few streams. Running Waters Waterhole on the Finke River is a rare example of a groundwater fed stream in the arid zone (Plate 4). The river picks up groundwater where it cuts across the Mereenie Sandstone aquifer but only maintains a flow for a few ten's of kilometres. Springs also become less frequent southwards and have small discharges. In the arid zone evapotranspiration is the dominant form of discharge mostly from riverine vegetation but also from salt lakes.

Impacts of long term rainfall variations

Long term changes in rainfall can have a significant effect on groundwater recharge and discharge. Jolly and Chin (1991) described the above average rainfalls of the mid-1970's that were widespread across the Territory (and much of Australia). They caused a major recharge event that saw groundwater levels raised significantly (Figure 12).

In the arid zone such high levels have not been reached since that time. In the humid zone a further high rainfall period from the late 1990's to the present has raised many water levels to record heights. Note that the timing of the rises in water levels varied in each bore shown in Figure 12, presumably because of variations in the local rainfall patterns. The Darwin bore also shows a rise in the mid 1970's but it is not as obvious due to the scale of the graph.

Despite increasing groundwater extraction from that area, peak wet season water levels still tend to be higher than the pre-1970's levels. There are numerous indications that the humid zone is experiencing above average rainfalls.

The rainfall records themselves show that this is the case (Figure 13) but there is also evidence in the landscape. For example a mass killing of mature trees including *Corymbia polycarpa*, took place on Pungalina Station, 130 km south east of Borroloola (Ursula Zaar, personal communication). The trees were fringing an ephemeral lake (Plate 10). Since an exceptionally big wet season in 2000/2001 the lake has remained near full and the trees were unable to cope with the wet conditions. Prior to then the lake was normally dry by about July each year.



Plate 10 Dead trees on the edge of a lake on Pungalina Station. Photo S. Tickell

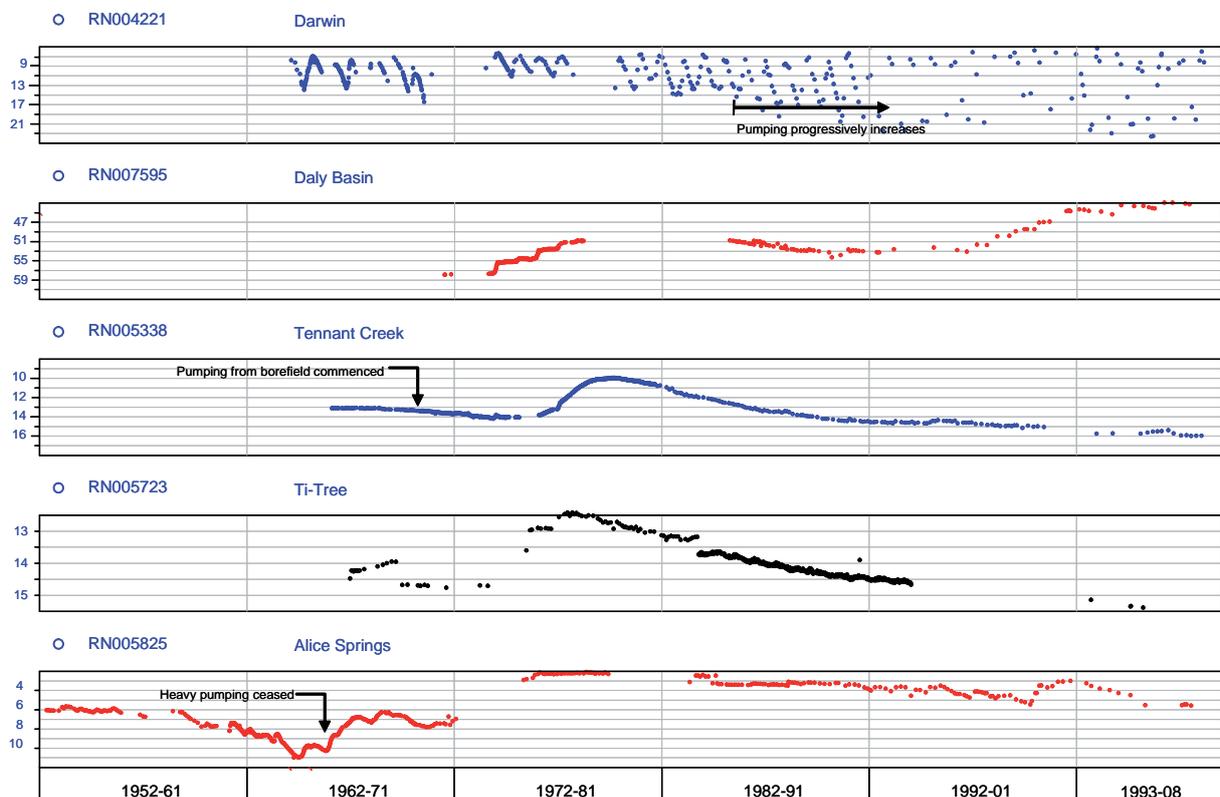


Figure 12 Bore hydrographs

A study of the growth rings in one of the trees (Peter Brockelhurst, unpublished data) indicated that it was at least 98 years old and had been scared by fires numerous times during that period. The death of the trees indicates that the recent rainfalls have been exceptionally high compared to the last hundred year's rain. The fire scar record showed that major fires were more frequent during periods of low rainfall.

A similar tree drowning was also observed in the Douglas/Daly area, in a swamp 6 km north of Ooloo Crossing (Roger Farrow, personal communication). In that case, a stand of mature eucalypts started to die around 2001 and have been replaced by the more water loving Melaleucas (Plate 9). Unlike the ephemeral lake on Pungalina Station, this swamp is a groundwater discharge feature. It is an indication of not only high rainfall but also of higher than average groundwater recharge and discharge.

In recent years dry season baseflows in some rivers have also been at record high levels. On a recent trip along the Daly River to map springs (Tickell, 2002) many seepages and springs were observed high in the riverbank and these had caused widespread slumping. Many large mature Melaleuca trees had been recently toppled into the river by the slumps. This event also gives the impression that it has not occurred regularly in the recent past (last hundred years?).

The record high watertables associated with the above average rainfalls in that area are an obvious cause of the slumping.

