Water Requirements in Deep Geothermal Systems

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The working fluid in a geothermal system is the medium through which heat is extracted from the sub-surface realm and brought to surface.

Access to a working fluid is one of four critical risk areas that need to be addressed when undertaking Geothermal Systems Assessments.

Surface water and groundwater are regarded as the most viable supplies of working fluid, although there is scope for the use of water co-generated from hydrocarbon operations. The use of CO2 as a working fluid has also been suggested, and research into this field continues.

Water is a valuable commodity, and it is essential that water access issues be addressed in the early stages of planning a geothermal project. Rainfall in Australia is unevenly distributed, both seasonally and geographically.

An outline of the full life cycle water requirements of a deep geothermal energy project is presented. Distinctions are made between Engineered Geothermal Systems and Hot Sedimentary Aquifers.

Keywords: Water, Working Fluid, Geothermal Systems Assessment, HSA, EGS, Reservoir, Canning Basin

Introduction

Access to a working fluid should be addressed during the initial exploration stage of a geothermal project rather than just being considered during the developmental and production phase. This is due to public concerns about water security, and also to water-use being subject to increasingly stringent regulatory frameworks.

Working fluid risk was identified by Cooper and Beardsmore (2008) as being one of four critical risk areas that need to be addressed when undertaking a Geothermal Systems Assessment of an area.

Cordon and Driscoll (2008) quantified the volumes, rates and quality of water required at successive stages of exploration, development and production of geothermal resources in a South Australian context, and these data are transferrable to geothermal projects elsewhere in Australia.

Exploration and development programs tend to follow similar paths, with each stage having its own water requirements. During the initial stages of a geothermal exploration program, it is usually necessary to drill a series of shallow heat flow holes to delineate the most prospective parts of an area. Once the company has achieved a level of confidence in defining their potential geothermal resource, deep geothermal resource drilling is planned and marks the beginning of the development stage as it is currently accepted that the first deep exploration well is converted into either an injection well or production well.

Climate

Australia's rainfall is highly variable, both seasonally and geographically, as demonstrated in data derived from the Bureau of Meteorology (Figures 1 and 2). Figure 1 details the 30 year average rainfall in Australia whilst Figure 2 shows the variability of rainfall in Australia over the previous 36 months.

Consequently, surface water volumes and groundwater recharge is extremely variable on a year-by-year basis. The Federal Government completed an assessment of Australia's water resources, including water availability, allocation and use, management and development, and water quality. These data were published in 2000 as part of the *Australian Natural Resources Atlas* (www.anra.gov.au/water).

Surface Water

The Australian Natural Resources Atlas (2000) divided surface water resources into 12 drainage divisions, 246 river basins and 325 surface water management areas.

It can be seen from Figure 1 that much of Australia is classed as arid (annual rainfall <250 mm) or semi-arid (annual rainfall 250-500 mm). In such areas, rainfall occurs sporadically and is often concentrated and intense—causing both local and widespread flooding. Evaporation rates tend to be high to extreme, leading to surface water drying out very quickly.

Even in areas where there is greater annual rainfall, evaporation rates can be extreme during the summer months when surface water often dries up entirely. The importance of groundwater as a constant source of water is therefore apparent.

