The importance of fractured rock aquifers

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THE IMPORTANCE OF FRACTURED ROCK AQUIFERS

Contents

Andrew Love
Primary Industries and Resources South Australia, and Centre for Groundwater Studies
GPO Box 1671 ADELAIDE SA 5001

Peter Cook
CSIRO Land and Water, and Centre for Groundwater Studies
PMB No 2, GLEN OSMOND SA 5064

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INTRODUCTION

Groundwater supplies in fractured rock aquifers can be obtained from a number of vastly different geological settings, including indurated sediments, low to high-grade metamorphics, acidic and basic volcanics, and intrusive igneous rocks. This type of aquifer underlies approximately 40% of the Australian continent (Fig. 1). Fractured rock aquifers are becoming increasingly important as water supplies, as the better known sedimentary aquifers are almost fully utilised. Water supplies from this source are used for irrigation, livestock supplies, small town water supplies, mining and remote communities throughout Australia. Despite their obvious importance, very little is known about how water is stored and transported in fractured rock aquifers.

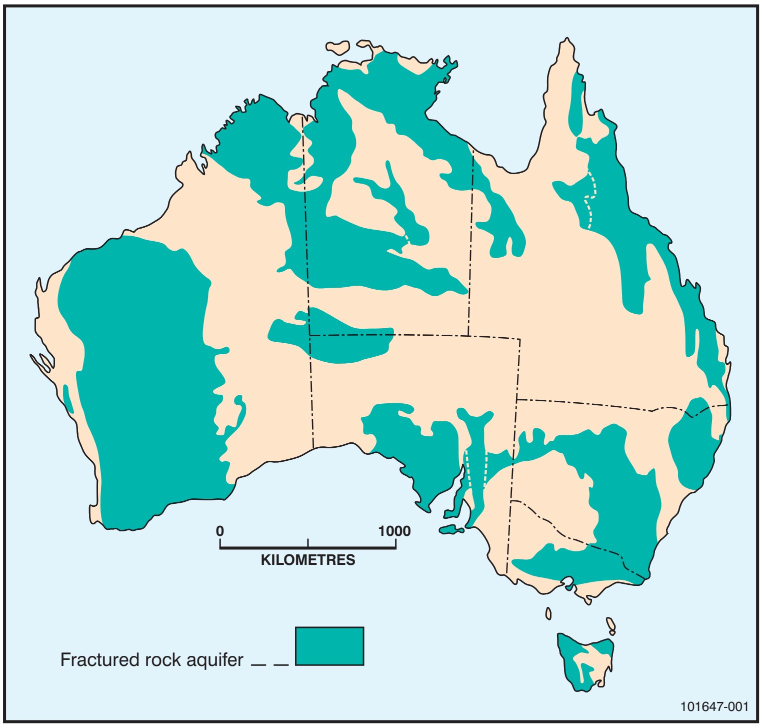


Fig. 1 Major fractured rock provinces in Australia (after Jacobsen and Lau, 1987).

CHARACTERISTICS OF FRACTURED ROCK AQUIFERS

There are two fundamentally different types of aquifers: porous media and fractured rock aquifers (Fig. 2). In a porous media aquifer, the underground water is stored in, and moves through, gaps between 'sand-sized' grains. Unconsolidated sand and gravel aquifers form the best examples of porous media aquifers. In contrast, fractured rock aquifers include basalt, granite, crystalline rocks, shale, slate, and some dolomites and limestones. Groundwater behaves very differently in fractured rock aquifers than porous media aquifers.

Fractured rock aquifers consist of two components: the fractures and the matrix blocks. Fractures include cracks, joints and faults, and can vary in length from centimetres to kilometres. Groundwater flow occurs only through the fractures whereas matrix blocks act as storage reservoirs. A simple classification is shown in Box 1.

