To the south-west, the Basin overlies a shallow concealed bedrock ridge separating it from the Southern Ocean.

Fossil evidence indicates that the Murray Basin began to form some 65 million years ago, after Australia separated from Gondwanaland and began its slow migration northwards. Following its formation, rivers and lakes have deposited sediments in the Basin. In the south-west, the sea invaded on at least three separate occasions for a total duration of 30 million of the past 60 million years. The result is between 200 and 600 metres of Cainozoic sediments and sedimentary rocks (65 to 34 million years old) set in a Paleozoic terrain (over 250 million years old), the maximum thickness being in the central parts between Renmark and Wentworth. The way in which groundwater flows through the Murray Basin today is controlled by the structure of the sedimentary sequences deposited in the Basin as a result of slow tectonic subsidence and the rise and fall of sea levels during these earlier times. Climate change over the past 500,000 years has also been important.

The Murray Basin is bounded on all sides by rocks that allow very little of the water that enters it to leave, except by way of the surface stream system or by direct evapotranspiration to the atmosphere. Further, any salt transported by groundwater can only leave the Basin by spilling to the river or by being blown out by wind action. Thus the Murray Basin acts as a major salt trap and the Murray-Darling river system acts as Nature's drain.

Three main groupings of sediments, which are crucial to an understanding of the groundwater patterns, can be identified within the Murray Basin. Starting with the deepest layers, these are the Renmark Group, the Murray Group and the Pliocene Sands found near the surface.

The **Renmark Group** is an accumulation of riverine sand, silt, and clay deposited in a tropical environment 30 to 50 million years ago. These sediments are found at the base of almost the entire Murray Basin (Figure 4). They start at about 100 to 200 metres below the surface and are up to 400 metres thick in the central parts. The Renmark Group sediments form a major confined aquifer, with groundwater flow moving from recharge areas around the margins of the Murray Basin towards the central western region, where the sediments are at their thickest. The pressure regimes are such that groundwater in this area leaks upwards into the overlying Murray Group sediments. This upwards leakage is a direct result of the closed nature of the Basin; in effect, the water has nowhere else to go.

Figure 4: The extent of the Renmark Group aquifer in the Murray Basin. The arrows show the direction of groundwater flow in the aquifer. Source: Evans et al. 1990.

In general, the salinity of the groundwater in the Renmark Group aquifer increases proportionally as the water flows from the recharge areas, where it is fresh, to the areas of upward leakage, where the salinity levels are up to 50,000 EC, equivalent to the salinity of sea water. This increase reflects natural processes. In the thicker parts of the aquifer, there is a noticeable layering of salinity, with water at the top of the aquifer being more saline.

Figure 5: The extent of the Murray Group aquifer in the Murray Basin. The arrows show the direction of groundwater flow in the aquifer Source: Evans et al. 1990.

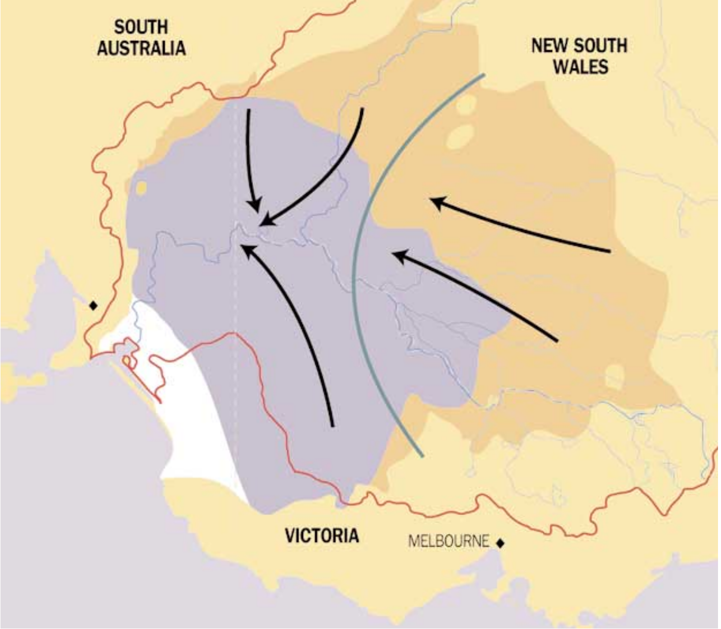


Figure 6: The Pliocene Sands aquifer, showing the extent of the Calivil Formation and the Loxton-Parilla Sands in the Murray Basin. The arrows show the direction of groundwater flow in the aquifer. The map also shows the approximate boundary between the Riverine Plain and the Mallee Region. Source: Evans et al. 1990.