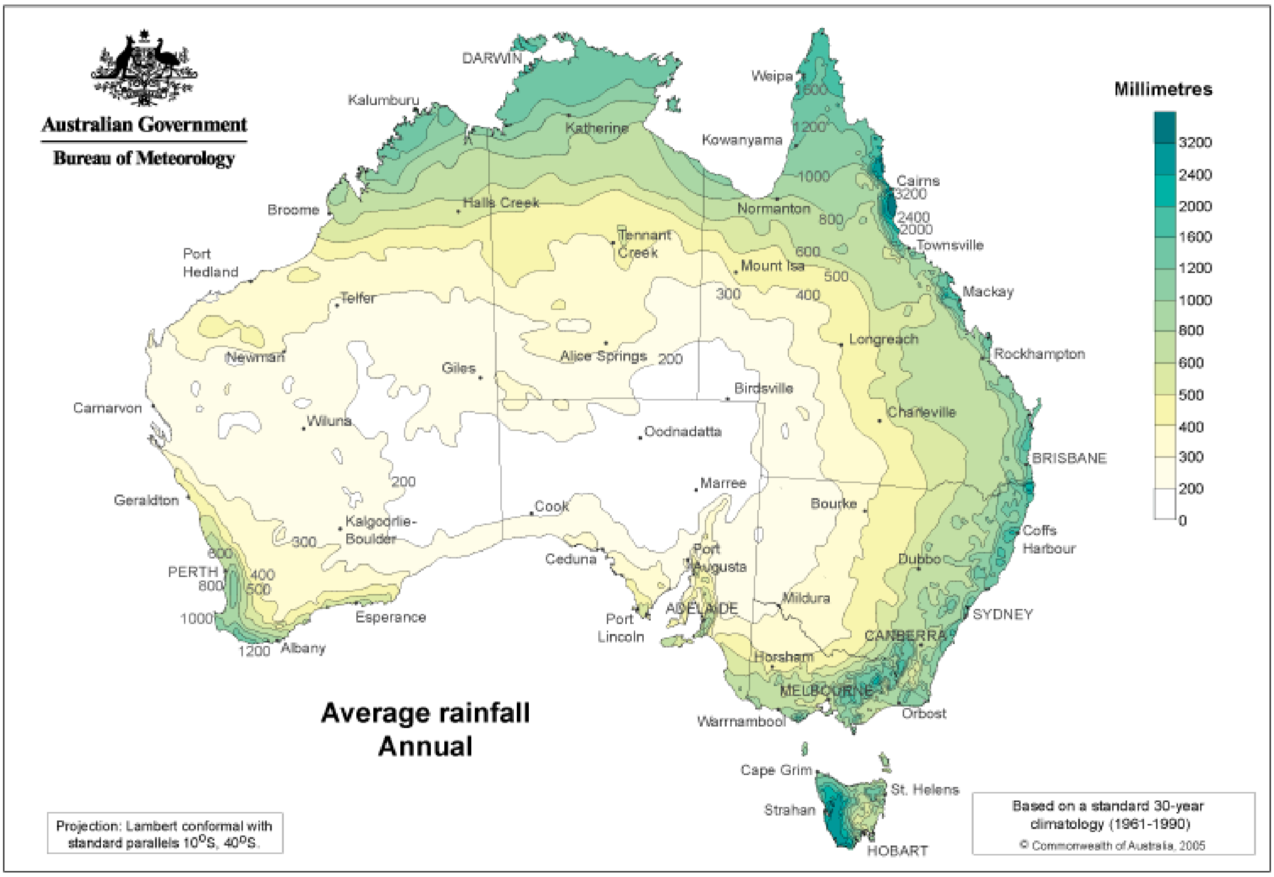

Figure 1. Average annual rainfall in Australia based on 30-year average 1960-1990 (sourced from www.bom.gov.au).