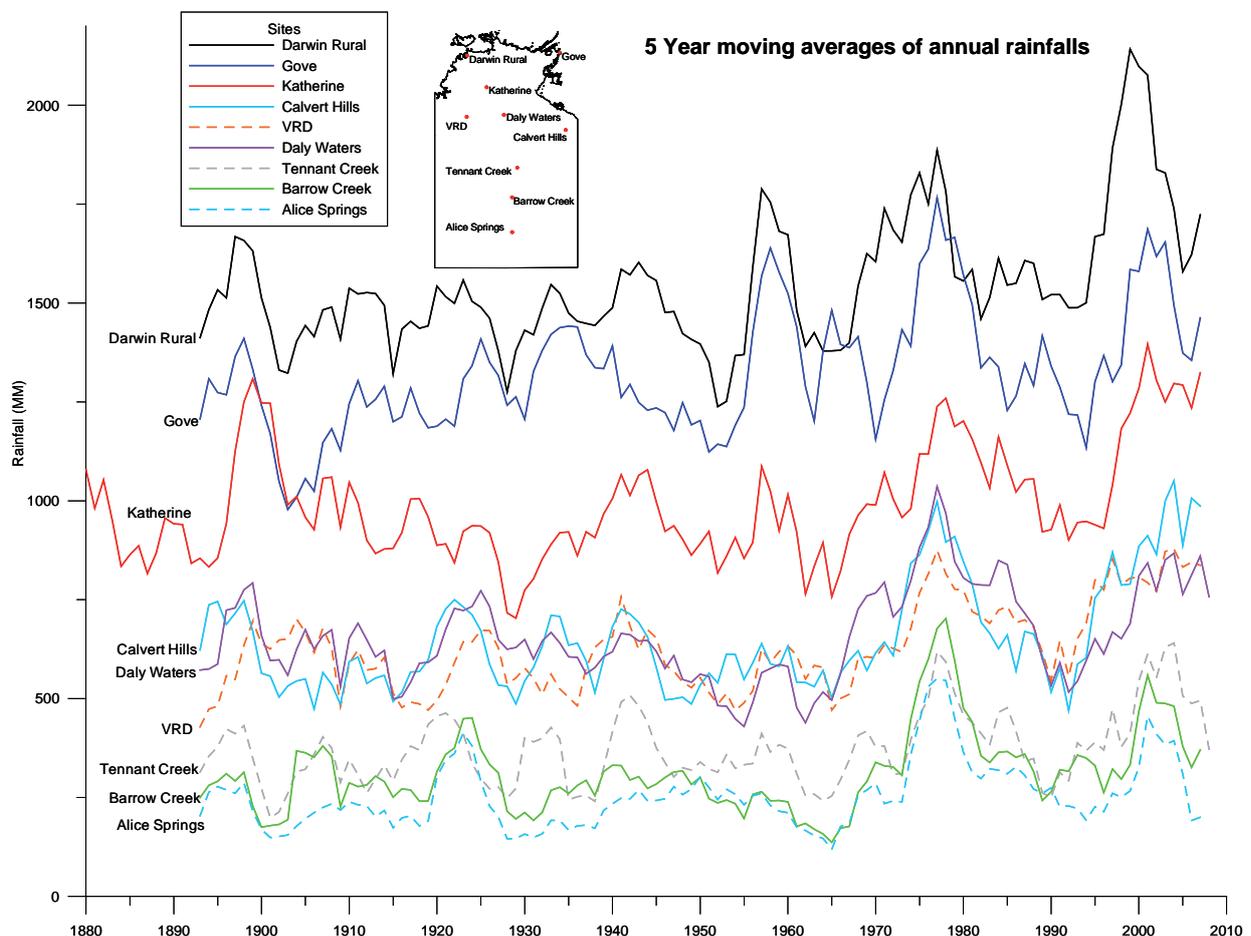


Figure 13 Rainfall records from sites across the Northern Territory (from Bureau of Meteorology, SILO data)



Water quality

All groundwater contains dissolved salts and other chemical constituents. The ions that are commonly present include: sodium, potassium, calcium, magnesium, chloride, bicarbonate, sulphate, iron, silica, nitrate and fluoride. Many other species can be present but normally only in trace amounts. If the concentrations are too high they can affect the usability of the water. Some ions such as arsenic, fluoride or nitrate can be harmful to human or animal health if concentrations are too high. On the other hand other constituents and properties such as salinity, hardness, pH or iron may not present health risks but can affect the taste of drinking water, be corrosive to plumbing, cause scale on plumbing or cause staining.

Sources of dissolved salts

The dissolved salts are normally natural in origin and are sourced from rainwater, airborne dust, soil or rocks. All rainwater contains salts, normally in very low concentrations. Evapotranspiration gradually concentrates these in the unsaturated zone. Over long periods a balance is achieved between the amount of salt stored there and the amount that is flushed down to the aquifer with recharge water. In high rainfall areas where recharge tends to be regular there is little opportunity for salts to become concentrated. In the arid zone however a much lower proportion of rain ends up as recharge but the salts remain in the unsaturated zone due to evaporation at or near the ground surface. Groundwaters there are correspondingly saltier on average.

The other main source of salts is from the bio-chemical breakdown of rocks during weathering. This is most notable in carbonate rocks such as limestone and dolomite. Recharge waters are commonly mildly acidic which results in the gradual dissolution of those rocks. Bicarbonate, calcium and magnesium ions are the products of this reaction and so groundwaters from aquifers in carbonate rocks are characteristically rich in those ions.

Bio-chemical breakdown of rocks is a much more active process in the humid zone compared to the arid zone. The more abundant water and lush vegetation in the north is conducive to that type of weathering. This is reflected in the chemical composition of groundwaters. In the arid zone sodium and chloride are the most abundant ions while in the humid zone calcium, magnesium, sodium and bicarbonate ions dominate. Chloride is a useful indicator for the origin of salts in groundwaters. Few rocks contain chloride but all rainwater carries small amounts that ultimately have been derived from sea spray. Sodium chloride waters are an indication that rainwater is the dominant source of salts. Where other ions are dominant, rock weathering is the main source.

Another source of anomalously high salinities are sedimentary formations that contain salt deposits laid down at the same time as the rock itself (evaporites). Halite (sodium chloride) and gypsum (calcium sulphate) are the most common evaporite minerals. Groundwaters in these rocks actively dissolve the geological salts. Notable examples of this process occur in the Anthony Lagoon Beds in the Georgina Basin and in the Jinduckin Formation, its equivalent in the Daly Basin. The former example appears as an anomalously saline area in the east central part of the "Salinity" side map. High fluoride concentrations also occur in these formations. The Bitter Springs Formation in the Amadeus Basin is also known to contain saline groundwaters related to evaporites.

Salinity

Salinity is the sum of all the dissolved constituents in water and is a general indicator of water quality. It is commonly expressed as Total Dissolved Solids (TDS, mg/L). The side map "Salinity" shows groundwater salinities from individual bores across the Territory. An obvious feature of the map is that groundwater salinities are broadly related to rainfall, the higher the rainfall, the lower the salinity. Local effects due to variations in recharge rate are superimposed on that pattern.

In the arid zone for example not all groundwaters have high salinities. In places where recharge can occur rapidly there is little opportunity for the salts to be concentrated by evapotranspiration. Sandy river beds can be sites of rapid recharge and are often underlain by fresh groundwaters. At the other extreme where recharge takes place slowly, the minute amount of salt brought in by rainwater and wind-blown dust is gradually concentrated in the soil and in the unsaturated zone by evapotranspiration. This takes place over thousands of years. The relatively small amount of recharge in these areas contains a proportionally higher concentration of salts.

In the humid zone the effect of recharge rate on salinity is generally not so obvious. Exceptions are aquifers that lie beneath the coastal plains where groundwater salinities can sometimes exceed that of seawater (34,000 mg/L TDS). Direct connection between the aquifer and the sea or estuary is a likely source of the salt in many cases. Tickell and others (2006) used stable isotopes of water to investigate saline groundwater beneath the Keep River Plains. They concluded that the saltwater originated from evaporative concentration of rainwater because of a very low recharge rate through the cracking clay soils.

Water quality and usage

The concentrations of certain ions as well as the salinity of groundwater can affect its suitability for different uses. It is impossible to set exact limits for human consumption because other factors also influence the levels that are acceptable. For example the climate, a person's age and the amount of water consumed can all have some influence. Because of this the National Health and Medical Research Council sets guideline values for the various components that are commonly found in drinking waters. These are listed in Appendix 1 together with some recommended limits for stock watering and other uses. Figure 14 shows the distribution of groundwaters that exceed the guideline values for human consumption for total dissolved solids (salinity), nitrate, sulphate and fluoride.