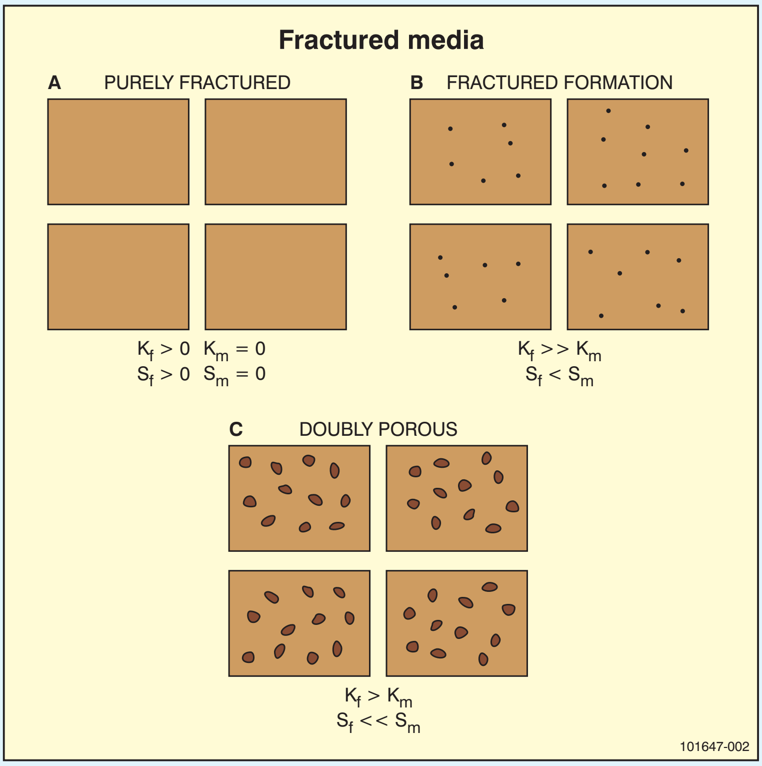
Obtaining reliable groundwater supplies in fractured rock aquifers is often complicated by irregular, and usually unpredictable, distributions of fractures, causing large spatial variations in bore yield. Experimental and theoretical studies have shown that the flow rate increases dramatically as the width (aperture) of the fracture increases. For example, if the size of the apertures is doubled, the flow rate increases by a factor of 8 (Snow, 1968). Maini and Hocking (1977) demonstrated that a system with horizontal fractures with apertures of 1 mm and spaced 1 m apart would have an equivalent hydraulic conductivity to that of a medium-grained sand.

Fracture apertures are highly variable and difficult to measure, but have been calculated indirectly by measurements of hydraulic conductivity from pumping tests. For example, McKay *et al.* (1993) calculated a range of apertures from 1 to 43 μm from a fractured clay. Apertures measured using an automotive feeler gauge and ruler ranged from 0.005 to 21 mm in outcrops of granite, metamorphic rocks and clay (Barton, 1996). In some studies, bore yield has been found to decrease with depth (Davis and Turk, 1964; Freeze and Cherry, 1979; Gale, 1982), presumably because of decreasing fracture apertures as a result of overburden pressure. However, this phenomenon does not occur throughout all fractured terrain, and highly productive fractures can sometimes be found at great depth.

In most cases, fractures have a preferred orientation, which may cause hydraulic conductivity to vary with direction. This can mean that the groundwater flow will often not be in the same direction as the hydraulic gradient (Schreiber *et al.*, 1999). In principle, the flow direction can differ from the direction of maximum hydraulic gradient by up to 90 degrees. Figure 3 illustrates a case where the hydraulic conductivity in the 'Y' direction is 12 times greater than that in the 'X' direction. This results in the direction of groundwater flow being deviated at an angle of 30 degrees relative to an isotropic porous media.

Groundwater flow rates in individual fractures can be extremely high, even where volume-averaged flow rates are low. Water velocities in excess of 40 m/day have been measured through fractures in a weathered shale (McKay *et al.*, 1995). Dissolved solutes and contaminants will move with the water through the fractures, but their transport velocity will be slowed by loss of solute from the fractures to the less mobile water stored in the matrix. The result is that different solutes may appear to move at different velocities (Grisak and Pickens, 1980; Grisak *et al.*, 1980). This may make prediction of contaminant transport rates difficult.