The middle group of sediments is the **Murray Group**. They are found in the western parts of the Murray Basin, primarily underlying the Mallee regions of South Australia and western Victoria (Figure 5). They were deposited as the sea invaded the Basin between about 32 and 12 million years ago. The initial invasion, advancing some 400 kilometres into the basin and drowning the river and swamp systems that had formed the Renmark Group sediments, produced a thin layer of clay. As the sea established and sea levels rose, about 100 metres of shallow water limestone was deposited. To the east and north, these open water sediments become finer grained nearer to the shore and the lagoons associated with the ancient coastline. The deposition of these sediments ended with the retreat of the sea.

The Murray Group limestones form an important aquifer in the western parts of the Murray Basin. For most of the Group, groundwater flow is northerly to north-westerly from recharge areas in the southern Wimmera of Victoria towards the Murray River between Loxton and Morgan in South Australia. The aquifer also accepts upwards leakage from the underlying Renmark Group aquifer and discharges directly to the River Murray in its downstream area. In the recharge areas, groundwaters are suitable for domestic consumption and irrigation, but in the discharge areas close to the River Murray, salinity levels range up to 50,000 EC.

The third major group is the **Pliocene Sands Aquifer**, made up of sediments deposited between 2 to 6 million years ago and forming a layer of sands and gravels that cover almost all of the Murray Basin (Figure 6). It can be divided into two parts. In the western parts, the deposits are of marine origin, a further invasion of the sea leaving a thick layer of unconfined sands and silts known as the Loxton-Parilla Sands. Their groundwater salinity levels are high, ranging from 58,000 EC over most of the Victorian areas to 130,000 EC in western New South Wales and northern South Australia. Locally in salt lake environments, salinity concentrations can range up to 500,000 EC, some ten times the salinity of sea water. Again, such variations are the result of natural processes that have been occurring for many thousands of years. Recharge is from the downward leakage of rainfall over most of its area and lateral transmission from other aquifers. To the east and onshore, the rivers and streams that were flowing at that time deposited the highly porous and permeable coarser sands and gravels of the confined Calivil Formation. Recharge occurs where the Formation is exposed at the surface and by leakage from rivers. Groundwater flow is radially inwards towards the centre of the Basin from high recharge capacity areas associated with where the major river systems enter the Riverine Plain. The gravels of the Calivil Formation contain excellent quality water suitable for irrigation (salinity levels down to 200 EC). Salinity increases with distance from the recharge areas on the edge of the Murray Basin.

Following the deposition of the Pliocene Sands Aquifer, changes in prevailing climatic conditions gave rise to significant changes to the surface geology. In the central west of the Basin, the Aquifer is locally overlain by the thin layer of Blanchetown Clay, deposited in the large former Lake Bungunnia system. The Lake was maintained by a climate that was considerably wetter than that of the present day. The demise of the lake, however, around 500,000 years ago, heralded the onset of a drier climate, which alternated between arid and humid conditions. During the more arid and windy periods, the extensive Loxton Parilla Sands in the western parts of the Basin were reworked into the dunefields that make up the Mallee Region of today. To the east, the slow change in climate caused the coarser materials of the Calivil Formation to be overlain by finer grained sands, silts and clays of the Shepparton Formation that now underlies the extensive relatively flat land surface of the Riverine Plain. It is a locally important aquifer, with water of highly variable quality.

In addition to the geological divisions that have been outlined above, the Murray Basin can also be subdivided into the Riverine Plain to the east (underlain by the Shepparton and Calivil Formations and the Renmark Group) and the Mallee Region to the west (underlain by the Loxton-Parilla Sands). This division reflects both landforms and the surface geological features that have been inherited from previous geological times, in particular the two parts of the Pliocene Sands Aquifer.