Groundwaters in carbonate rocks have high hardness which can cause calcium carbonate deposits to build up in the bore itself, hot water systems and other plumbing. Excessive iron in groundwater is common and can give the water an unpleasant taste, cause staining of laundry, pipe encrustation and odour problems. In the arid zone high salinities often limit the uses of groundwaters. Many groundwaters in the Humid zone that are from non-carbonate rocks have a low pH which can lead to corrosion of metal piping. Various water treatments are available to reduce these problems.

On a more local scale particular ions can be present in amounts exceeding the guideline values. For example in areas such as Pine Creek where metallic mineral deposits are common, anomalously high arsenic is locally encountered. Similarly high radium concentrations occur in some Daly Basin groundwaters just west of Katherine. It appears to be related to a particular geological horizon (Martin and Qureshi, 1996).

High nitrate concentrations are usually regarded as indication of groundwater pollution associated with human activity. In the arid zone nitrate often exceed the guideline value (50 mg/L) for human consumption despite the sparse population and near natural conditions (Figure 14). Barns and others (1992) concluded that it is produced by bacteria in termite mounds and in the soil. Fire also plays an important role in increasing the available nitrogen at the soil surface.

Fluoride is encountered in high concentrations in groundwaters of the Anthony Lagoon Beds in the Georgina Basin as described above and in a variety of formations in Central Australia including granite, metamorphics, shallow calcrete and some sandstones in the Amadeus Basin.

Pollution and groundwater

Many human activities can lead to contamination of groundwater by a variety of undesirable chemicals. Such pollution is often long lasting because of the generally slow rate of movement of groundwater. Remediation is technically difficult and expensive, so prevention is by far the best approach.

Shallow unconfined aquifers are the most at risk from contamination. Karstic aquifers are particularly vulnerable because solution cavities connecting the surface to the watertable can provide rapid access of pollutants.

There is presently only minor industrial and agricultural development in the Territory and no major instances of pollution have been recorded. Leakage from fuel storage tanks has resulted in several cases of aquifers being contaminated by hydrocarbons. Potential sources of groundwater pollution include landfills, agricultural chemicals, septic tanks and mine waste dumps. Measures that can be taken to minimise the risk of contamination include proper design of waste facilities, a high standard of bore construction, optimising the use of agricultural chemicals, appropriate management of chemicals and appropriate land management practices.

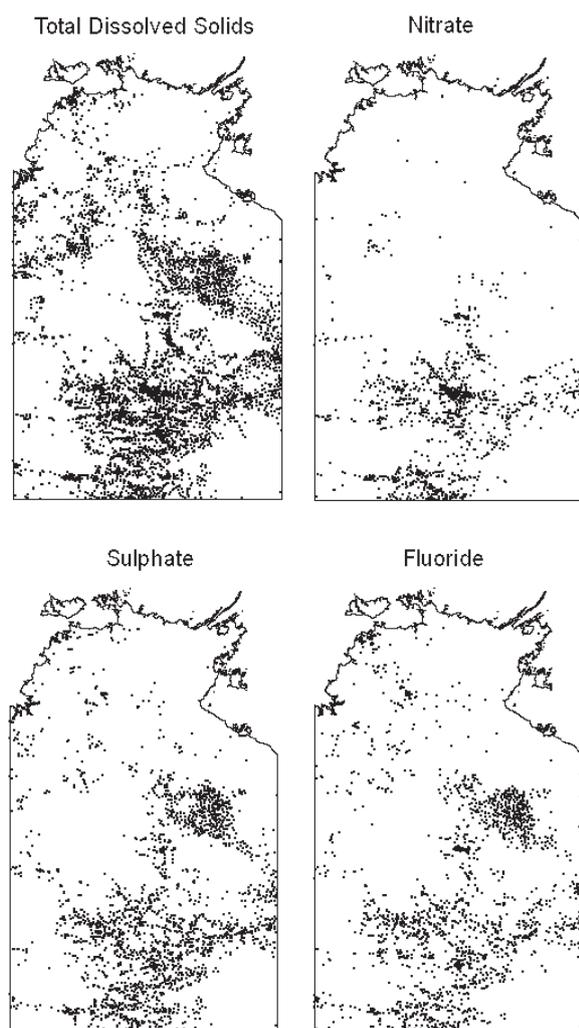


Figure 14 Bores with water quality exceeding the guideline values for human consumption



Use and management of groundwater

Groundwater is a widely utilised resource across the Territory. It supports a diverse range of ecosystems and makes possible many of the human activities that otherwise would be difficult in such a harsh climate. The utilisation of groundwater and aspects of its management are described below.

Nature and groundwater

Many streams in the humid zone are fed from groundwater discharge and maintain flows for part or all of the dry season (see Groundwater Discharge side map). These form corridors of riverine vegetation, waterholes, springs and flowing streams. The presence of free water and even of shallow watertables maintains a much greater diversity of flora and fauna than would otherwise be present in a dry savannah. The degree to which they are dependant on groundwater is largely unknown. The main knowledge available on groundwater dependency of ecosystems comes from a series of studies carried out on the Daly River (Erskine and others, 2003). These included studies on the pig-nosed turtle, riparian vegetation, *Vallisneria nana* (a water plant) and periphyton and phytoplankton. A series of recommendations for water management were made based on these studies.

Groundwater dependent ecosystems also occur in the arid zone but to a much lesser extent than in the wetter areas of the north. Red gums that flank many inland streams are an obvious example but small wetlands around springs and groundwater fed waterholes are another type. Many of the latter areas are refuges for plants and animals that would otherwise not survive in such an arid environment (Box and others, 2008).

A widespread but largely unseen groundwater dependent ecosystem comprises faunas that live within aquifers themselves, in the pore spaces, fractures and caves. Communities of crustaceans, insects, worms, gastropods, mites and fish termed stygofauna are adapted to subterranean life and have been identified in

aquifers across Australia (Humphreys, 2006). Little work has been done on stygofauna in the Territory apart from sampling of springs and bores in the Katherine area and springs on Pungalina Station. This work has not been published but the presence of stygofauna has been confirmed (W. Humphreys, personal communication). An investigation of the sand/gravel aquifer associated with the palaeo-Ord River in Western Australia identified the presence of stygofauna (Humphreys, 1999). That aquifer continues to the east into the Territory. Similarly stygofaunas have been described from shallow calcrete aquifers in Western Australia that continue into the arid western side of the Territory (Humphreys, 2001).

Many of the Territory's national parks and reserves have been sited to highlight groundwater discharge features and their associated ecosystems. These include springs and spring fed streams. In the humid zone parks such as Elsey, Flora, Berry Springs, Howard Springs, Douglas Hot Springs and Litchfield have many water features that are dependent on groundwater discharge for much of the year. Even in arid Central Australia some parks contain groundwater discharge features that maintain ecosystems that would otherwise not exist there. Parks such as Finke Gorge and West MacDonnell feature many groundwater fed waterholes and their associated ecosystems.

People and groundwater

History of Groundwater Use

Today most towns and communities are dependant on groundwater as are industries such as cattle, mining and tourism. Some important events in the history of groundwater use are described below.