Box 1



Hydrogeological classification of fractured media (after Streltsova, 1976; Sharp, 1993). At one extreme, 'purely fractured' media are those where all of the water is stored in the fracture and none within the rock matrix; examples may include granite and other crystalline rocks. In 'fractured formation' systems, the matrix porosity is low, but storage in the matrix is still larger than the fractures. Rock types with these characteristics include slate and some basalts. 'Double porosity' systems have higher matrix porosity and may include claystone, siltstone and sandstone. In 'double porosity' systems, significant flow may also occur through the rock matrix. K_f is the hydraulic conductivity in the fracture, K_m is the hydraulic conductivity in the matrix, S_f is the storage in the fracture and S_m is the storage in the matrix.

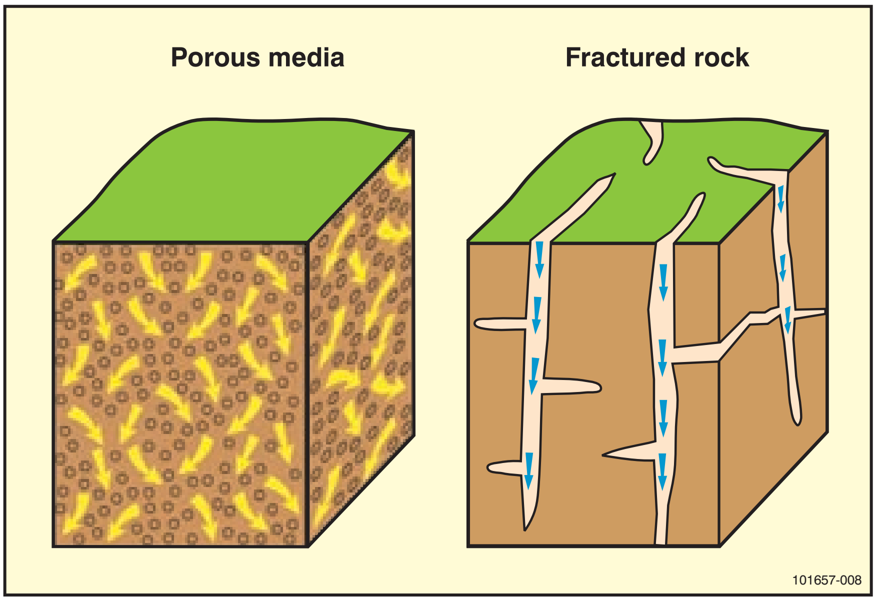


Fig. 2 The difference between a sand aquifer and a fractured rock aquifer is that, in the former, water moves between an interconnected network of gaps between the sand grains. In the latter, water must find its way through an array of irregularly spaced, and often unconnected, cracks in the rock.