At present, the Murray Basin contains about 4,600 million ML of water, two thirds of which is useful for

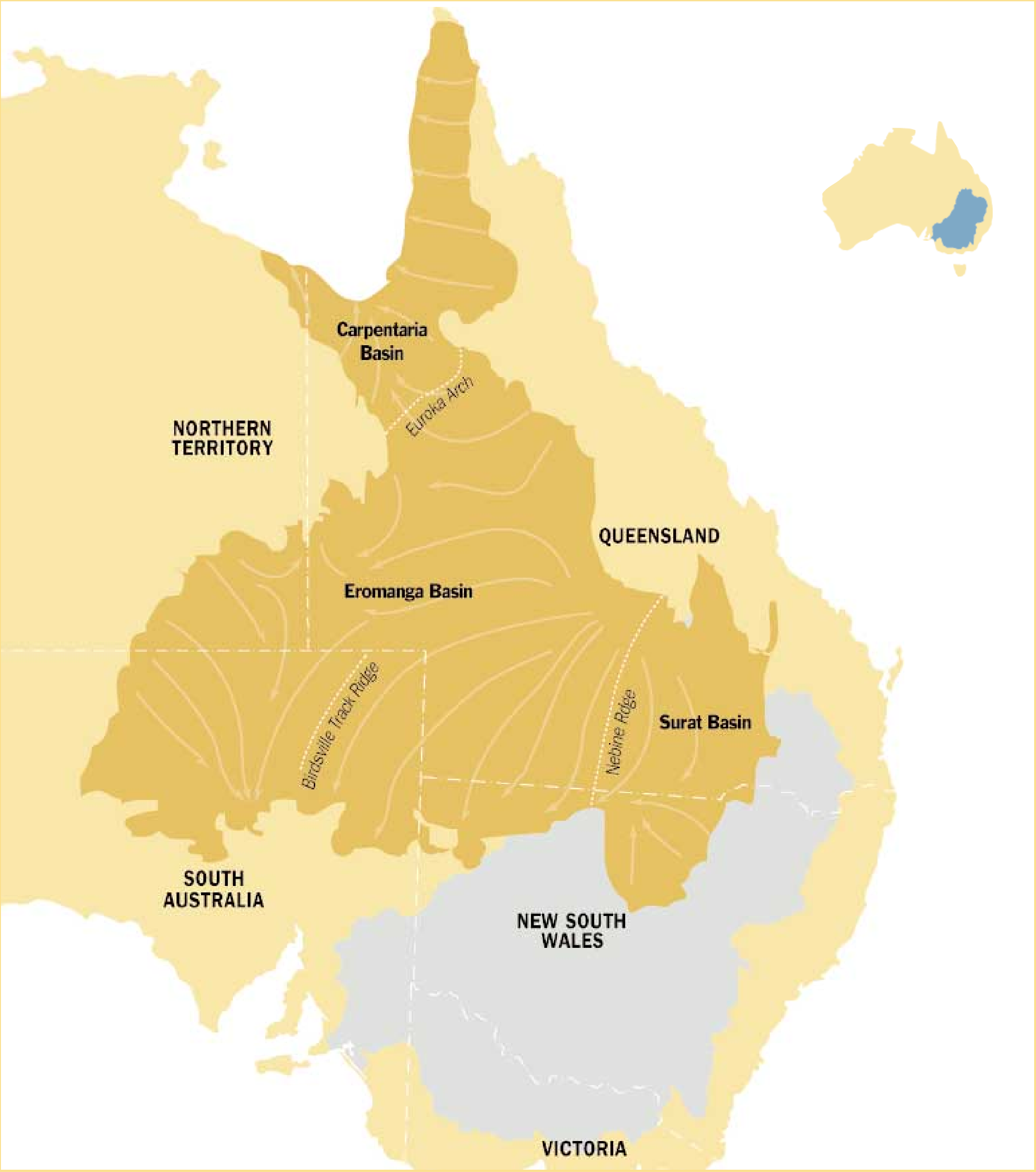


Figure 7: The Great Artesian Basin. The map shows the main directions of groundwater flow and the main structural divides within the Basin, namely the Euroka, Nebine and Birdsville Track Ridges. Source: Habermehl and Lau 1997.

