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20 Years of Exploitation of the Yarragadee Aquifer in the Perth Basin of Western Australia for Direct Use of Geothermal Heat

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ABSTRACT

Aquifers in the Perth Metropolitan region of Western Australia have been explored and exploited for water supply since the late nineteenth century. The availability of warm groundwater from the Yarragadee confined aquifer at relatively shallow depths was very popular with laundries, public baths and for industrial applications throughout the early twentieth century but it was not until 1997 that the first direct use geothermal project for bathing and swimming was implemented in Perth. By the end of 2015, a dozen of commercially successful geothermal schemes will use low enthalpy geothermal water supplies from the Yarragadee aquifer at depths ranging from 800 to 1,150 m for heating leisure centres, building air and outdoor pools in the Perth Metropolitan Region. With distributed heat estimated to more than 25 GWh (billion watt-hour) per year, Perth currently has the biggest concentration of operating geothermal direct use projects in Australia. The development of geothermal projects in Perth was made possible by early achievements pioneered by designers from the groundwater industry. This paper presents the hydrogeological setting of the Yarragadee aquifer which is the main geothermal resource in Perth, the design considerations, the economic and environmental considerations, and the best practices and circumstances that led to the 100% success rate of direct use geothermal projects in Perth.

1. INTRODUCTION

Geothermal energy has been used by humans for millennia and across most continents (Cataldi, 1999). Applications are commonly divided into two categories, electricity generation and direct use. Electric power production by binary plants using the Organic Rankine Cycle or the more-efficient Kalina Cycle requires fluid temperatures ranging from 85°C to 200°C while conventional power plants require temperatures of more than 200°C to be viable (Zarrouk and Moon, 2014). Direct use of geothermal energy on the other hand can be applied to a wide range of applications (Barbier, 2002) and is typically associated with lower-temperature geothermal resources (those with a temperature of less than 200°C), though some applications may require higher temperatures. The technology, reliability, economics and environmental benefits of direct use geothermal energy has been demonstrated in a wide range of settings throughout the world (Lund, 2005) although very few applications are reported in Australia.

Perth is the capital and largest city of the Australian state of Western Australia (WA) with an estimated population of 1.9 million people living in the Greater Perth. Aquifers in the central onshore Perth Basin near the city of Perth are one of the most important water resources for the Perth Metropolitan Area (PMA), groundwater providing 46% of the Water Corporation Integrated Water Supply Scheme (IWSS); about 30% of this is sourced from the confined Yarragadee aquifer which extends across most of the Perth Basin at depth of at least 500 m underneath Perth (Davidson and Yu, 2008). Geothermal direct use heating has developed in the Perth Basin since the mid 1990’s, coinciding with the exploitation of major aquifers. The development of successful geothermal projects was made possible by early achievements pioneered by designers from the groundwater industry, who successfully completed bores in the aquifer producing groundwater at a temperature of more than 40°C. One of such bores was used for reticulation and bathing at Perth Zoological Gardens as early as 1898. Most of the geothermal operations currently operating in Perth use the Yarragadee aquifer, at a depth between 750 and 1,150 m, and a temperature between 40 and 52°C (Olmeadow and Marinova, 2011; Pujol, 2011). Heat-depleted groundwater is injected back at a shallower depth within the aquifer so as to maintain a neutral water balance. To date, direct use geothermal projects in Perth have a 100 % success track record and exploit more than 2 GL (billion litres) of geothermally warmed groundwater each year (versus 50 GL for the Perth water supply).

Previous published studies, particularly since January 2008 with the release of the first geothermal acreage in the Perth Basin (Ghori, 2011), have helped to assess the geothermal potential in Perth, at the basin scale and to depths of up to 5,000 m. However, there hasn’t been a systematic description of the Yarragadee aquifer (the only hydrothermal or Hot Sedimentary Aquifer (HSA) resource currently utilised in Perth) published in the context of direct use geothermal applications and there is very little information available about the best practices and circumstances that have led to the 100% success rate of direct use geothermal projects in Perth.

This work aims to review and summarise existing knowledge as well as un-published results from commercial geothermal developments and water bore drilling targeting the Yarragadee aquifer for geothermal applications which were collated for the purpose of this paper.

2. BACKGROUND GEOLOGY AND HYDROGEOLOGY

2.1 Perth Basin Geology

The northerly trending Perth Basin has a broad half-graben structure and extends along the southernmost 700 km of the western coast of WA and contains a Silurian to Pleistocene succession which may exceed 15 km in thickness and overlies Precambrian basement (Playford et al., 1976; Cockbain, 1990; Crostella and Backhouse, 2000). The eastern boundary of the basin is formed by the north-trending Darling Fault which separates the basin from the Archean rocks of the Yilgarn Block. The western boundary is approximately 150 km offshore, where the sedimentary sequences thin towards oceanic crust in deep water.