fractured rock aquifers provide water to many people

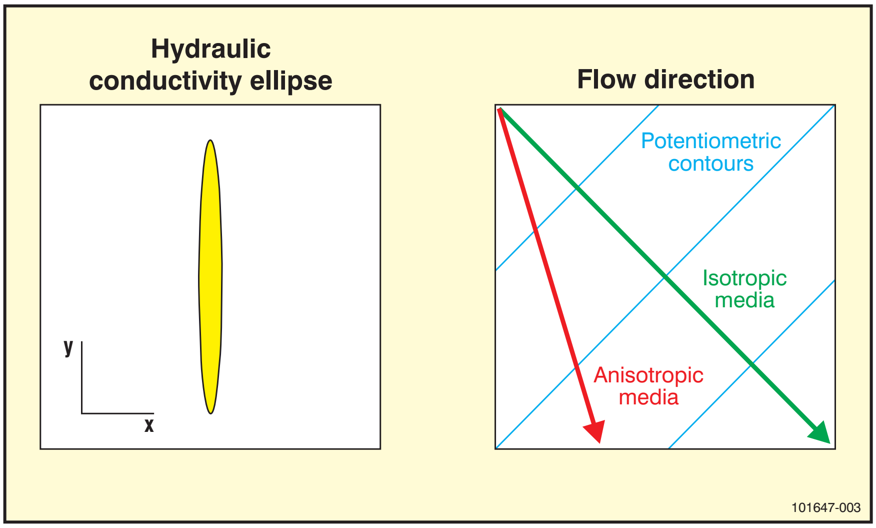


Fig. 3 Flow directions in isotropic and anisotropic (fractured) aquifers. In an isotropic (porous media) aquifer, the flow direction is perpendicular to the potentiometric contours. In a highly anisotropic media (K_Y/K_X = 12), the flow direction will deviate significantly from that in an isotropic porous media. Fracture orientation is parallel to the Y direction.

GROUNDWATER ISSUES

Quantity sustainability and recharge

Many of the traditional methods for estimating recharge in porous media aquifers cannot be directly transferred to fractured rock systems. Fractured rock aquifers are characterised by high spatial variability in hydraulic conductivity (Fig. 4), making traditional hydraulic methods for estimating groundwater flow difficult to apply. Specific yield may also be extremely variable and difficult to measure, making groundwater recharge estimation from bore hydrographs unreliable. Sufficiently accurate data on aquifer thickness or porosity is generally not available for reliable determination of aquifer storage.

In Australia, examples of areas where groundwater from fractured rocks forms an important water resource include:

- The Clare Valley, South Australia, where expansion of the viticultural industry is increasing demand at a rapid rate.
- The Atherton Tableland, northeastern Queensland, where groundwater from basalt aquifers is being extracted for irrigation of sugar cane. These same aquifers may be supplying baseflow to streams which drain World Heritage rainforest areas.
- The Howard River Basin, Northern Territory, where groundwater extraction for Darwin's water supply may be stressing phreatophytic vegetation in the area, including rainforests and tourist springs.
- In New South Wales, approximately 30 towns in the New England region and central and southern tablelands are dependent on water supplies from fractured rock aquifers.
- In arid areas of Central Australia, many remote communities depend on groundwater supplies in fractured rock aquifers.

Irrigation of sugar cane and horticultural crops in the Atherton Tablelands, northern Queensland, relies in part on water sourced from fractured basalts. (courtesy J. Bean). Photo 47051

Bore siting

The low yield of the rock matrix and unpredictable distribution of fractures can make siting of bores in fractured rock aquifers problematic. This will be most pronounced where fractures are widely spaced. In some cases, irregularities in drainage patterns as a result of faults, joints or geologically controlled structures have been targeted (Allen and Davidson, 1982). Geophysical methods such as resistivity soundings can sometimes locate large zones of discontinuity.

On a smaller scale, fracture patterns are less predictable. In the Clare Valley, groundwater availability appears to be controlled by closely spaced (<20 m), small aperture fractures which have no obvious surface expression. On a larger scale, it may be possible to improve the success rate of bores, but bore siting remains problematic in areas where there are no obvious geological structures. Records of unsuccessful bores are not readily available, making reliable statistics of success rates in different environments impossible to determine. However, in the Archaean Shield of Western Australia,

Vineyards in the Clare Valley, Barossa Valley highlands and Southern Vales areas of South Australia rely on groundwater from fractured rock aquifers for irrigation of vines. The photo shows grape vines in the Skillogalee Valley, southeast of Clare, where groundwater is extracted from a fractured dolomite. (courtesy SA Tourism Commission). Photo 43547