humans. The ultimate source of the salt in the Basin appears to be from sea spray borne salt brought in with the prevailing winds from the Southern Ocean over the past 500,000 years. (The salts residing within the marine sediments of the Murray Basin have long been flushed to the sea, except those within the deeply buried fine grained clays and muds.) Current estimates suggest that the Basin contains about 1,000 million tonnes of salt, of which less than 0.04 per cent is transported out of the Basin annually by groundwater discharge into the River Murray. The salt dissolved in rainfall is continually replacing the salt lost through groundwater discharge.

ii. The Great Artesian Basin

The Great Artesian Basin (GAB) is one of the largest sedimentary basin aquifer systems in the world, with a total area of over 1.7 million square kilometres, about 22 per cent of Australia. It extends over large parts of

The Yass Valley to the north of Canberra in south-east New South Wales. Such small catchments in the fractured rocks country, where much of the vegetation has been cleared, are affected by dryland salinity and their groundwaters contribute to high salinity levels in their streams. Small catchments of this type occur along the slopes of central Victoria and along the western side of the Great Dividing Range in New South Wales.

Queensland and smaller parts of New South Wales, South Australia and the Northern Territory, including almost all of the Queensland portion of the Murray-Darling Basin and a large part of the plains country of northern New South Wales (Figure 2).

The GAB is a multi-layered confined aquifer system, much older than the Murray Basin (Figures 7 and 8). It consists mainly of two groups of sandstones alternating with siltstones and mudstones, and is up to 3,000 metres thick. The deeper 'J' (Jurassic) aquifer is separated from the 'K' (Cretaceous) aquifer by a thick layer of impermeable mudstone and siltstone. The GAB can be divided into three sub-basins, Carpentaria, Eromanga, and Surat. The divisions occur where bedrock underlying the sandstones forms dividing ridges, thus creating the smaller sub-basins. The Euroka Ridge forms the divide between the Carpentaria and Eromanga Basins and the Nebine Ridge divides the Eromanga Basin from the Surat Basin. The Birdsville Track Ridge, a structure in the eastern part of the Eromanga Basin and parallel with the Nebine Ridge, corresponds with the topographic divide that defines the north-west boundary of the MDB. Thus the Surat Basin and a small proportion of the Eromanga Basin underlie the MDB.

On the eastern margins of the GAB, the rocks representing the main aquifers outcrop along the western foothills of the Great Dividing Range and then dip westward under the land surface. Groundwater recharge occurs in these outcrop areas, as well as by way of downward leakage from the alluvial fan aquifers associated with the major rivers (see below). Within the GAB aquifers, groundwater flows at great depth, generally to the west, at a speed of between 1 and 5 metres a year. Most groundwater discharge occurs as springs along the western, south-western and northern margins of the GAB, as well as into the salt lakes in the northern parts of South Australia, predominantly outside the MDB. In effect, the water that enters the GAB from within the Murray-Darling Basin is lost to the MDB's system as it flows to discharge zones further west.

The Great Artesian Basin contains large quantities of groundwater, an estimated 8,700 million ML, with natural pressures from the deeper aquifers being above ground-surface in many places. Water quality is generally good, at 830 to 1,600 EC, but up to 16,500 EC in the upper Cretaceous aquifers (98 to 65 million years old). It is generally suitable for most uses except irrigation, as its high sodium content makes the water chemically incompatible with the soil. Water temperatures range from 40 to over 60°C, with bores in central Queensland exceeding 80°C.

iii. The shallow aquifers of the Darling River Basin

Covering over 650,000 square kilometres of the northern half of the Murray-Darling Basin and largely overlying the Great Artesian Basin is the Darling River Basin. Its extensive alluvial fans of Cainozoic age are associated with the larger rivers draining the Great Dividing Range the Macquarie, Gwydir, Namoi, Border, and Condamine (Figure 2). The fans are made up of sequences of coarse sediments up to 150 to 200 metres thick, especially in New South Wales. To the west and south-west, the sediments become more fine-grained, thinning out and eventually disappearing up against older rocks in the Bourke region. These complex alluvial fans and associated groundwater systems have a number of physical similarities to the Riverine Plain of the Murray Basin to the south. The Darling River Basin is effectively a closed groundwater system, with the aquifers draining internally and discharge by way of the land surface and surface rivers. The only outlet is a narrow infilled trench along the Darling River. The major difference with the Murray Basin is the fact that there is no basin structure to confine the aquifers as they move from the major recharge areas in the east out across the western plains.