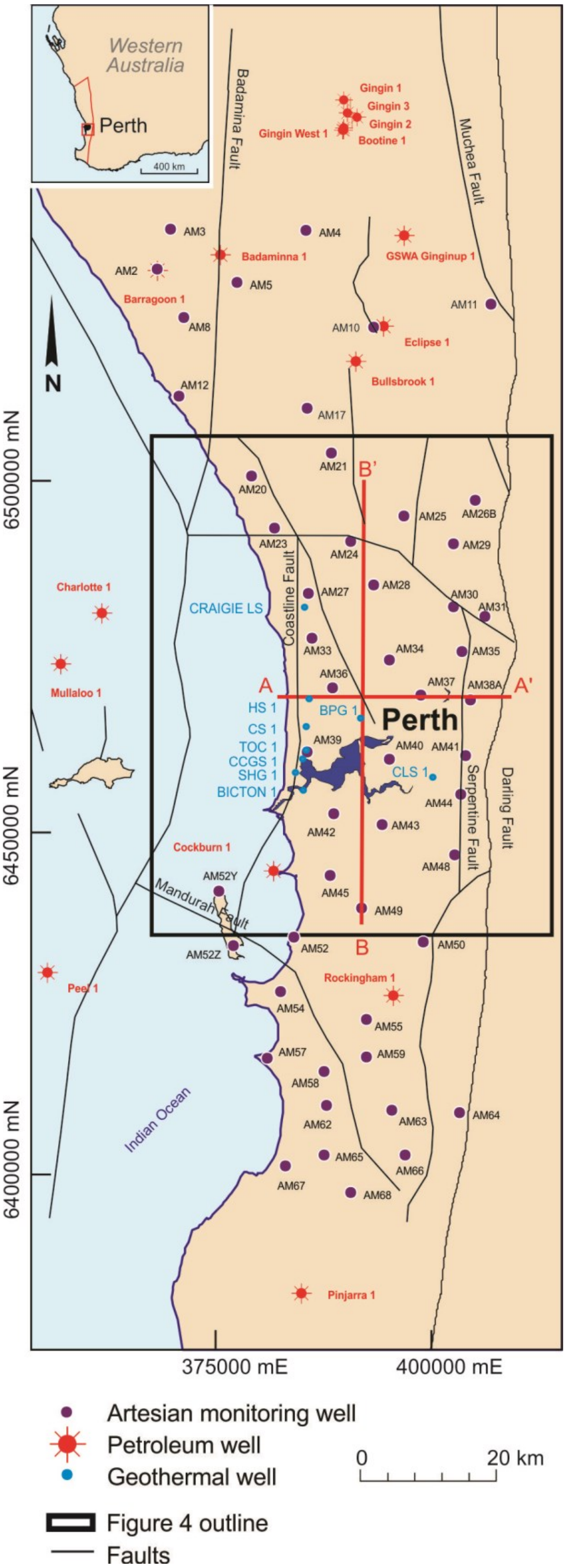

Figure 1: Perth Metropolitan Area Structural Map Showing Yarragadee Bores

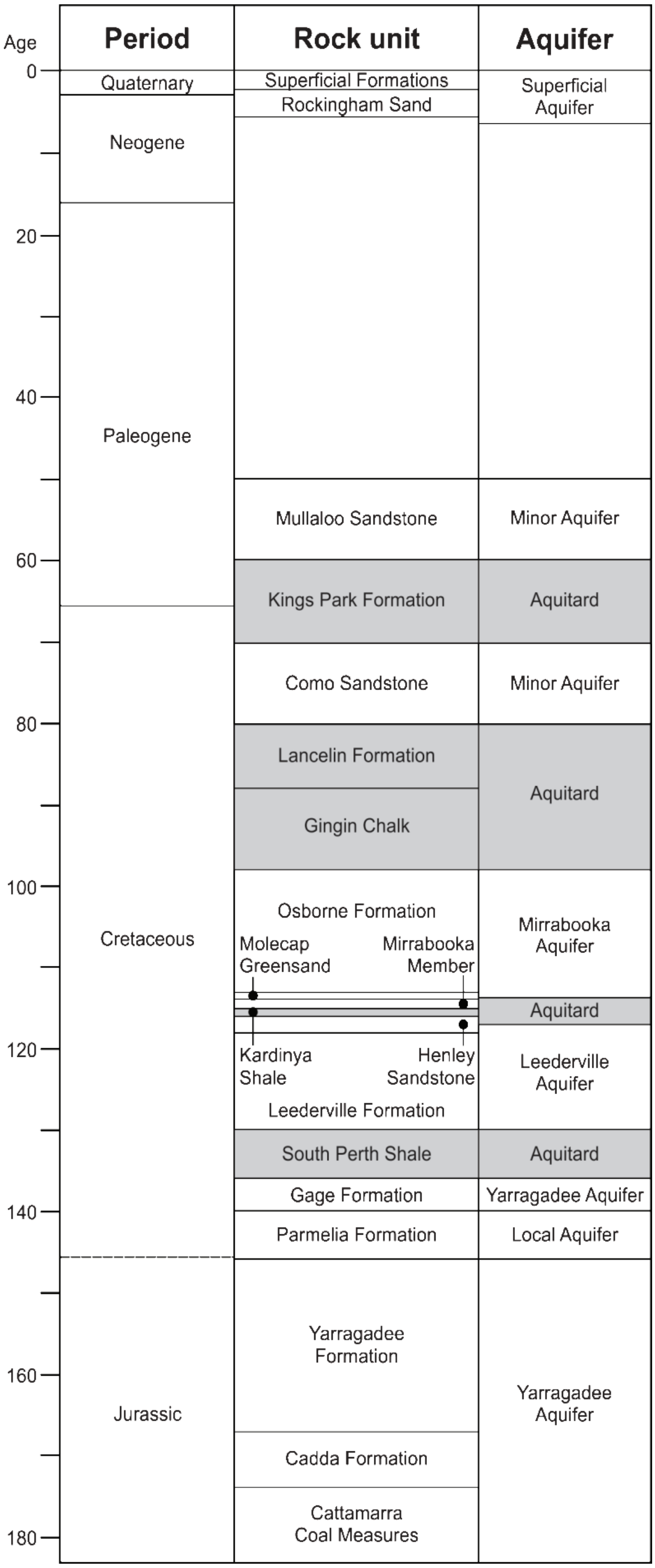

Figure 2: Generalised Stratigraphic Column for Sediments in the PMA

The area of the Perth Basin under review in this paper covers the central portion of the basin near the city of Perth and overlies the southern end of the Dandaragan Trough, which is a major structural subdivision within the basin (Davidson, 1995; Davidson and Yu, 2008; Timms et al., 2012) and focuses on the upper 3,000 m of sediments ranging from Quaternary to Jurassic age. The Trough is bounded by normal faults: the high angle Darling Fault to the east and the westerly dipping Badamina Fault, located offshore to the west. The Trough is bounded by normal faults: the high angle Darling Fault to the east and the westerly dipping Badamina Fault, located offshore to the west. A map of the Perth Metropolitan Region showing structural subdivisions within the central portion of the basin near Perth is shown in Figure 1. A generalised stratigraphic column for sediments ranging in age from Jurassic to Quaternary in the Perth Metropolitan Area is shown in Figure 2. Schematic geological cross sections for the study area are provided in Figure 3.