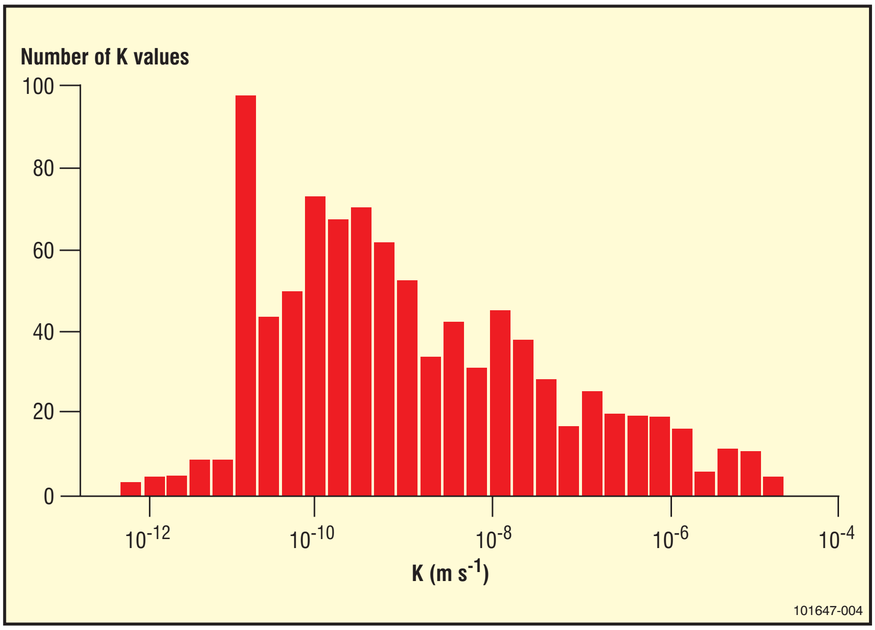


Fig. 4 Histogram showing the distribution of hydraulic conductivity in a granite aquifer in Aspo, Sweden (after Tsang *et al.*, 1996). Hydraulic conductivity varies by many orders of magnitude within a single geological unit.

approximately 2600 bores were drilled in 13 districts as part of a Government drought relief program during 1969–70. The percentage of successful bores (where yield was sufficiently high for the intended use) ranged from 23.5% in one district to 1% (AWRC, 1975). In the Clare Valley, drilling by PIRSA resulted in greater than 90% success rate, much higher than reported by local drillers (Morton *et al.*, 1998). One reason for the high success rate of the Government bores may be that they were drilled to greater depths, resulting in a higher probability of intersecting larger fractures.

In Western Australia, New South Wales and some parts of South Australia, explosives have been used in an attempt to increase supplies. Most of the evidence is anecdotal, and it appears at best to have had limited success (Allen and Davidson, 1982). Provided that fractures can be located accurately, hydraulic fracturing appears to be a promising technology. Hydraulic fracturing has had considerable success in the oil industry (Fig. 5) but has not been widely adopted in the water industry, presumably due to prohibitive costs.

Well interference, well field design and mine dewatering

Well interference is a commonly reported problem where there is a concentration of groundwater users within a small region. The low and variable porosity and hydraulic conductivity of fractured rocks means that drawdown can be very large, even for a low extraction rate. There are numerous reports of extraction from deep irrigation wells drying up shallower domestic supplies (e.g. Dandenong Ranges, Victoria; Clare Valley and Mount Lofty Ranges, South Australia). Because of the low porosity of many fractured rock aquifers, seasonal variations in the watertable level tend to be very large, even though recharge may be small. Long-term monitoring may be required to distinguish the effects of well interference from natural variations of the watertable.

Where there is a strong, preferred orientation of fractures, the drawdown cone can be highly anisotropic (Fig. 6). Well field design in fractured rock aquifers may need to consider fracture orientations. In particular, the efficiency of groundwater pumping schemes to ameliorate salinity problems may be improved by careful well location (Cook *et al.*, 1999). Dewatering of open pit and underground mines can also create difficulties in fractured geological systems. Major problems include the prediction of water levels and rates of inflow, and usually there is insufficient data for meaningful modelling. Mine dewatering is a particular concern in Western Australia, where there are approximately 150 wet mines and almost 60% of the State is underlain by fractured rocks. At the Burra copper mine in South Australia, inappropriate bore siting resulted in the major water-bearing fractures not being intersected, with consequent incomplete dewatering (Cobb *et al.*, 1982).