The shallow alluvial fan aquifers of the Darling River Basin hold large quantities of groundwater. Recharge to these valley systems is generally by way of leakage from their associated rivers in the eastern parts of the Basin. Some groundwater finds its way into the underlying GAB sediments, whilst the water pressure within the deep GAB aquifers is such that they leak upwards into the shallower aquifers further to the west. Thus groundwater moves in both directions, up and down, depending on distance from the Great Dividing Range.

In the Darling River Basin, salinity increases in a generally westward direction, with the more westerly aquifers containing water too saline for most uses, up to 8,000 EC. As well, the ability of the aquifers to yield water progressively declines as the sediments become more finely grained with distance from the Great Dividing Range.

iv. Local fractured rock groundwater systems of the Great Dividing Range

Beyond the Murray Basin and the Great Artesian Basin, most of the remaining parts of the MDB, namely the Great Dividing Range, the Cobar Tableland, and the Mt Lofty Range and other uplands on the west and south-west margins of the Basin, are underlain by fractured rocks (Figure 2). These areas are characterised by large numbers of small, shallow unconfined groundwater systems, many only a few square kilometres in extent, in marked contrast to the extensive regional aquifers described thus far. The flow length of these aquifers is small, with recharge and discharge areas separated by only 1 to 20 kilometres.

Within the MDB, among the most important areas of fractured rocks are the northward-draining slopes of the Great Dividing Range in northern Victoria and westward-draining slopes and tablelands of New South Wales. These are some of the areas of higher rainfall within the MDB. The predominant rock type is older Paleozoic rocks (from 1 billion to 230 million years old) that have been folded and faulted to leave varying patterns of fractured material. Superimposed on this fracture distribution are the results of over 200 million years of weathering and erosion, especially on the lower slopes of the uplands. In places, extensive deep weathering profiles have left little of the original rock character, instead leaving behind varying thicknesses of clay material. These weathering products are an important component of the landscape, with their variable ability to act as aquifers and alter the patterns of water flow. This gives rise to a general two layer model of aquifer development in the lower parts of the landscape, with the upper layer, the soil aquifer, prone to drying out during periods of low recharge.

Groundwater flow patterns correlate closely with topography. In most places, the shape of the watertable closely resembles the shape of the land surface. This is more so in the hilly areas, becoming less important as relief flattens out. Recharge occurs over most parts of the landscape, but is highest in areas of skeletal soils and rock outcrop. Most groundwater discharge occurs within decades of recharge (a very short period in groundwater terms) and usually close to its recharge site.

Groundwater salinities vary considerably. The shallow soil aquifer is usually the most saline within a catchment, with the deeper groundwater being in places much fresher. In the fractured rock systems, higher salinities are found in the drier areas, such as in the western Victorian highlands around Bendigo, where the groundwater is up to 33,000 EC. Some catchments have been shown to contain between 500 and 1,000 tonnes of salt per hectare within these shallow weathered materials. Groundwater salinities in the temperate-humid central highlands of New South Wales are as low as 1,600 EC. In spite of the small size of most of these systems, they are the source of large quantities of the salt entering the streams of the Murray-Darling Basin and have a substantial negative impact on water quality all the way to the Murray Mouth.

The other fractured rock areas, in north-east New South Wales, south-east Queensland, the Cobar Tableland, and the western and south-western margins of the MDB, all contain small aquifers that provide water for domestic and stock use. However, these aquifers are of only local significance. They do not have a regional-scale role as described above for those in New South Wales and northern Victoria through their contributions to land and water salinisation.