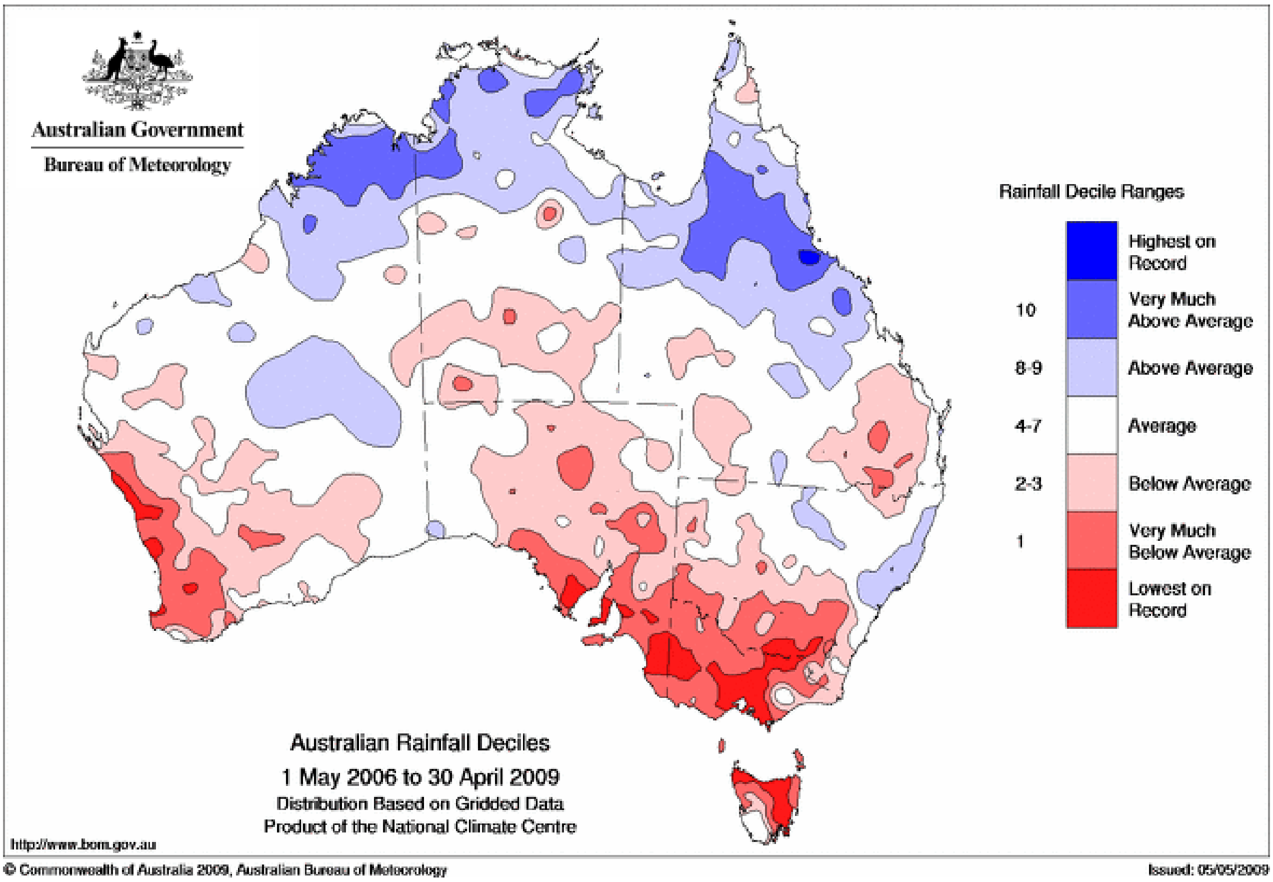

Figure 2 Rainfall deciles for 36 month period 1st May 2006 to 30th April 2009 (sourced from www.bom.gov.au).

The Australian Natural Resources Atlas (2000) concluded that 26% of Australia's surface water management areas (SWMAs) were at a high level of development and approaching or beyond sustainable extraction limits (Table 1).

Development status	Number (%) of SWMAs
Low development (<30% of nominated sustainable flow regime)	195 (60%)
Moderate development (between 30% and 70% of nominated sustainable flow regime)	46 (14%)
High development (between 70% and 100% of nominated sustainable flow regime)	50 (15%)
Overdeveloped (>100% of nominated sustainable flow regime)	34 (11%)

Table 1. The level of development of Australia's 325 SWMAs. The surface water sustainable flow regime is defined as the volume and pattern of water diversions from a river that includes social, economic and environmental needs. Sourced from the Australian Natural Resources Atlas, 2000.

It is also worthy to note that 55% of Australia's water is supplied by SWMAs that are considered overdeveloped.

Groundwater

The availability of groundwater is generally controlled by two important parameters: the type of strata that hosts the aquifer (i.e. whether it is a sedimentary or fractured rock aquifer system) and the degree of connectivity of the voids (whether they be fractures within the rock, or pore throats in sedimentary grains). Sedimentary aquifers typically yield at higher rates and store a greater volume of water compared to fractured rock aquifers.