The area is compartmentalised to the north by the Gingin scarp and by the major Mandurah and Serpentine faults to the south. It is likely that similar smaller-scale normal faults, generally with west block down movement and strike northwest (Department of Water, 2011), occur throughout the Jurassic sediments in the Trough. Faults inferred from stratigraphic correlation and 2D seismic north of Perth (Leylands, 2011) and inferred from gravity data (Wilkes, 2011; Corbel, 2012) are shown in Figure 4. Displacements along the faults are unknown and further seismic and structural studies are required to confirm the presence of these faults. There is evidence that some minor movement of faults has continued into the early Cretaceous South Perth Shale and overlying Leederville Formation (Leylands, 2011).

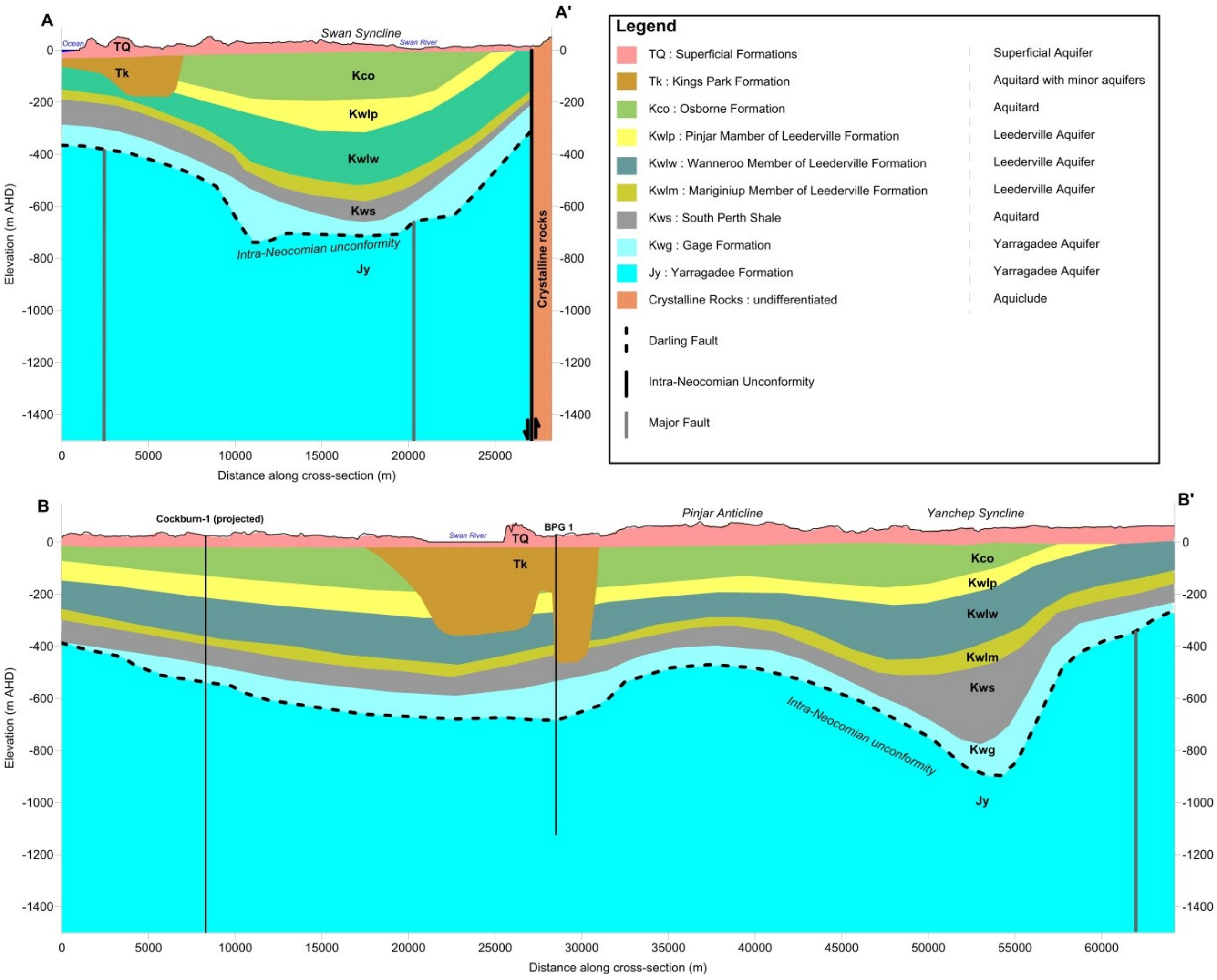

Figure 3: A-A' and B-B' Schematic Geological Cross Sections

2.2 Hydrogeological settings of the Yarragadee Aquifer

The study area has been described by Davidson (1995) and Davidson and Yu (2008), and more recently by Timms et al. (2012) and Delle Piane et al. (2014).

Among the three main stratigraphic units exhibiting aquifer properties (Figure 2) beneath the urbanised PMA, only the mid-Jurassic (Bathonian) clastic sedimentary rocks of the Yarragadee Formation contain sufficiently warm groundwater (ie at temperatures of 40°C or more) for geothermal direct use projects. In the Perth Region, the aquifer consists of the Gage Formation and Yarragadee Formation. A complete section of the Yarragadee aquifer was intercepted during the drilling of oil exploration well Cockburn-1 in 1967, about 15 km to the south-west of Perth (Figure 1). The base of the aquifer in Cockburn-1 was intercepted at about 1,725 m (Delle Piane at al., 2013), slightly shallower than the inferred depth to the base of the aquifer of 1,800 to 2,000 m near Perth (Davidson and Yu, 2008). Closer to Perth, the upper section of the aquifer has been intercepted down to 1,156 m during the drilling of geothermal production bore BPG-1 (Figure 1) in 2011 which is currently the deepest geothermal bore in Perth. A description of the Yarragadee aquifer is found in Davidson (1995) and Davidson and Yu (2008), and more recently in Timms et al. (2012) and

Delle Piane et al. (2014), and is completed herein with recent unpublished data derived from deep water supply and geothermal projects targeting the Upper Yarragadee aquifer and collated for the purpose of this paper.