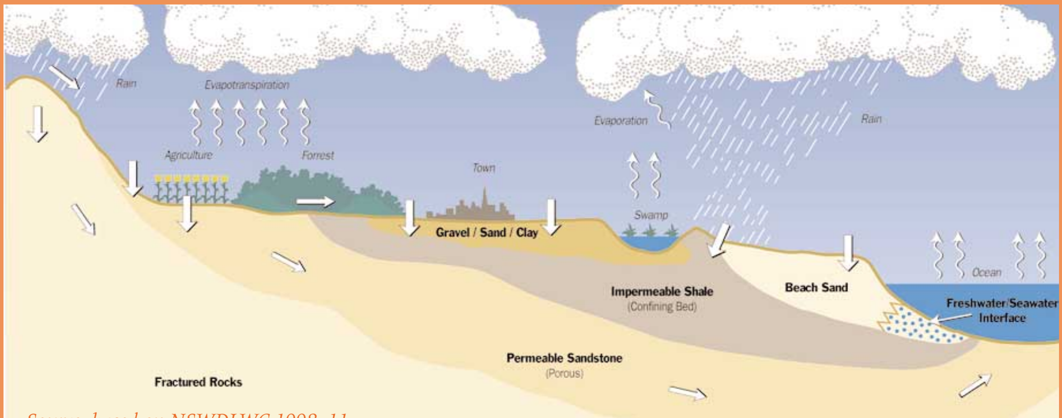
Groundwater

Groundwater is defined as all water that is found beneath the surface of the earth.

It is found in all types of rock and soil, but there are three main types of stores or aquifers that can be identified, namely sedimentary rocks, fractured rocks, and surficial deposits. Water enters aquifers in recharge areas, as a result of precipitation passing through the root zones of plants or from rivers and other surface water bodies. Recharge occurs mainly where the aquifers are exposed at the surface. Water leaves aquifers in discharge areas, normally in streams, lakes, swamps, springs and seepage areas.

The time taken for water to pass through an aquifer (from recharge to discharge) depends on the nature of the rocks and the size of the aquifer. The separation between the two locations can range from a few kilometres to thousands of kilometres. Also, the time involved can vary considerably. In the case of surficial aquifers, the same locations can be both recharge and discharge areas, depending on the seasonal conditions, such as floods and droughts. It is therefore imperative that groundwater issues be considered in terms of both the total surface and underground catchments.

It is important to see groundwater and surface water as part of the total hydrological system or cycle, which can be defined as the continuous interchange of water between land, sea and other water surfaces and the atmosphere. Thus, for example, water enters streams from surface run-off and some passes down to the groundwater; groundwater also comes to the surface by way of springs and seepage. A critically important aspect of the link between surface water and groundwater is that groundwater is the main source of water in streams during periods when they are not being fed by surface run-off. This is known as base flow and it keeps streams flowing during periods of dry weather. The more water that is stored in the aquifers, the more there is for discharge into streams, thus increasing the base flow.



Source: based on NSWDLWC 1998, 11.