A further controlling factor in groundwater availability is the rate of recharge to the aquifer system versus the rate of extraction. Regions of high rainfall typically have significant volumes of groundwater available in shallow aquifer systems (assuming an aquifer is present). In drier climatic regions, aquifers tend to be located at deeper levels below the Earth's surface, and are often associated with large volumes of water still resident from the geologic past. Present day replenishment rates in these arid to semi-arid areas are typically low.

The Australian Natural Resources Atlas (2000) divided groundwater resources into 69 groundwater provinces and 538 groundwater management units (GMUs).

Development status	Number (%) of GMUs
Low development (<30% of nominated sustainable yield)	274 (53%)
Moderate development (between 30% and 70% of nominated sustainable yield)	81 (16%)
High development (between 70% and 100% of nominated sustainable yield)	104 (20%)
Overdeveloped (>100% of nominated sustainable yield)	57 (11%)

Table 2. The level of development of Australia's 516 GMUs (note: 22 GMUs were not assessed). The groundwater sustainable yield is defined as the volume of water extracted over a specific timeframe that should not be exceeded to protect the higher social, environmental and economic uses associated with the aquifer. Sourced from the Australian Natural Resources Atlas, 2000.

Great Artesian Basin (GAB)

The Great Artesian Basin (GAB) covers an area of over 1,711,000 km2 (Figure 3), and has estimated water storage of 8.7 million GL, although only a very small proportion of this water is recoverable from bores.

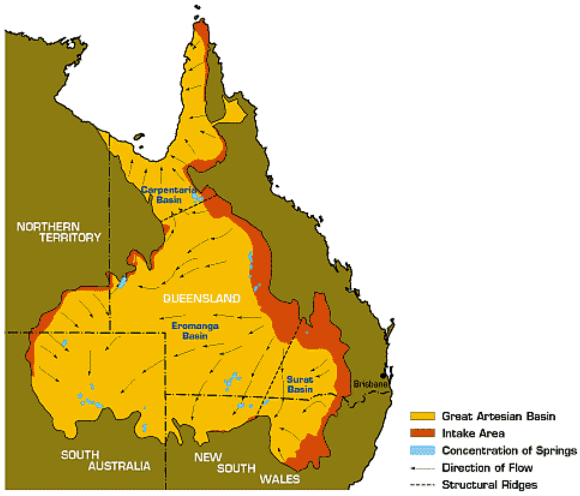

Figure 3. Map of the GAB highlighting intake areas, direction of flow and concentration of springs (source http://www.nrw.qld.gov.au).

The GAB consists of alternating layers of water bearing (permeable) sandstone aquifers and non-water bearing (impermeable) siltstones and mudstones. This sequence varies from less than 100 m thick on the outer extremities of the GAB to over 3,000 m in the deeper parts. Water temperatures vary from 30°C in the shallower areas to over 100°C in the deeper areas, controlled primarily by depth of burial.

Throughout most of the GAB, groundwater generally flows to the south-west, although more to the north-west and north in the northern section. The rate at which it flows through the sandstones varies between 1—5 m/yr. Recharge by infiltration of rainfall into outcropping sandstone aquifers occurs mainly along the eastern margins of the GAB, and specifically along the western slopes of the Great Dividing Range. Natural discharge occurs mainly from mound springs in the south-western area. These springs are natural outlets through which the groundwater flows to the surface.

Some of the oldest waters are found in the south-western area of the GAB. These have inferred ages of up to 2 million years (dating back to the base of the Pleistocene). The sedimentary rocks that make up the GAB were deposited during the Jurassic and Cretaceous Periods (195–65 million years ago).