Using sedimentary logging at approximately 1:1000 on the cores from Cockburn-1, Timms et al. (2012) found that the formation is dominated by coarse-grained sands (51%) with framework grains of quartz (≈80%) and feldspars (≈15%), while the remainder is composed of fine-grained sands and floodplain facies (23%) with less frequent quartz (50 to 60%) and carbonaceous swampy deposits (26%) with about 40% quartz. There is general aluminosilicate enrichment as the lithologies decrease in grain size, with swamp deposits dominated by kaolinite (≈55%). The aluminosilicate enrichment is accompanied by a decrease in total porosity from about 24% in coarse- and medium-grained sands to 7% in swamp deposits. The porosity shows a slight declining trend with depth ie ≈-1% every 100 m (Timms et al., 2012).

2.3.3 Hydraulic Properties

The hydraulic properties of the aquifer are discussed in Davidson and Yu (2008) and in the Perth Regional Aquifer Modelling System (PRAMS) version 3.2 (Cymod Systems Pty Ltd, 2009). In those studies, the units of permeability and transmissivity are often quoted as m/day or m^2/day which are dependent of fluid properties. In order to maintain independence of fluid properties, intrinsic permeability and transmissivity are used in this paper with units of Darcies (D) and Darcy-metre (Dm).

Over the last decade, many short duration bore pumping (injection) tests (up to 48 hours) have been undertaken on Yarragadee water supply bores and geothermal production (injection) bores in Perth to assess the bores productive (injective) capacity and near bore aquifer characteristics (intrinsic permeability and skin). Data provided by Rockwater Pty Ltd for 18 Yarragadee aquifer bores were reviewed as part of this study. The systematic review of these tests provides intrinsic permeability values for the local sandstone beds or lenses (ie within a radius of a couple kilometres near the pumped bores) that are affected by the cumulative and opposing effects of boundary conditions due to the shale beds and leaky confined conditions provided by the interbedded siltstones. Permeabilities derived from these tests range from 0.6 to 10.4 D showing significant variability (St.Dev. 2.4 D) because of the discontinuous and lensoidal nature of the aquifer. The average permeability (3.3 D) is high.

Unlike porosity, no clear variation trend with depth is apparent from the data available for the Upper Yarragadee aquifer and permeabilities appear to be primarily controlled by facies changes with depth (ie interbedded sandstones, siltstones and shales), the discontinuous nature of the intervals conducive to groundwater production and injection and possibly the fault block were the bores are located but more data is required to clearly establish the relationship between permeability and depth.

The average regional horizontal permeability of the upper-section of the aquifer was estimated to be about 0.55 D (0.7 m/day at 40°C) using flow-net analyses (Davidson, 1995) and was later revised to 0.40 to 1.60 D (0.5 to 2 m/day at 40°C) when calibrating the PRAMS regional model (Cymod Systems Pty Ltd, 2009). These values are slightly lower than those derived from pumping tests in bores, or measured on cores because: (i) they are representative of the entire thickness of the aquifer composed of approximately 50% sandstone 50% siltstones and shales. However, in completed bores, siltstone and shale are usually isolated resulting in comparatively higher permeabilities when tested and (ii) include the cumulative and opposing effects of boundary conditions due to the shale beds and leaky confined conditions provided by the interbedded siltstones which cannot be determined from diamond core permeability testing in laboratory.

Typically, 100 to 300 m of aquifer is screened in Yarragadee production bores. Since the proportion of medium- to coarse-grained sandstone is around 50% of the total aquifer thickness, the net pay or effective aquifer thickness range from 50 to 150 m in most cases. This results in transmissivity values generally exceeding 100 Dm and often in the order 300 Dm. This allows for low to very low energy requirements for pumping (injecting) the geothermally warmed groundwater with downhole electro-submersible pumps (ESP) and is a feature of the efficiency and viability of direct use geothermal systems in Perth.

2.3.4 Groundwater flow, Recharge and Discharge

Groundwater in the Yarragadee aquifer is recharged by downwards leakage from overlying shallower aquifers in those areas where the Cretaceous confining beds (South Perth Shale or Otorowiri Formation) are absent and there are downward hydraulic gradients. The main recharge areas are a 10km-wide 40km-long strip to the north of AM24 (Leylands, 2011) and possibly the area between the Serpentine and Darling faults south-east of Perth. In recent years, the Department of Water has been undertaking comprehensive drilling and geophysical assessments to better define the recharge window to the Yarragadee aquifer north of Perth (Department of Water, 2011). Over the Perth Metropolitan Area the Yarragadee aquifer is confined by low-permeability units of the South Perth Shale.

Prior to 1997, groundwater flowed in a southerly direction in the northern sector and westerly in the southern sector of the study area based on potentiometric surface maps in Davidson and Yu (2008) and eventually discharged offshore, possibly over saltwater wedges into the overlying strata. In more recent years, increased abstraction for the Perth water supply has created a significant area of reduced hydraulic pressure within the Yarragadee aquifer, centred at the coast, about 15 km of Perth and the potentiometric surface now slopes downwards to the north-west with steepening gradients, as illustrated in Figure 4. The current rate of decline of the potentiometric surface is approximately 0.5 m per year near Perth. This needs to be considered when determining the depth of the base of the pump chamber casing to accommodate the ESP in geothermal production bores.