Salinity

Dryland salinity is one of Australia's largest environmental problems, and in many areas it is associated with fractured rock systems. In particular, large areas of salinisation occur on weathered crystalline rocks in Western Australia. Fractures can be important 'carriers', causing cross-catchment transfer and surface discharge. Other significant dryland salinity areas in fractured rock are parts of the central and southern tablelands and New England region of New South Wales. In central Victoria, underlying fractured rock aquifers exert upward pressure on shallower sedimentary systems and contribute to the salinity problem.

dryland salinity –
an environmental problem

Groundwater contamination

High water velocities through fractures mean that contaminants can potentially travel large distances very quickly. The direction of contaminant migration may be difficult to predict from hydraulic head data, particularly if there is a strong anisotropy in hydraulic conductivity. There is currently little published information on the movement of contaminants through fractured rocks in Australia, although it has been highlighted as a major concern in numerous overseas studies (e.g. Harrison *et al.*, 1992; Hardisty *et al.*, 1998). For example, landfills are often located on clay deposits, which can be prone to fracturing (Fig. 7). There are numerous industrial waste plumes in the basalt aquifers below Melbourne's western suburbs, moving towards streams and Port Phillip Bay (e.g. Finegan, 1994).

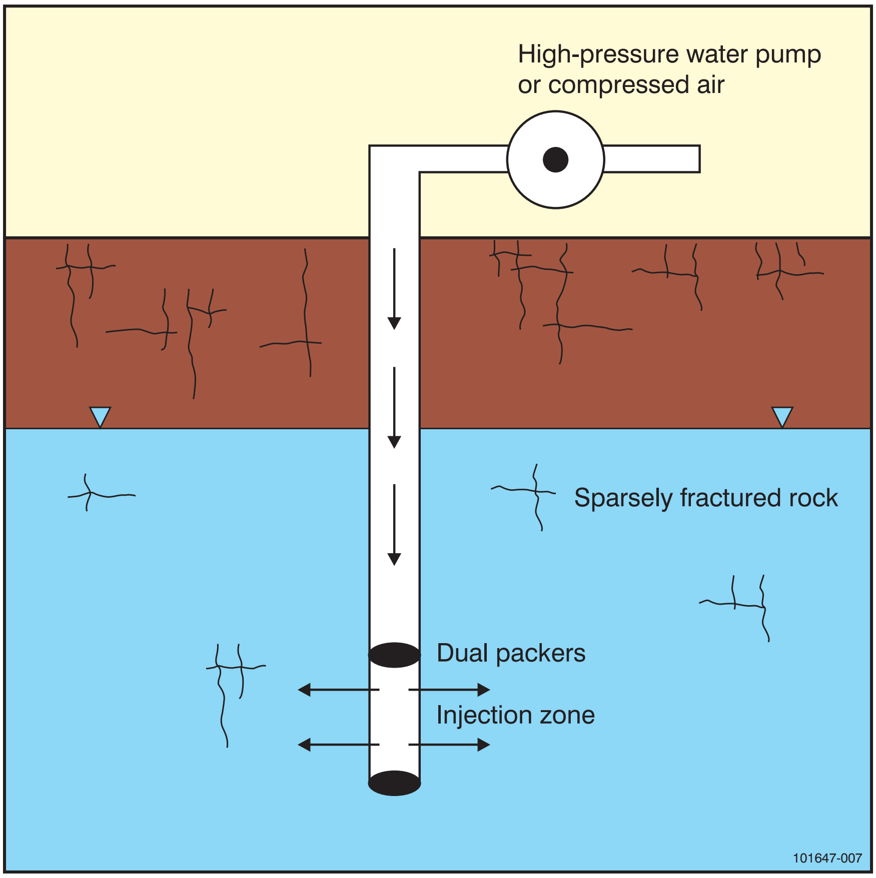


Fig. 5 Hydraulic fracturing plays an important role in improving well yield and enhancing petroleum reserves. It involves pumping fluid with a propping agent into the zone of interest at a high enough rate and pressure to wedge open and increase the size and length of a fracture. Approximately 40% of all petroleum wells are hydraulically fractured (Gidley *et al.*, 1989). As the well yield is directly related to fracture aperture, any increase in the size of the fracture will dramatically improve the yield.