Coproduced Fluids

In some areas of oil and gas development, high temperatures are coupled with high volumes of water produced as a by-product of hydrocarbon production. This is of particular significance to the Cooper Basin where geothermal licences for a number of companies overlap with existing hydrocarbon operations. Each oil and gas field has a large evaporation pond to house water co-produced from the extraction of hydrocarbons, so water sources are spread throughout the basin area. The size of the ponds varies depending on fluid rates to surface. Further assessment of water sources co-produced by hydrocarbon operations could prove beneficial to geothermal energy projects in these areas.

In the United States, water is produced from massive water-flood recovery fields and from most mature hydrocarbon areas; the disposal of this co produced water is an expensive problem (Tester *et al*., 2006). Curtice and Dalrymple (2004) estimated that co-produced water in the United States amounts to at least 40 billion barrels per year, primarily concentrated in California and states bordering the Gulf of Mexico.

The key factors required for successful geothermal electrical power generation include sufficiently high fluid rates from a well or group of wells in relatively close proximity to each other, at temperatures in excess of 100°C.

Carbon Dioxide as a Working Fluid

Whilst most geothermal operators consider water to be the optimal working fluid, there is ongoing research into other fluids such as super-critical CO2 (Brown, 2000; Pruess, 2006). Whilst CO2 has many benefits including being a non-polar fluid, low viscosity at temperatures and pressures within the reservoir, and a large buoyancy effect; there are several drawbacks such as a lower heat capacity and large frictional losses (due to gas-phase flows in the production well-bore) which leads to lower thermodynamic performance within the system (Atrens *et al*., 2009).

Working Fluid Risk

Regulatory processes will always be an inherent risk in the Australian context given the increasing value being applied to water resources. However, the main technical risks are the volumes of water required to initially charge an Engineered Geothermal System (EGS), and the quantities of water needed to sustain any ongoing circulation losses during development and production.

Until recently, it was thought water chemistry issues would not adversely impact geothermal projects in Australia so long as operators controlled the quality of water introduced to the system. However—as the April 2009 incident at Geodynamics' Habanero Project demonstrated—corrosion may be an issue where natural fluids are produced. Whilst unfortunate, the identification of this risk does allow for companies to incorporate mitigating strategies in designing their wells and associated infrastructure.

Water Requirements

Engineered Geothermal Systems (EGS)

The water requirements for EGS projects are determined by the volume required to initially charge the system, and volumes required to sustain the system once water losses are accounted for.

Cordon and Driscoll (2008) surmised that the development stage would require 280,000 m3 of water based on the assumption that an EGS module consists of one injector (1st well) and two producers (2nd and 3rd well) of 8.5" open-hole diameter. Wells are typically drilled to a depth of 3,000–5,000 m and modelling studies suggest a separation between wells of 600 m would be optimal to create sufficient volume heat exchangers that operate for a period of approximately 20 years.

Thirty one separate stages were identified by Cordon and Driscoll (2008) in the development phase of the project, each with varying water requirements.

Once the exploration well has been drilled, a series of small-scale injection tests are used to assess the undisturbed hydraulic properties in the open section of the well. These tests may include slug tests (to study the response of the well-aquifer system to an impulse in flow), production tests (which yield information on the pressure and temperature conditions deep in the well where a future heat exchanger is planned) and low-rate injection tests (determine the hydraulic properties of the un-stimulated open-hole section of the well).

The next phase of development is to stimulate or create a reservoir in the well via initiation of shearing within joints at a predetermined depth. The stimulation involves injecting water in steps with increasing flow rates; and a post-stimulation test is undertaken to evaluate the enhancement of permeability in the reservoir

Once the stimulation and the post-stimulation test of the well is completed, an assessment is made to see if the extent and quality of the reservoir is suitable for progressing to the next stage, the targeting and design of a 2nd well to intersect the reservoir. During the drilling of the 2nd well, wellhead pressure on the 1st well is monitored for any pressure response from the drilling activities in the 2nd well. Once the 2nd well is completed, similar tests to that carried out in the 1st well are required to determine the extent of the hydraulic link between the wells.

A small-scale circulation test between the two wells using tracers is carried out to evaluate the reservoir properties. Should hydraulic data indicate impedance within the reservoir, then remedial treatments can be implemented to improve reservoir connectivity between the wells.