2.3.5 Water quality

Groundwater in the Yarragadee aquifer tends to be much older than the groundwater in the overlying aquifers, and this is reflected in its chemical composition. It generally falls on a mixing line between a sodium chloride type and sodium-bicarbonate type groundwater where recharge to the aquifer occurs through the overlying calcareous units of the Leederville Formation and the South Perth Shale confining unit is absent (Davidson, 1995). Groundwater salinities in the Yarragadee aquifer range from fresh to brackish and generally increase with depth and distance from recharge zone north of Perth (Playford et al., 1976; Davidson 1995). Although the hydrochemistry of the aquifer is relatively benign, injection of heat-depleted groundwater back in the aquifer requires careful planning and design. The potential problems of injection are scaling, corrosion, fine particles, air entrainment, and bacterial growth, which, in severe cases can lead to an irremediable bore and formation damage if not considered in feasibility and design criteria. If these conditions are observed in an injection bore they should be thoroughly investigated and mitigated.

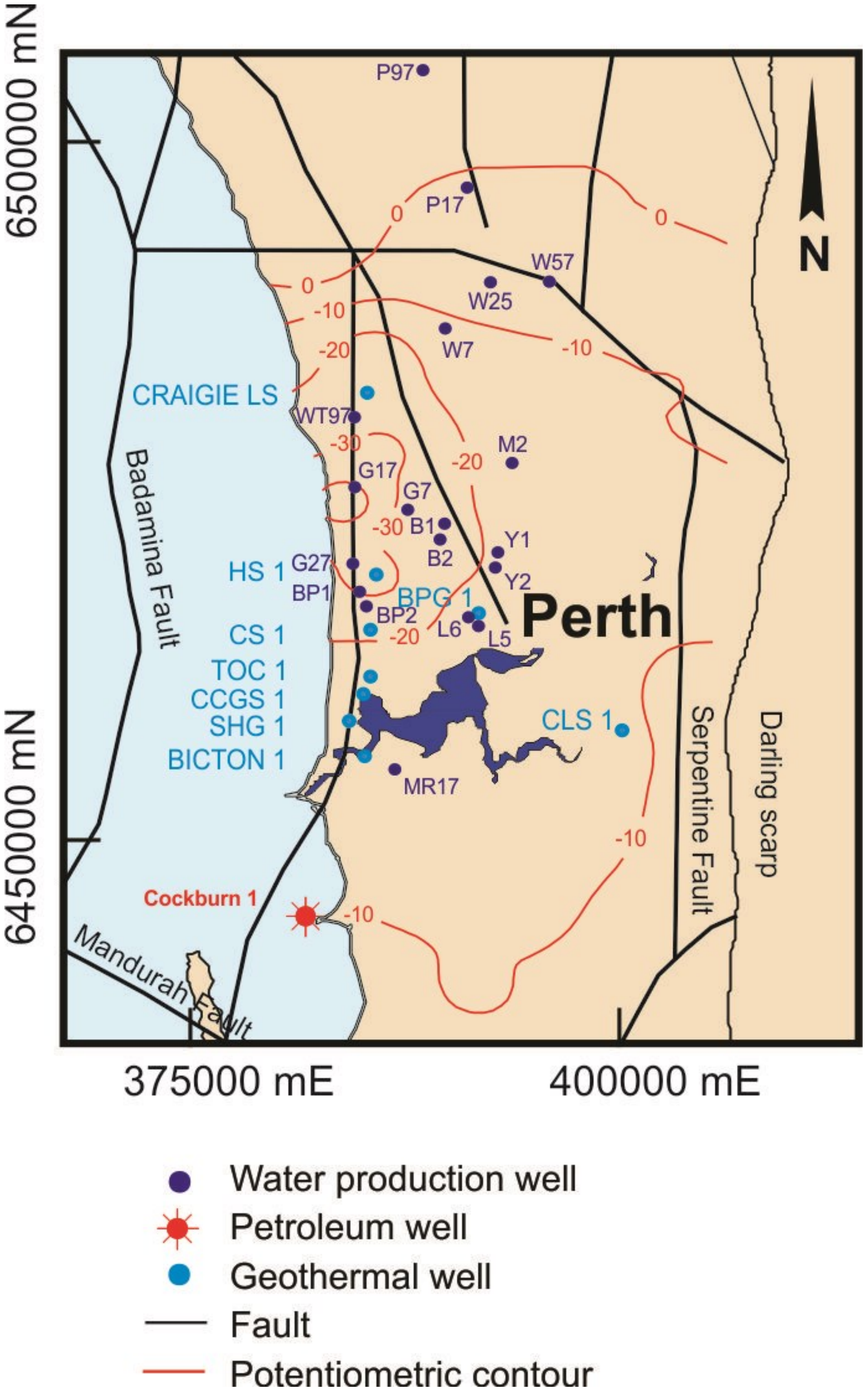

Figure 4: Yarragadee Aquifer potentiometric Surface

2.4 Geothermics

The Perth Basin has been subject to intense petroleum exploration, both onshore and offshore. As part of this exploration program, deep temperature measurements were taken. These temperature measurements were used to calculate temperature gradient map (Chopra and Holgate, 2007; Hot Dry Rock Pty Ltd, 2008). Ricard et al. (2012) shows that the temperature gradient varies between 20 to 36.5 °C km^{-1} with maximum temperature varying from 80 to 130 °C at 3,000 m at the Perth Basin scale. The distribution of temperature in the Perth Metropolitan Area and especially in the lower Yarragadee Formation remains largely unknown, with only a single deep oil exploration well (Cockburn-1) located 17 km south west from Perth and temperature data available only at 900m and below 2,200 m.