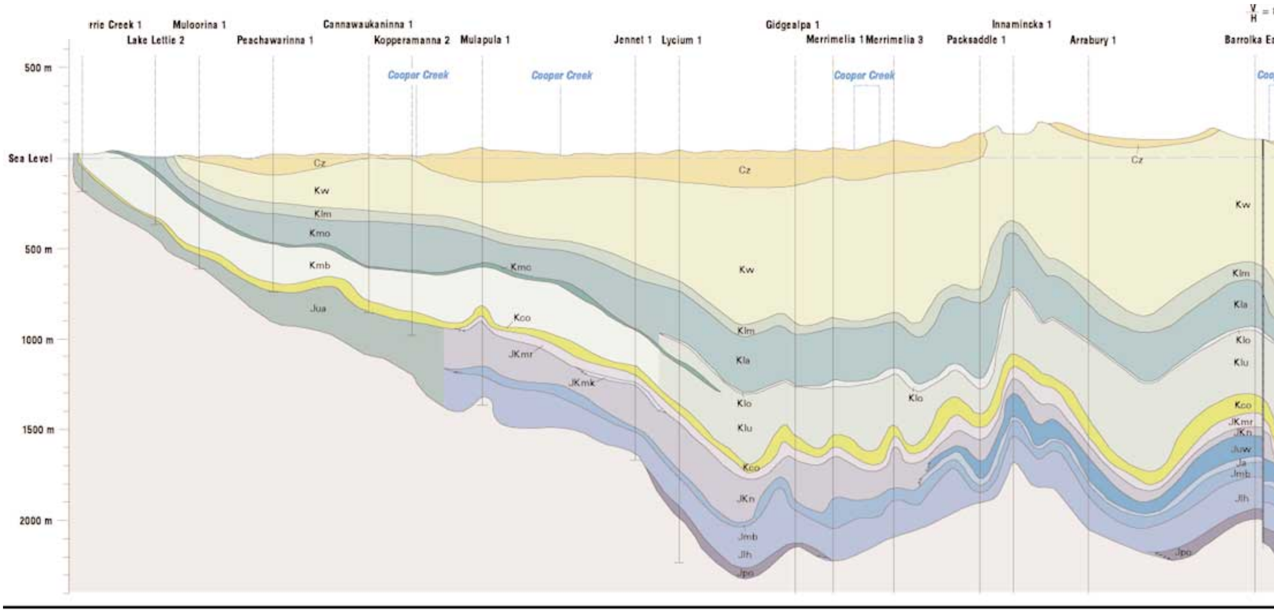


Figure 8: East-west cross section of the southern part of the Great Artesian Basin, within the northern Murray-Darling Basin. The named verticle lines represent bores drilled for water and petroleum. The various sedimentary layers are of Cainozoic (C), Cretaceous (K) and Jurassic (J) age (respectively up to 65 million years old, 65 to 141 million years, and 141 to 205 million years) and, in the eastern part, of Triassic (TR) age (205 to 250 million years). Source: Habermehl and Lau 1997.

Major groundwater issues in the MDB

The issues involving groundwater within the MDB are largely the result of European-style land uses and the ways in which the groundwater systems operate.

Four issues merit particular attention:

- land and water salinisation, particularly in the Murray Basin and the southern and eastern fractured rocks areas;
- overuse of groundwater, particularly in the Darling River Basin;
- groundwater wastage in the Great Artesian Basin; and
- the potential for much greater use of groundwater in many parts of the MDB.

Whilst in general terms, these issues are primarily associated with particular parts of the Basin, they are by no means confined to them. For example, salinisation is not confined to the Murray Basin and the fractured rocks areas, nor is the wastage of groundwater limited to the Great Artesian Basin.

i. Rising groundwater levels and land and water salinisation

The fundamental reason for the massive disruption of the region's groundwater systems has been the establishment of European-style land uses involving the replacement of the deep rooted native vegetation by shallow rooted crops and pastures. Water that would have been used by the native vegetation for transpiration now passes the reduced root zone and enters the watertable. The situation is further compounded by the distribution of rainfall compared to the growing seasons of introduced plants. The southern parts of the Murray-Darling Basin are characterised by winter dominant rainfall, becoming more uniform to summer dominant further northwards. As the introduced plants have little need for water in the dormant winter phase, maximum rainfall is available to be transmitted through to the watertable. In places, the increase in recharge has been 50 to 100 fold.

Underlying most of the southern part of the MDB is the Murray geological basin (Figure 2). Known as the Murray Basin, it has a limited storage capacity and the sediments are largely saturated. Its thin and flat nature means that it can fill quite rapidly, and there is evidence that it has been subject to high water levels six or seven times over the past 500,000 years. While previous fillings took 2,000 to 3,000 years, the current one is taking less than a hundred years, due to the land use changes in both dryland