Contamination from agricultural activities appears to have raised nitrate levels in fractured rocks in some areas of northwestern Tasmania, and the Lower South-East of South Australia; and occurrences are probably more widespread. Ivkovic *et al.* (1998) found nitrate, faecal indicator bacteria and pesticide contamination to 100 m depth in the Mount Lofty Ranges. The use of septic tanks in parts of all States has resulted in elevated nitrate levels in rural residential subdivisions not serviced by reticulated water supplies. Timescales of contamination of aquifers can be much more rapid in fractured rock systems than in sedimentary basins.

Contaminants may diffuse from fractures into immobile water in the rock matrix, making clean up difficult using pump and treat methods. In these systems, diffusion rates between the fractures and matrix will control the clean-up time-frames. If contamination has occurred over several decades, then it may take the same period of time or even longer to remove these contaminants from the system, irrespective of the pumping rate (Parker *et al.,* 1994; Wood, 1996).

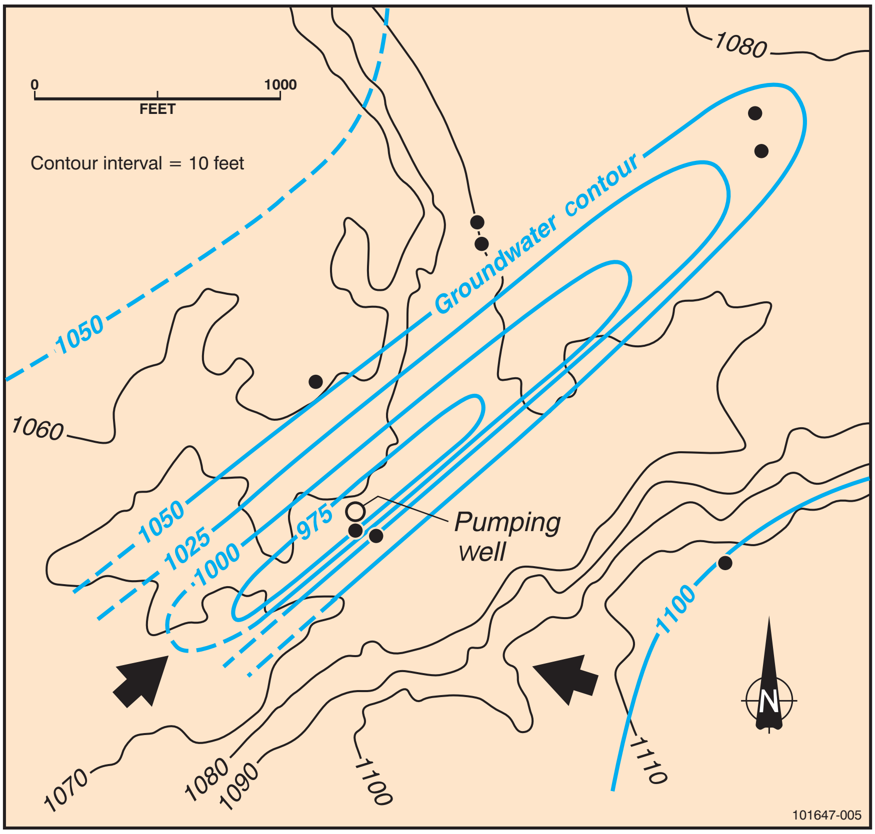


Fig. 6 Draw down cone after five days continual pumping in a crystalline bedrock aquifer. The cone is strongly anisotropic in the northeast–southwest direction of the major fractures (after Caswell, 1992).