Although the temperature distribution was investigated by Bestow (1986) and Hot Dry Rocks Pty Ltd (2008) at the Basin scale, the first systematic analysis of the temperature distribution in the Perth Metropolitan Area was performed in 2011 (Reid et al., 2011). The study collected temperature data in Department of Water groundwater monitoring bores across the entire Perth Metropolitan

Area. Unfortunately, most of the groundwater monitoring bores do not intersect a significant portion of the Yarragadee Formation and the study did not consider production temperature data available from commercial direct use geothermal projects utilizing the Yarragadee Aquifer since 1996 or water supply bores targeting the upper section of the Yarragadee aquifer. It is likely that upward flow in the western part of the Perth Metropolitan Area result in higher temperatures locally. This is in agreement with three dimensional thermal conductive and advective modelling studies (Reid et al., 2012; Schilling et al., 2013) in the Perth Basin which have showed the potential influence of faults and advective flows on the temperature distribution both locally and regionally.

Temperature measurements available for the Perth Metropolitan Area including Department of Water monitoring bores, Petroleum wells, and including production data from geothermal and deep water supply bores collated for the purpose of this study are presented in Figure 5. Expected temperature at 1,000 m below sea level ranges from 36 to 58 °C (Figure 5a) and at 2,000 m below sea level (estimated average depth to the base of the Yarragadee Formation), the temperature can range from 55 to 90 °C (Figure 5b). The lower temperatures are consistent with the areas downward flows (recharge) for the Yarragadee aquifer (AM24; Figure 1) while the higher temperatures are consistent with measured upward heads in the west of the Perth Metropolitan area (AM33; Figure 1). There has been some numerical modelling of groundwater flow and heat transport (Pujol, 2010; Reid et al., 2012; Schilling et al, 2013) in the Perth Basin, however there is no detailed groundwater flow and heat transport model which uses recently acquired thermal conductivities (Delle Piane, 2014) and hydraulic properties derived from pumping tests to match the observed temperatures and potentiometric head in the Perth Metropolitan area.

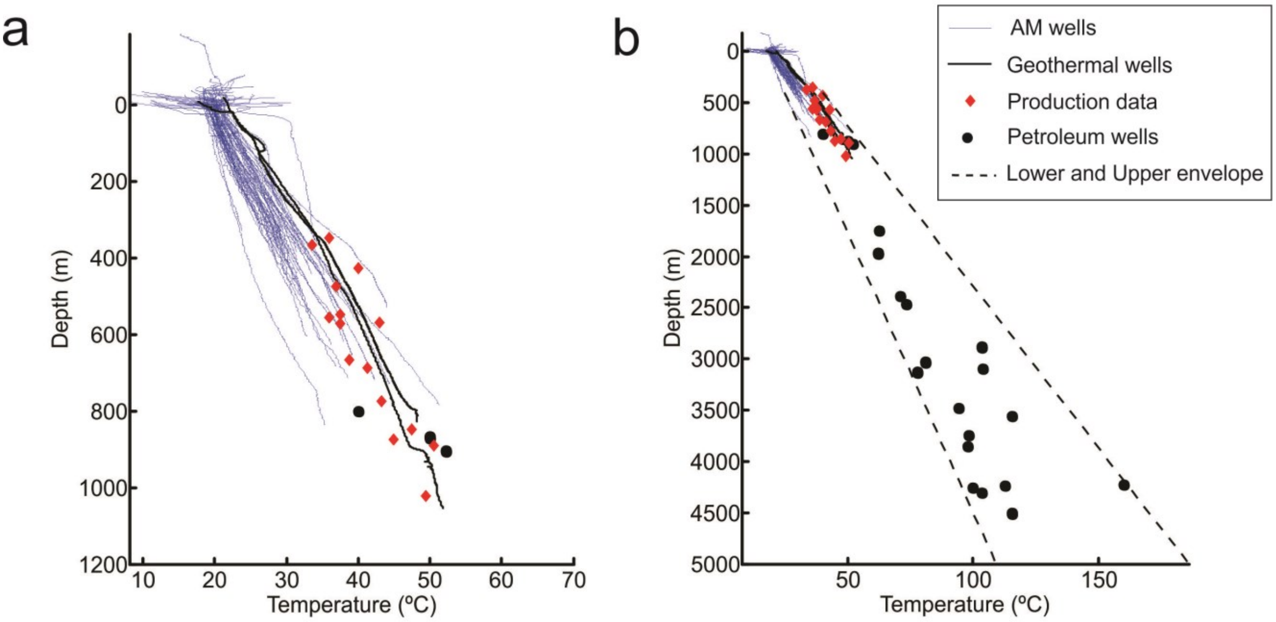

Figure 5: Perth Metropolitan Temperature Data (using Ricard and Chanu, 2013) and production data from geothermal and deep water supply bores in the Perth Metropolitan Area

3. PERTH BASIN GEOTHERMAL DESIGN

3.1 Drilling and Bore Construction

Owing to the depths and pumping rates targeted at up to 1,150 m and 5,000 m^3/day respectively, high powered drilling rigs with at least 50 tons draw works capacity and triplex mud pumps with displacements of 550 gal/min have been required for the construction of geothermal bores up in Perth.

In late 1996, the Melville Water Polo Club operating from the Bicton swimming pool, proposed to draw geothermally warmed water from a deep bore within the Yarragadee aquifer to warm the pool via a heat exchanger. This resulted in the first bore constructed solely for geothermal heating purposes in Perth (BICTON-1; Figure 1) being drilled in March 1997 in Bicton, about 10 kilometres south-west of Perth. A 216 mm (8 ½”) diameter pilot hole was drilled to 750 m and geophysical logs were run to full depth; the measured Bottom Hole Temperature (BHT) of 41°C exceeded the project minimum requirements (36°C). The pilot hole was reamed to 311 mm (12 ¼”) diameter from surface down to 679 m depth and was completed with 178 mm (7”) diameter steel casing pressure-grouted from 679 m depth to surface to isolate the Cretaceous fresh aquifers within the Leederville Formation between 100 and 400 m depth. Stainless steel screens of 127 mm (5”) diameter were telescoped through the casing below 679 m depth. The bore produced 40°C groundwater at 0.8 bar bore head overpressure (the bore was sunk at a low elevation on the southern side of the Swan River).