The use of groundwater by people in the Territory began in prehistoric times with the Aborigines. They largely relied on waterholes, lagoons, springs and shallow unlined wells for their water supplies. Due to the importance of water to their survival, especially in the inland regions, they incorporated the locations of many watering points into their Dreamtime stories and associated them with significant events in those stories.

Macassan Fishermen visited the northern coastline to collect and process trepang (sea slugs). They usually stayed for the duration of the dry season and either used Aboriginal water sources or constructed shallow lined hand dug wells. These visits ceased in the mid 1800's following European settlement.

The British Government attempted to colonise the northern coastline. Three attempts were made at establishing settlements between 1824 and 1849 at Fort Dundas, Fort Victoria and Fort Wellington. All three obtained their water supplies from springs and wells. These settlements were abandoned primarily due to the prevalence of diseases such as scurvy and malaria. They were unable to supply sufficient water, fresh food, timber or any other tradable commodity to passing ships.

The Overland Telegraph line from Adelaide to Darwin was completed in 1872, linking up with the underwater cable from Batavia (Jakarta). Repeater stations were built along the route at sites where reliable water supplies were found. Waterholes (often groundwater fed) in the MacDonnell Ranges were the first watering points after a 300 kilometre dry stage from the last watering point at Dalhousie (50 km south of the current South Australia/Northern Territory border). North of the Alice Springs area, shallow wells provided water for many of the telegraph stations.

Darwin was established in the late 1860's. Shallow wells at Doctors Gully and Stokes Hill supplied the early settlement. Later a number of missions were established along the north coastline at locations such as Millingimbi and Bathurst Island. All water for these developments was obtained from springs or shallow wells.

The Pastoral Industry commenced on the Barkly Tablelands with cattle and sheep being driven across from Queensland in 1868. Water supplies were obtained from waterholes until a drought between 1897 and 1903 spurred owners to seek groundwater supplies.

The station owners having come from Queensland were very keen to obtain artesian water. Non-artesian supplies had to be pumped with pumping plants powered by boilers. The fuel was the local trees and each bore had to have an attendant who cut the timber and maintained the pumping plant.

The Government Resident lobbied the South Australian Government in 1890 to drill a deep hole in an attempt to locate artesian water. The resulting bore was drilled on Alexandria Pastoral Station in 1892/93 to a depth of 536 metres at a cost of £8026.

The hydrogeological advice received prior to drilling was vindicated and this bore still produces ample supplies of good quality water from approximately 80 metres from the sub artesian aquifer. Many bores were constructed on the Barkly Tablelands in the following 30 years. This increased the carrying capacity of the land tenfold.

Most of these bores are still operating today. Until 1930 many of these bores were equipped with pumping plants that were driven by wood fuelled boilers. These were then replaced with diesel engines as timber supplies were scarce.

With the establishment of bores and wells along the Overland Telegraph Line new settlers were able to migrate to the north. Kelly Well (south of Tennant Creek) was constructed in 1875 as the first of four stock wells to be established on the Overland Telegraph Line. During the 1870's a number of cattle stations were also established.

These stations were in areas where water supplies could be obtained either from springs in river or creek beds or wells adjacent to them.

The first bores were drilled in 1899 and 1900 at Charlotte Waters and Anacoora. These bores were drilled in the Great Artesian Basin to 450 and 381 metres respectively. Anacoora flowed at a rate of 46 L/sec when first constructed. The Charlotte Waters bore was drilled for the telegraph line while Anacoora was located on a supply route between Oodnadatta and Alice Springs. Until the Second World War most water supplies were obtained from springs or shallow hand dug lined wells.

World War II saw the non Aboriginal population of the Territory increase dramatically. The majority of the troops arrived after Darwin was first bombed in 1942. Water supplies for the troops were obtained from lined, hand dug wells or springs. After Darwin was bombed, 11 additional airfields were constructed between Darwin and Katherine. The water supply needs of the thousands of troops could not be met by well and spring sources alone. Between July 1942 and October 1944 approximately 90 bores were constructed primarily by the 2/1 Australian Boring Section of the Royal Australian Engineers to meet these needs. Bores were normally constructed with six inch steel casing. Depths ranged from 30 to 74 metres and yields were up to 2 L/sec. Eleven different drillers were involved in the work.

Significant mining developments took place after the war. These began with uranium at Rum Jungle in the 1950's and accelerated in the 1960's with bauxite at Nhulunbuy, uranium at Ranger and manganese at Groote Eylandt. All these mines relied on the development of groundwater resources for their water supplies.

Land rights were gained by the Aboriginal population in 1976 together with the right to manage their own communities. The responsibility for securing water supplies was transferred from the missionaries and the pastoralists to State governments.

Commonwealth funded programs supported an enormous increase in investigation work to locate suitable groundwater resources. Much of today's knowledge of the Territory's groundwater resources was acquired from this work which is still continuing.

The majority of towns and communities now use groundwater as their sole water source. Darwin and Katherine are the two exceptions. Darwin's major source is Darwin River Dam and Katherine pumps water directly from the Katherine River but both places supplement those sources with groundwater.

The Territory has a small irrigated horticulture industry in the Darwin, Douglas / Daly, Katherine and Ti-Tree areas. It is entirely reliant on groundwater. The pastoral industry is now widespread with the Barkly Tablelands, the Victoria River District and the Alice Springs region being the main cattle producing areas. Groundwater again is the dominant water source but rivers, waterholes and small dams are also used where local conditions permit.

There are currently seven major mines operating in the Territory producing gold, uranium, bauxite, manganese, lead / zinc / silver and mineral sands. Groundwater provides the main water source for most of these operations. It is used for domestic purposes, ore processing and dust suppression.

Groundwater Monitoring

Groundwater levels are measured by the Northern Territory Government in some 900 bores across the Territory (Figure 15). Regular water level measurements were begun in 1952 at Alice Springs. Most observation bores are in a few key areas including the Mereenie borefield and the Town Basin at Alice Springs, the Ti-Tree Basin, the Tennant Creek borefield, the Daly Basin and the Darwin rural area. Outside of those areas few bores are regularly monitored. The bores are measured at least twice a year and many now have pressure transducers and data loggers installed, allowing for near continuous recording. Groundwater quality is not monitored on a regular basis.