In Western Australia, wet mines such as the Goldsworth Pit in Archaean iron formation pose a technical challenge for appropriate bore siting for mine dewatering. (courtesy P. Commander). Photo 47052

Alluvial silt and clay beneath Wagga Wagga are underlain by fractured shale and slate. High aquifer pressures in the shale and slate have caused watertables in the alluvium to rise, resulting in salinisation which has caused damage to roads, pipes, buildings and other infrastructure. A dewatering scheme has been implemented to reduce aquifer pressures beneath the worst affected areas. The shape of the cone of depression induced by the pumping may be related to the orientation of major fractures. (courtesy New South Wales Department of Land and Water Conservation). Photo 47053

Salinity in catchments of the central tablelands of New South Wales has been caused by clearing of native vegetation. Many of these catchments are underlain by granitic rocks. The photograph shows a large salt scald in a monzonite catchment near Goulburn. (courtesy P. Richardson). Photo 47054

CONCLUSIONS

A lack of understanding and predictive capability of groundwater movement in, and recharge to, fractured rock aquifers has resulted in groundwater management being largely problematical. The major problem is the inability to measure parameters that control the flow system (e.g. location and size of fractures). Management has often been reactionary, reliant on monitoring results from salinity and groundwater levels to assess the health of a fractured rock system. Because of low porosity, and large spatial and temporal variability of water levels and salinity, monitoring in fractured rock aquifers needs to occur over longer timescales than for sedimentary aquifers. By the time monitoring has detected changes in the hydraulic balance of a system, it may be politically difficult to reduce allocations to the required level. Prediction of contaminant migration is similarly difficult, but may be particularly important due to potential high transport velocities.

To date, traditional methods have not been highly successful in understanding the movement of water and solutes in fractured rock systems. The challenge for the future is to develop new techniques which will allow improvement in the technical understanding of these systems. An improved technical understanding will underpin successful management of these resources into the next century.

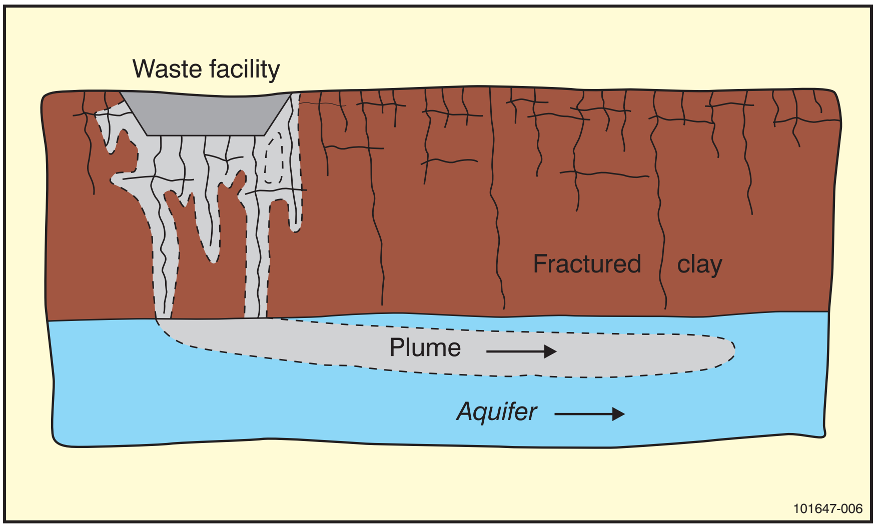


Fig. 7 Schematic illustration of contaminant migration through a fractured clayey aquitard, into an underlying sand aquifer (after Harrison *et al.*, 1992).

A large part of Melbourne is underlain by an aquifer developed within a highly fractured basalt. In many places, the fractures have allowed contamination of the groundwater by leakage from a range of industrial facilities. (Photographer© Rick Altman/Frontline) Photo 47055

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