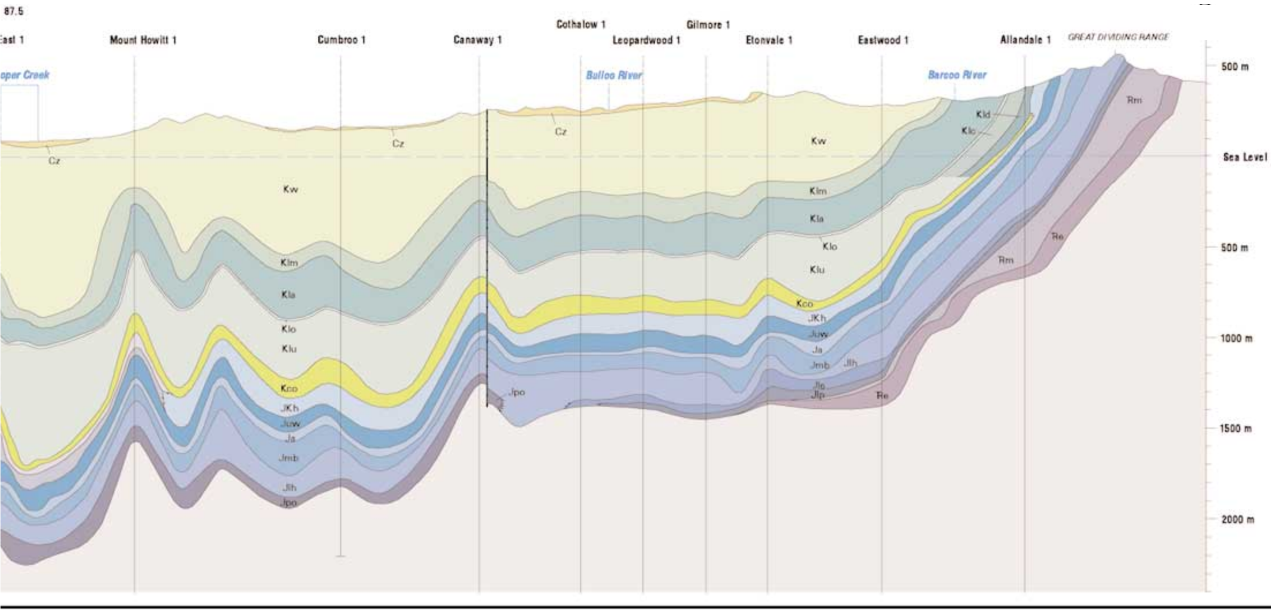
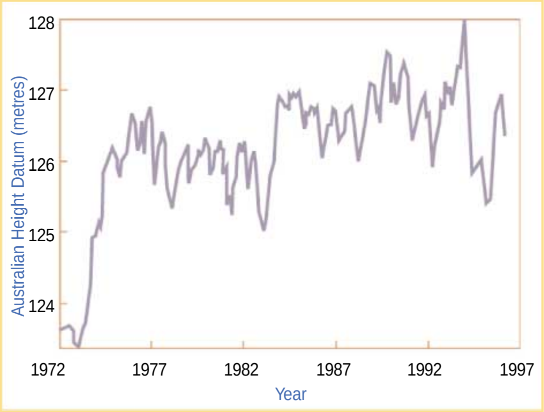


Figure 9(a): Rising groundwater levels in the Denimein-Berriquin Irrigation Districts in southern New South Wales. Source: Crabb 1997, 157.

Figure 9(b): Groundwater levels in the Calivil Formation measured in Bore No. 51640 at Bridgewater in the Loddon Valley, northern Victoria. The yearly rise and fall in groundwater level are due to recharge during the winter months and groundwater pumping in the summer. The very high rises occurred in very wet years, in 1973, 1983, and 1993. However, the water level did not return to the 1972 or 1982 levels even though there was mostly average annual rainfalls in the intervening years. Source: Victorian Groundwater Data Base, Department of Natural Resources and Environment, Melbourne.



and irrigated farming areas. Studies have indicated rises in groundwater levels of up to 30 metres since the 1880s in some locations, while over the past 25 to 30 years, there have been significant rises throughout the southern parts of the MDB, with only pauses during periods of drought (Figure 9). Similar observations can be made for the uplands fractured rocks aquifers adjoining the Murray Basin.

Of all the resource degradation problems associated with groundwater, none is more significant than land and water salinisation. The salinisation process is closely linked to the changes in groundwater levels and flows. As the groundwaters rise, the naturally-occurring salts (principally sodium chloride) are dissolved and brought towards the surface, where the salt is concentrated by evaporation.

Table 1: Area of land affected by dryland salinity in Australia

State	**Known area salt affected, in hectares, in 1996**	**At equilibrium***
Western Australia	1,804,000	6,109,000
South Australia	402,000	600,000
Victoria	120,000	1,200,000
New South Wales	120,000	7,500,000
Tasmania	20,000	Unknown
Queensland	10,000	74,000
Northern Territory	Minor	Unknown
Australia	**2,476,000**	**> 15,483,000**

*Source: PMSEIC 1999, 8. The potential area affected at equilibrium is the area prone to rising water tables and consequent salinisation if there is no further intervention.