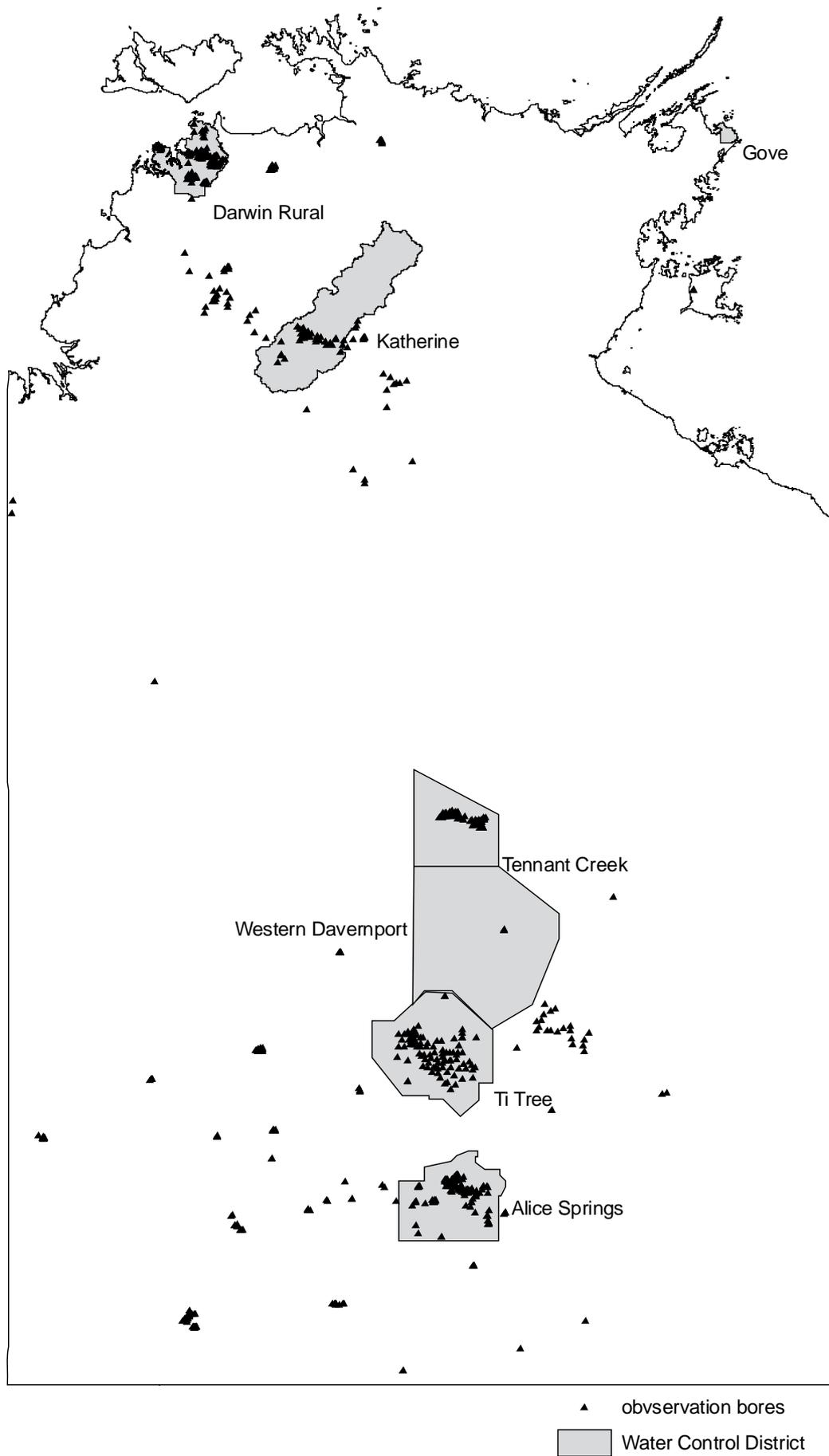


Figure 15 Water level monitoring bores and “Water Control Districts”

Regulations

The primary legislation relating to water in the Territory is the *Northern Territory Water Act, 1992*. It governs the investigation, allocation, use, control, protection, management and administration of water resources. The relevant Minister administers the Act through the Controller of Water Resources currently part of the Department of Natural Resources, Environment, The Arts and Sport. Some of the key aspects of the Act in relation to groundwater include:

Water bores

Water bores may only be drilled by a driller licensed in the Northern Territory. A bore construction permit is required for bores drilled within a Water Control District (see below). No permit is required for bores outside of Water Control Districts. Drillers are required to submit a bore completion report to the department detailing strata, water intersections, bore construction and other information about the bore. Strata samples and water samples must also be lodged with the department.

Water Extraction Licences

Landholders have the right, without a licence, to take groundwater on their land for domestic purposes, wandering stock, and for domestic gardens of up to 0.5 hectares. Outside Water Control Districts water for other purposes can be taken up to a maximum pumping rate of 15 L/sec.

Water Extraction Licences are required when pumping a bore situated inside a Water Control District other than for stock and domestic purposes. An exception is the Darwin Rural Water Control District where the bore needs to be pumping more than 15 L/sec for a licence to be required.

Water Control Districts

A Water Control District can be declared in an area where there is a need for closer management to avoid stressing of groundwater reserves, river flows or wetlands. Districts declared include the Darwin, Gove, Katherine, Tennant Creek, Western Davenport, Ti-Tree and Alice Springs regions (Figure 15).

Water Allocation Plans

Water Allocation Plans can be declared for Water Control Districts to manage water extraction to sustainable levels. The plans will allocate water resources to the types of beneficial uses declared for the water resource. Beneficial uses are the uses for water as declared under the Act. They are the basis for, water allocation planning and include cultural, agriculture, aquaculture, public water supply, environment and industry. Water Allocation Plans have been declared for the Ti-Tree, Katherine and Alice Springs Water Control Districts to date.

In parts of Central Australia recharge rates may be too low to permit sustainable extraction of groundwater. Mining of the groundwater resource will be an inevitable consequence of some major developments. For example the aquifer that is used for Alice Spring's water supply is not being replenished at the same rate as water is extracted. The economics of pumping from progressively greater depths will eventually lead to the establishment of new borefields at locations more distant from the town.

Climate Change

The increase in average rainfall experienced by much of the humid zone over the past thirty years was described in the previous section "Impacts of long term rainfall variations". The reason for the change is unknown. It may be related to global warming or it could be a natural cycle. Whatever the case it has resulted in higher recharge to aquifers, elevated watertables and increased baseflows to streams.

Given that the greatest population growth and most agricultural developments have taken place since the mid -1970's there is a danger that the current rainfall regime in the north could be regarded as normal. Water allocation systems must be flexible enough to take into account that sustainable groundwater yields could suddenly decrease back to pre-1970's volumes if the rainfall were to revert to the long term average or less.

Where to get Groundwater Information

Groundwater information for the Northern Territory is available through the Department of Natural Resources, Environment, The Arts and Sport (NRETAS). It can be obtained from the internet or from the department's offices in Alice Springs or Darwin. The web site (<http://www.nt.gov.au/nreta/>) contains general information about the occurrence, water quality and use of groundwater. An online mapping tool, "NRETAS Maps" contains details about existing water bores, technical reports and maps (<http://internal.nreta.nt.gov.au/onlinesystems/nretamaps.html>).

Both the Alice Springs and Darwin NRETAS offices have rural advice sections where general information about groundwater and drilling can be obtained. Bore construction permits and water extraction licenses can also be applied for. A database containing details of existing water bores, groundwater levels measured in monitoring bores and stream flows is maintained by NRETAS and the information is available to the public on request. Technical reports are held at the NRETAS library in Darwin and at the Arid Zone Research library in Alice Springs.