Following the Bicton pioneer achievement and a growing concern that the Yarragadee aquifer was over-exploited with a declining potentiometric surface, the regulatory body, the Department of Water, ceased issuing groundwater allocation licences. A new design concept (Figure 6) including an injection bore to return the heat-depleted groundwater at a shallower depth within the aquifer to maintain a neutral water balance was implemented in 2001 with the Christ Church Grammar School geothermal project (CCGS-1; Figure 1) and has prevailed until today.

Key design parameters for operating geothermal systems in Perth are given in Table 1. A typical bore design is presented in Figure 6. In this design, the production bore includes a pump chamber casing (N°1 in Figure 6), to accommodate a submersible pump, and a production casing (N°2 in Figure 6) and inline wire wrapped screens at the target production depth (N°3 in Figure 6). The injection replicates the production bore design with a single injection casing and inline wire wrapped screens (at the target injection depth. The vertical separation, and the occurrence of beds of shale and siltstone (N°4 in Figure 6) between the production and injection intervals in the aquifer prevents the direct recycling of the injected groundwater and ensures a sustainable supply of groundwater with a constant temperature. This is in agreement with three dimensional numerical modelling studies (Pujol, 2010) which have showed that injection of the heat-depleted groundwater is unlikely to affect the pumped groundwater temperature over periods of 40 years in most cases.

Table 1: Direct use Geothermal Systems in Perth

Geothermal Operation	Year of commis-sioning	Depth (m)	$\mathrm{BHT}^{A,B,C}$ (°C)	HX max temp. (°C)	Inj. max temp. (°C)	Max pumping rate (m^3/day)	Average pumping rate (10^3 m^3/yr)	Heat-exch. capacity (kWt)	Max Produced heat (MWht/yr)	Capacity factor (%)	add'l energy source
Bicton P.C. (BICTON-1) [1]	1997	750 (p)	41.0^{A}	40	N/A*	700	90	400	1050	30	none
Christchurch G.S. (CGGS-1) [1]	2001	628 (i) 757 (p)	41.2^{A}	42.4	30.4	1050	160	610	2230	42	none
Challenge S. (CS-1) [2]	2004	650 (i) 750 (p)	N/R	43	35	5200	880	2020	8190	46	gas
Claremont A.C. (TOC-1) [1]	2004	608 (i) 864 (p)	44.5^{A}	43.2	31.2	700	100	410	1400	39	none
Craigie L. C. (CRAIGIE-LS) [3]	2006	452 (i) 802 (p)	39.6^{A}	38.3	30.3	1550	N/R	600	N/R	N/R	gas
Saint Hilda's S. (SHG-1) [1]	2011	681 (i) 1007 (p)	51.8^{C}	49.8	39.8	2100	230	1020	2670	30	none
Canning L.C. (CLS-1) [4]	2012	588 (i) 1165 (p)	45.9^{A}	47	38	2250	N/R	980	N/R	N/R	none
Beatty P.L.C. (BPG-1) [1]	2013	799 (i) 1156 (p)	52.5^{C}	49.1	39.1	2150**	325**	1050	3780	41	gas
Hale S. (HSG-1) [1]	2014	496 (i) 1006 (p)	45.8^{B}	47.0	32	2750	N/R	2000	2620	15	none
Totals	-	-	-	-	-	**18450**	**>2000**	**9090**	**>25000**	-	-
Mandurah A.C.	2015**	700 (i) 1100 (p)	Bores are currently being drilled								
Riverton L.P.	2015**	710 (i) 1200 (p)	Bores are currently being drilled								
Cockburn C. W.	2015**	550 (i) 1100 (p)	Bores may be drilled in the end of 2015								

[A]: un-corrected BHT of unknown lag time

[B]: corrected BHT from 2 or 3 points

[C]: quasi-equilibrium BHT (recorded > 7 days post drilling)

*: no injection, water is used for irrigation of parks and gardens in Mosman Park

**: pumping rate is currently limited to 2160 m3/day. However the bore is capable to pump up to 3024 m3/day

[1]: Rockwater Pty Ltd completion reports unpublished data

[2]: Edward Olmeadow *et al* 2011. Water Resource Management DOI 10.1007/s11269-011-9785-2