A decision to drill the third well is made once the stimulation and post-stimulation tests in the second well indicate the extent and quality of the reservoir. Again, a series of tests are conducted between all three wells to confirm that circulation is established and that reservoir characteristics are acceptable to the business plan.

Finally, circulation tests with increasing flow rates are undertaken to move the project from the development stage to the production stage.

As there are very few operational EGS's in the world, hydrothermal projects are generally used as analogies to provide an estimate of water usage for the production phase of geothermal energy projects. In a typical, successful hydrothermal reservoir, wells can produce 5 MW or more of net electric power through a combination of high temperatures and high flow. For instance, a well in a shallow hydrothermal reservoir producing water at 150°C needs to flow at about 125 kg/s (~125 l/s) to generate 4.7 MW (Tester *et al*., 2006) of net electric power to the grid.

Hot Sedimentary Aquifers (HSA)

HSA systems differ from EGS projects in that there are substantial volumes of water inherently within a naturally occurring reservoir. Primary porosity and permeability are seen to decrease with increasing depth due to the effects of compaction (Figure 4). There is thus a trade off between temperature and the flow rate potential of the reservoir at depth. In instances where the target isotherm lies at depths where compaction processes have destroyed a significant proportion of the primary porosity and permeability, hydraulic stimulation procedures, similar to those described in the previous section, would be engaged to enhance reservoir properties.

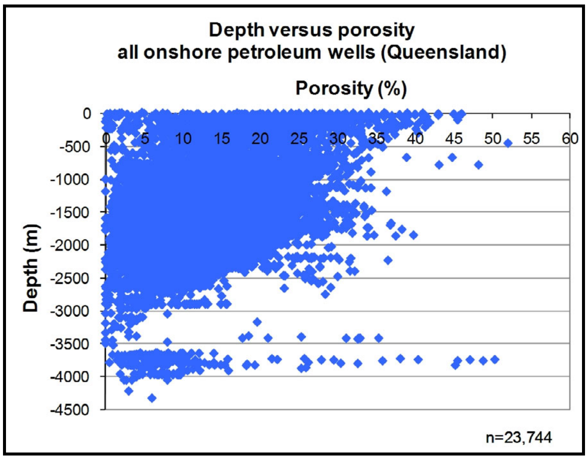

Figure 4. Depth versus porosity plot for all onshore petroleum wells in Queensland

In order to commercially exploit a HSA geothermal resource, detailed knowledge of the aquifer and water-flow characteristics needs to be ascertained. Flow characteristics are especially important in order to ensure reinjection does not cool the system and exhaust the resource too quickly. Two criteria need to be fulfilled: high yielding aquifers and hot water within the aquifer.

HSA systems utilise water at temperatures typically between 100°C and 150°C. Water at this temperature will not flash spontaneously into steam at sufficient pressures to turn electricity generator turbines; thus binary cycle electricity generation is utilised. The heat contained within the water is transferred to another medium with a lower boiling-point, termed the 'working' or 'binary' fluid. The high-pressure vapour of the binary fluid can then be used to turn a turbine.

Driscoll *et al*. (2009) noted in their Canning Basin geothermal assessment several high-yielding aquifers, most notably the Grant Group sandstones which extend throughout much of the basin and are several kilometres thick in places. Two GMUs, the Desert and the Wallal GMU, cover the vast majority of the Canning Basin, and both have very low to minor development of the Grant Aquifer with high sustainable yields (218 and 296 Gl/yr respectively). Assuming the geothermal system requires flow rates of 100 l/s, the water is reinjected back into the same aquifer, and there is 2% water loss, then water requirements would be ~64 Ml/yr for production. The Grant Aquifer can therefore be regarded as having excellent development potential.

Summary

Changes in rainfall distribution and intensity have been well documented in Australia. Geothermal operators will need to offer creative solutions to acquire and secure their water supplies over the lifetime of the project.

Access to groundwater is limited and regulated, so advanced planning is required by companies.

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