Glossary

acoustic doppler flow meter: A type of instrument for measuring stream velocities and flows. Sound waves are emitted and the waves that are reflected from particles in the water are recorded. The Doppler Shift of the returning signal is used to calculate the velocity.

alluvial: Deposited by streams or running water.

aquifer: A body of rock or sediment which holds and allows water to move through it, and which is capable of yielding usable quantities of groundwater to boreholes and or springs.

artesian: An artesian aquifer is one confined by overlying impermeable beds. When it is penetrated by a borehole, the water level will rise above ground level.

baseflow: The proportion of water flowing in streams and rivers that comes from groundwater. Stream flow during at the end of the dry season may be virtually all baseflow.

bauxite: A type or rock mined for its high aluminum content.

bore: A hole drilled vertically in the ground to tap an aquifer, and containing a pipe through which groundwater can be pumped.

borehole: A drilled hole. Those drilled for groundwater are normally vertical.

borefield: A group of bores in a particular area used for groundwater extraction.

cable tool drilling: A method of drilling in which a heavy chisel shaped bit is suspended from a steel cable and repeatedly bounced off the bottom of the borehole to chip away at the rock. The rock cuttings are periodically removed by a bailer.

calcrete: A rock composed of calcium carbonate that is deposited from soil water or groundwater.

capillary action: The action by which water is drawn upwards through fine pores in soil or rock by surface tension.

carbonate rock: A rock such as limestone or dolomite, consisting largely of the carbonate minerals; calcium carbonate or calcium magnesium carbonate.

casing: A steel or plastic pipe inserted into a borehole to prevent collapse and to provide a seal.

confined aquifer: A confined aquifer occurs where an aquifer is overlain by a confining bed. The confining bed prevents upward movement of the groundwater. Such aquifers are usually completely saturated with water which is commonly under pressure. Therefore when a bore intersects the aquifer, water rises up the bore. If the pressure is sufficient to drive the groundwater above the ground level, the bore is called artesian.

diffuse recharge: The widespread downward seepage of rainwater through the soil and then into the aquifer.

discharge: Outflow of water from an aquifer.

dolomite: A sedimentary rock composed mainly of the mineral dolomite (calcium magnesium carbonate).

ephemeral: An ephemeral stream or spring is one which only flows intermittently.

evaporation: The process whereby liquid water turns to a vapour.

evaporite deposits: A sedimentary rock composed primarily of minerals produced from a saline solution as a result of extensive evaporation of a water body.

evapotranspiration: The loss of water from the soil through both evaporation and transpiration from plants.

fluvatile: Formed by the action of rivers.

fractured: A fractured rock is one that is broken by joints, cracks or faults.

groundwater: Water beneath the surface of the earth which saturates the pores and fractures of sand, gravel, and rock formations.

groundwater dependent ecosystems:

A community of plants and animals that rely partially or completely on groundwater for its existence.

hydrogeology: The study of groundwater and its relationship to the geologic environment.

hydrograph: A graphical plot of ground water levels against time for bores or of discharge against time for streams.

infiltration gallery: A gravel filled trench used to extract groundwater from shallow aquifers. Water is gathered through horizontal slotted pipes laid in the gravel.

interbeds: A thin bed of one kind of rock between or alternating with another kind.

intergranular porosity: The porosity between grains or particles in a rock or sediment.

isohyets: A contour on a map joining points of equal rainfall.

karst: A term describing typical geologic/topographic attributes of limestone or dolomite resulting from mineral solution. Caves, sinkholes and underground drainage are typical karstic features.

karstic aquifers: An aquifer in which fractures or pores have been enlarged by solution of the rock, typically in limestone or dolomite.

laterite: A residual iron rich rock formed by chemical weathering. It accumulates in the soil profile.

limestone: A sedimentary rock composed mainly of the mineral calcite (calcium carbonate).

matric suction: The suction exerted by the soil material (matrix) that induces water to flow in unsaturated soil. It is a negative pressure that results from the combined effects of adsorption and capillarity due to the soil matrix. Water flows from a soil with low matric suction (a wet soil) to soil with a high matric suction (a dry soil).

metamorphism: The action of heat and or pressure on rocks that changes their physical and chemical properties.

monsoon: A tropical weather system that effects northern Australia during summer. It brings winds from the north west, often abundant rain and cyclones.

monsoon vine forest: A mixed species forest with a closed canopy that is commonly associated with springs and other areas with abundant soil moisture.

mound spring: A spring surrounded by a mound formed from deposits of calcium carbonate, clay and plant material.

palaeovalley: Buried river system with a distinct valley cut into the underlying bedrock. Also referred to as palaeochannel or paleodrainage.

permeability: The capability of a geologic formations to transmit water.

pH: A measure of the relative acidity or alkalinity of water. Water with a pH of 7 is neutral; lower pH levels indicate increasing acidity, while pH levels higher than 7 indicate increasingly basic solutions. The range is 1-14.

point source recharge: Water entering an aquifer from a discreet point source such as a cave.

porosity: The degree to which the total volume of sediment or rock is permeated with spaces or cavities through which water or air can move.

porous: Having numerous small spaces in a rock, either connected with each other or not.

potentiometric surface: An imaginary surface representing the static head of groundwater in a bore that taps an aquifer or in the case of unconfined aquifers, the watertable.

primary porosity: Voids in a rock formed when the rock was deposited. The spaces between sand grains are an example of primary porosity.

recharge: Water added to an aquifer.

rotary drilling: A well drilling method achieved by the rotary action of a drill bit. The ground-up rock is removed by circulating drilling mud or air which may be forced down the drill pipe and out via the annular space between the drill pipe and the hole.

salinity: The concentration of mineral salts dissolved in water. It may be expressed in terms of a concentration or as electrical conductivity.

sand spears: A series of narrow diameter bores that are jetted or driven into shallow sand aquifers. They are often connected to a single pump.

sandstone: A sedimentary rock composed of sand grains cemented together.

secondary porosity: Voids in a rock formed after the rock has been deposited; not formed with the genesis of the rock, but later due to other processes. Caverns in limestone are examples of secondary openings.

semi-confined aquifer: One in which the upper confining layer is leaky, but still contributes significantly to the flow of the aquifer.

silcrete: A rock composed mainly of silica, formed either by soil forming processes or precipitated from groundwater in the zone where the watertable fluctuates.

siltstone: A sedimentary rock composed of silt sized particles.

solution cavity: Opening in rocks produced by dissolution, commonly of limestone or dolomite.

spring: An area where there is a concentrated discharge of groundwater that appears as a flow of water at the surface.

stable isotopes of water: Varieties of hydrogen and oxygen that contain more neutrons than the common types. They are present in trace amounts in all waters and are used as environmental tracers.

stream bed seepages: Zones along stream beds which receive groundwater seepage.

stygo fauna: Subterranean fauna that lives in aquifers. They include crustaceans, insects, worms, gastropods, mites and fish.

surface water: Water that is on the earth's surface, such as in a stream, river, lake, or reservoir.

total dissolved solids: The amount of dissolved material in water usually measured in milligrams per liter (mg/L).

transpiration: The process by which water that is absorbed by plants, usually through the roots, is evaporated into the atmosphere from the plant surface, via tiny pores on the leaves and stems.

unconfined aquifer: An unconfined aquifer is a permeable formation which extends from the land surface down to a confining base. It is generally partly filled with water and open to air pressure above. When penetrated by a bore the water remains in the bore at the same level at which it was struck. This is because the water pressure at the water table is at atmospheric pressure. The water surface in such an aquifer is called the watertable.

unconsolidated sediments: A sedimentary deposit in which the particles are not cemented together.

unsaturated zone: Zone in the upper layers of the soil, unconsolidated sediments, and bedrock where the pore spaces are not completely filled with water (i.e. not saturated).

watertable: The water level of an unconfined aquifer, below which the pore spaces are generally saturated.

weathering: Chemical, physical and biological decomposition of rocks. This can result in the formation of a soil profile.



Acknowledgements

As the compiler of the explanatory notes and the accompanying map I take pleasure in thanking my NRETAS colleagues for their assistance in many ways. I am particularly indebted to Des Yin Foo, Anthony Knapton, Danuta Karp, John Wischusen, Maria Woodgate, Jon Sumner and Caroline Green for their critical comments on the map and report. Daryl Chin and Bob Read of the Northern Territory Power Water Authority also provided helpful editorial comment. The section on “history of groundwater use” has been adapted from information on the NRETAS web site written by Peter Jolly and Bev Phelts.

I have benefited from the numerous discussions with my current and former colleagues about the hydrogeology of many far-flung places in the Northern Territory. In particular I am thankful to Peter Jolly, the long-time head of the groundwater section of NRETAS. Peter has a deep knowledge of the Northern Territory’s groundwater. He was responsible for both carrying out and initiating ground-breaking investigations on many aspects of groundwater.

Finally my thanks to Lynton Fritz for doing a first class job of drafting. He drew the map both accurately and artistically. Rossimah Sinordin provided assistance in compiling GIS datasets.

Steven Tickell

References

- Ahmad, M. and Scrimgeour, I. R., 2006. Geological map of the Northern Territory, 1:2,500,000 scale, Northern Territory Geological Survey, Darwin.
- ANZECC, 2000. Australian and New Zealand guidelines for fresh and marine water quality. Volume 3, Primary industries / Australian and New Zealand Environment and Conservation Council, Agriculture and Resource Management Council of Australia and New Zealand.
- Barnes, C.J., Jacobson, G and Smith, G.D., 1992. The origin of high nitrate groundwater in the Australian arid zone. *Journal of Hydrology* 137, pp181–197.
- Box, J.B., Duguid, A., Read, R.E., Kimber, R.G., Knapton, A., Davis, J., Bowland, A.E., 2008. Central Australian waterbodies: The importance of permanence in a desert landscape. *Journal of Arid Environments* 72, pp1395– 1413.
- Cook, P.G., Herczeg, A.L., Pidsley, D. and Farrow, R., 1998. Hydrological investigation at Howard East, N.T. 2. Eucalypt savanna site: soil physics and groundwater geochemistry. CSIRO Land & Water technical report 13/98.
- Coram, J. E., Dyson, P. R., Houlder, P.A. and Evans, W.R., 2000. Australian groundwater flow systems contributing to dryland salinity. A Bureau of Rural Science project for the National Land and Water Resources Audit.
- Dames and Moore, 1992. Preliminary assessment of the feasibility of artificial recharge to augment water supplies at Pine Creek, Northern Territory, report for Power and Water Authority, Northern Territory.
- Domahidy, G., 1990. Hydrogeology of the Granites – Tanami mining region. Explanatory notes for 1:250,000 scale map. Northern Territory Power and Water Authority.
- Erskine, W.D., Begg, G.W., Jolly, P., Georges, A., O’Grady, A., Eamus, D., Rea, N., Dostine, P., Townsend, S. and Padovan, A., 2003. Recommended environmental water requirements for the Daly River, Northern Territory, based on ecological, hydrological and biological principles. Report No.4, Supervising Scientist, Darwin NT
- Haig, T., Knapton, A. and Matsuyama, A., 2003. Water resources of the Tiwi Islands: main report, Report 26-2003d, Natural Systems Division, Northern Territory Department Of Infrastructure, Planning And Environment
- Harrington, G. A., Herczeg, A.L. and Cook, P.G., 1999. Groundwater Sustainability and Water Quality in the Ti-Tree Basin, Central Australia, CSIRO Land & Water technical report 53/99, updated 2001.
- Howe, P., O’Grady, A.P., Cook, P.G., Knapton, A., Duguid, A. and Fass, T., 2007. A framework for assessing the environmental water requirements of groundwater dependent ecosystems, Report 2 Field Studies. Land and Water Australia, Adelaide.
- Humphreys, G., Tickell, S., Yin Foo, D., and Jolly, P., (1995), Sub-Surface Hydrology of the Keep River Plains, Water Resources Division, Power and Water Authority, Northern Territory Government. Technical Report 25/95D.
- Humphreys, W. F. 1999. Groundwater fauna sampling in the Kimberley north of 16°S and east of 128°E. In Kinhill Pty Ltd, (2000), Ord River Irrigation Area Stage 2 Proposed Development of the M2 Area, Environmental Review and Management Programme Draft Environmental Impact Statement Appendix M.
- Humphreys, W.F., 2001. Groundwater calcrete aquifers in the Australian arid zone: the context to an unfolding plethora of stygal biodiversity. *Records of the Western Australian Museum Suppl.* 64: 63-83.
- Humphreys, W. F., 2006. Aquifers: the ultimate groundwater-dependent ecosystems. *Australian Journal of Botany*, 54, 115-132.
- Jacobson, G., Lau, G. C., McDonald, P.S. and Jankowski, J. 1989. Hydrogeology and groundwater resources of the Lake Amadeus and Ayers Rock region, Northern Territory. Bureau of Mineral Resources, Australia, Bulletin 230.
- Jolly, P., 2002. Daly River Catchment Water Balance. Report 10/2002, Natural Resources Division, Northern Territory Department of Lands, Planning and Environment.
- Jolly, P. and Chin, D., 1991. Long term rainfall – recharge relationships within the Northern Territory, Australia – the foundations of sustainable development. International Hydrology and Water Resources Symposium, Perth, 2-4 October 1991.
- Jolly, P., Chin, D., Prowse, G. and Jamison, M. 1994. Hydrogeology of the Roe Creek borefield. Report 10/1994A, Water Resources Branch, Northern Territory Power and Water Authority.

- Jolly, P., George, D., Jolly, I. and Spiers, Z., 2000. Analysis of Groundwater Fed Flows for the Flora, Katherine, Douglas and Daly Rivers. Report 36/2000D. Natural Resources Division, Northern Territory Department of Lands, Planning and Environment.
- Karp, D., 2004. Sinkhole survey in the Katherine region. Report 16/2004D Northern Territory Department of Lands, Planning and Environment.
- Karp, D., 2005. Evaluation of groundwater flow by dye tracing, Katherine region. Report 22/2005D, Northern Territory Department of Natural Resources, Environment and The Arts.
- Lau, J.E., Commander, D. P. and Jacobson, G. 1987. Hydrogeology of Australia, Bureau of Mineral Resources, Australia, Bulletin 227.
- Lau, J. E. 1989. Logging of diamond drill core from Roe Creek borefield, Alice Springs. Northern Territory Power and Water Authority, report 49/1989.
- Lau, J. E., 1993. Logging of diamond drill core, Kelly Well borefield, Tennant Creek. Report 66/1993A, Northern Territory Power and Water Authority.
- Martin, P. and Qureshi, H. 1996. High concentrations of radium in groundwater of the Daly Basin. Report 73/1996D, Water Resources Branch, Northern Territory Power and Water Authority.
- McGowan, R.J. 1989. Hydrogeology of the Pine Creek mining region, explanatory notes for 1:250,000 scale map. Northern Territory Power and Water Authority, report 10/1989
- Mory, A.J., 1991. Geology of the offshore Bonaparte Basin northwestern Australia. Geological Survey of Western Australia. Report 29, 47pp
- National Land & Water Resources Audit, 2001. Australian water resources assessment 2000. National Land & Water Resources Audit, Canberra.
- National Water Commission, 2005. Australian water resources 2005, National Water Commission, Canberra.
- N.H.M.R.C., 2004. Australian drinking water guidelines. National Health and Medical Research Council, Natural Resource Management Ministerial Council. Australian Government.
- O'Grady A.P., Eamus, D., Cook, P., Lamontagne, S., Kelley, G. and Hutley, L.B., 2002. Tree water use and sources of transpired water in riparian vegetation along the Daly River, Northern Territory, Darwin. Department of the Environment and Heritage Commonwealth of Australia, Canberra.
- Pavelic, P., Dillion, P., Barber, C., Toze, S., Yin Foo, D., Jolly, P. and Knapton, A., 2002. Water banking trial at Waruwi, South Golburn Island, NT. Stage 3 report to Department of Infrastructure, Planning and Environment, .Northern Territory. Report WRD02035.
- Pearson, J.S., 1985. Timber Creek groundwater resource evaluation. Report 16/1985, Water Resources Division, Northern Territory Department of Mines and Energy.
- Read, R. and Tickell, S. J. 2008 The Ti-Tree Basin aquifer. 1:250,000 scale map. Northern Territory Department of Natural Resources, Environment and the Arts.
- Seidel, G., 1999. Testing for reconstruction of production bore P25 Roe Creek, Report 04/1999A, Natural Resources Division, Northern Territory Department of Lands, Planning and Environment.
- Senior, B.R., Truswell, E.M., Idnurm, M, Shaw, R.D. and Warren, R.G., 1995. Cainozoic sedimentary basins in the eastern Arunta Block, Alice Springs region, Central Australia, AGSO Journal of Australian Geology and Geophysics 15(4): 421-444
- Tickell, S.J., 2002. A survey of springs along the Daly River between Beeboom and Daly River Crossings, Report 06/2002D, Northern Territory Department of Infrastructure, Planning and Environment.
- Tickell, S.J., Cook, P., Sumner, J., Knapton, A. and Jolly, P., 2006. Evaluating the Potential for Irrigation Induced Salinisation of the Keep River Plains. Technical Report No. 30/2006D, Northern Territory Department of Natural Resources the Environment and The Arts.
- Wilson, D., Cook, P., Hutley, L., Tickell, S. and Jolly, P., 2006. Effects of land use on evapotranspiration and recharge in the Daly River catchment. Report 17/2006D, Northern Territory Department of Natural Resources, Environment and The Arts.
- Wischusen, J. D. H., Fifield, L. K. and Cresswell, R.G., 2004. Hydrogeology of Palm Valley, Central Australia, a Pleistocene flora refuge? Journal of Hydrogeology, 293(2004), 20-46.

Appendix 1. Water quality guidelines

The guidelines for human consumption were obtained from: Australian Drinking Water Guidelines. National Health and Medical Research Council, 2004, (<http://www.nhmrc.gov.au>). Recommendations for stock and mango irrigation use are from the Northern Territory Government Department of Regional Development, Primary Industry Fisheries and Resources.

Salinity

Domestic use - 500 mg/L:

Salinity is the sum of all the salts present and it provides a convenient guide to water suitability. Above this limits taste may be unacceptable but it does not pose a health problem. Total salinity and the concentrations of individual salts can be reduced by reverse osmosis, ion exchange or distillation. If most of the salinity is due to hardness it can be reduced by softening the water.

Stock use - 10,000 mg/L:

There may also be a need to assess concentrations of specific salts causing purgative or toxic effects, especially if the salinity is greater than 2500 mg/L. If salinity is in the range 4000 to 5000 mg/L stock may have an initial reluctance to drink or there may be some scouring, but they should adapt without loss of production. From 5000 to 10,000 mg/L loss of production and a decline in animal condition and health would be expected. Stock may tolerate these levels for short periods if introduced gradually.

TDS (mg/L)	Water salinity rating	Plant suitability
<390	Very low	Sensitive crops
390-780	Low	Moderately sensitive crops
780-1740	Medium	Moderately tolerant crops
1740-3120	High	Tolerant crops
3120-4860	Very high	Very tolerant crops
>4860	Extreme	Generally too saline

General irrigation water quality guidelines (adapted from ANZECC, 2000, <http://www.mincos.gov.au/publications>).

Irrigation use

A general guide for irrigation water salinity is listed above. It should be noted however that other factors such as soil characteristics, climate, plant species, irrigation management and the specific composition of the dissolved salts must also be considered. Expert advice is always recommended. Salinity recommendations for mangoes and grapes, both grown commercially in the Northern Territory are 780 and 900 mg/L respectively

Nitrate

Domestic use - 50 mg/L:

Based on health considerations a limit of 50 mg/L is recommended for babies less than three months old and 100 mg/L for older children and adults. Nitrate levels can be reduced if necessary with the ion exchange process.

Stock use - 130 mg/L:

Excess nitrate can cause toxic symptoms and even death by reducing the oxygen carrying capacity of the blood. Stock may tolerate higher nitrate concentrations in drinking water provided nitrate concentrations in feed are not high. Levels above 1500 mg/L are likely to be toxic.

Fluoride

Domestic use - 1.5 mg/L:

This limit is based on health considerations. Excess fluoride can be removed by treating water with aluminum sulphate or bone char.

Stock use - 2.0 mg/L:

Excess fluoride can cause tooth damage to growing animals and bone lesions and embrittlement in older animals. If livestock feeds or salt licks contain fluoride, the drinking water limit should be reduced to 1.0 mg/L.

Iron

Domestic use - 0.3 mg/L:

Above this limit taste may be unacceptable but it does not pose a health problem. High iron concentrations give water a rust brown appearance resulting in staining of laundry, pipe encrustation and odour problems. A common way to remove iron is to aerate the water by cascading it into a tank and allowing the iron floc to settle.

Hardness

Domestic use - 200 mg/L:

Hardness is a measure of the amount of calcium and magnesium in the water. Hard waters can cause the build up of scale in hot water pipes and fittings. They also require more soap to obtain a lather. It can be reduced by softening the water.

pH

Domestic and stock use - 6.5 to 8.5:

This is a measure of the acidity or alkalinity. Values less than 6.5 indicate acidic water and can result in corrosion of pipes and fittings. When pH is more than 7.5 the water is alkaline and encrustation of pipes with calcium carbonate can occur. pH can be adjusted to a more desirable level by the addition of either an appropriate acid or alkali.

Chloride

Domestic use - 250 mg/L:

Above this limit taste may be unacceptable but it does not pose a health problem.

Irrigation use

For mangoes and grapes chloride should not exceed 250 and 175 mg/L respectively.

Sulphate

Domestic use - 250 mg/L:

Above this limits taste may be unacceptable but it does not pose a health problem. Purgative effects may occur if the concentration exceeds 500 mg/L.

Stock use - 1000 mg/L:

No adverse effects should be expected below 1000 mg/L. Between 1000 and 2000 mg/L sulphate can cause diarrhoea, particularly in young cattle. Concentration above 2000 mg/l can cause chronic or acute health problems.

Sodium

Domestic use - 180 mg/L:

Above this limit taste may be unacceptable but it does not pose a health problem. People with severe hypertension or heart disease should seek medical advice if sodium exceeds 20 mg/L in drinking water.

Irrigation use

For mangoes and grapes chloride should not exceed 230 and 115 mg/L respectively.

Calcium

Stock use - 700 mg/L:

Levels above 700 mg/L may cause phosphorus deficiency by interfering with phosphorus absorption in the gastrointestinal tract.

Magnesium

Stock use -

In high doses magnesium can cause scouring and diarrhoea in cattle. Levels up to 2000 mg/L have been observed to have no adverse effects. There is insufficient information available at present to set a guideline value.