[3]: Worley Parsons completion report unpublished data

[4]: Pennington Scott completion report unpublished data

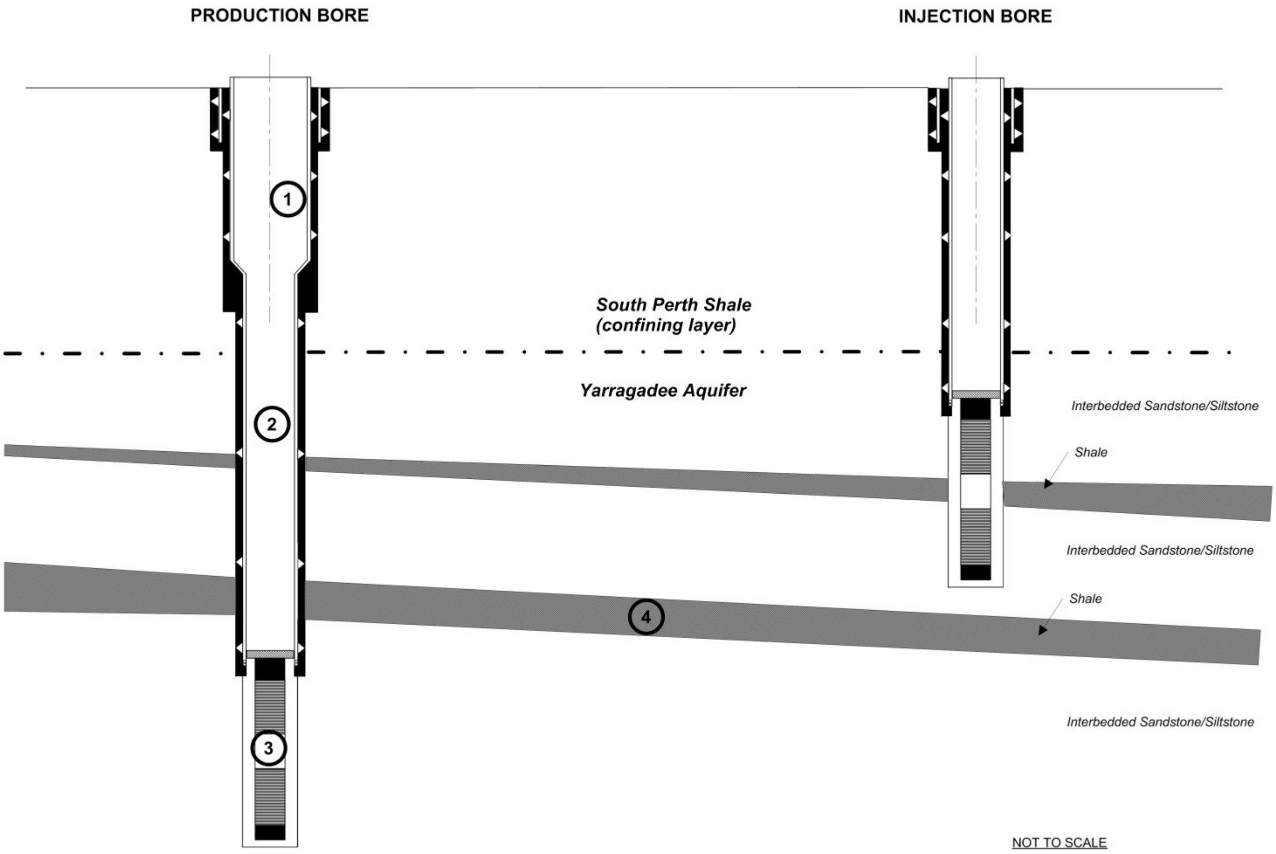

Figure 6: Typical Geothermal Bore Design

3.2 Geothermal Heat Exchange Plant

Each drilling and bore construction project has experienced challenges that have been successfully resolved resulting in improved designs and methodologies for following projects - for example injection packers or automatic self-cleaning (scanner) filter.

Once the drilling and bore construction phase is completed, a significant risk to the long term success of geothermal projects is irreversible clogging of the injection bores either through suspended solids, air-entrainment, bio-fouling and/or chemical reactions (Ungemach, 2003). Clogging of bores can result in a significant reduction in the capacity to inject the heat-depleted groundwater into the aquifer and the necessity to use an alternative backup such as gas-boilers. Olmeadow (2010) found that the initial inability to maintain positive pressures during injection at Challenge Stadium (Figure 1; bore CS-1) geothermal plant resulted in air entrainment and pyrite precipitation within the injection bore screens two months post commissioning. This resulted in a costly remediation program to return the screens to their optimum specification conditions.

To prevent air entrainment and associated geochemical reactions, the industry standard is to design the system to be pressurized (typically 100 to 400 kPa overpressure). In recent years downhole injection packers have been used to provide maximum control over the operating injection pressure. Furthermore to mitigate the potential for scaling and encrustation at the aquifer/screen interface the injection zone is set at a depth where the natural groundwater quality and temperature is similar to that of the heat-depleted groundwater.

In most projects, suspended solids in the pumped groundwater have also contributed to the gradual clogging of the injection screens and in some case the surrounding aquifer formation, resulting in decreasing injection efficiencies and increasing injection pressures over time up to a point where remediation of the injection bore is required, on average every 5 to 10 years and annualised maintenance costs are small (circa $5,000 to $15,000 per year) and comparable to conventional systems. In areas where the Yarragadee formation is particularly fine-grained and poorly sorted, remediation of the injection bore has had to be undertaken within the first three years of operation at some sites resulting in slightly higher maintenance costs. However, one project with poor injection bore design (screen aperture size and depth setting) has initially necessitated remedial work of the injection bore to be undertaken on a yearly basis until suspended solids in the pumped groundwater dropped to a point where typical maintenance frequency applied. Finally, in recent years automatic self-cleaning (scanner) filter have been used to remove suspended solids prior to injection.

Despite the minor challenges discussed above, all of the geothermal systems in Perth are significantly cheaper to run (including remediation and maintenance costs) compared to conventional gas-boiler and air-source heat pump systems (Olmeadow, 2010; Pujol, 2011). The main features of a successful geothermal heat exchange system are presented below along with power, energy, capacity factor and energy efficiency design criteria.

3.3 System Sizing

Direct use geothermal heat-exchange systems used for heating pools and building space in Perth work by abstracting the geothermally warmed groundwater, circulating the water through heat exchangers to maintain the pool water and building air at the desired temperature, and then re-injecting the heat-depleted groundwater (usually at 30 to 40°C) back into the source aquifer via shallower injection bores so as to maintain a neutral water balance. The groundwater is pumped via an electro-submersible pump (ESP) in the production bore.

Heated pools are generally kept at 26 to 28°C but some leisure centres also operate leisure pools at up to 32°C and spas at 36°C. The temperature of the pool heating water is typically 10 to 12°C warmer than the desired pool temperature, but spas often require a lower temperature split as the pool leaving temperature is higher (36°C) leaving only a 6 to 7°C available split in the case of a 45°C geothermal water supply. An injection temperature 1-2°C higher than the pool average temperatures (ie 28 to 30°C for most pools and 34°C and 38°C for leisure pools and spas) can generally be achieved without compromising the economic selection of heat exchangers (Table 1). Space heating in Perth is only required for a few months of the year and is often undertaken opportunistically when spare heating capacity is available from the geothermal bore.

Most geothermal plants are designed to operate with minimal friction losses through the pipework plant room (heat exchange units, control valves and filter); pressure losses rarely exceed 200 kPa (about 20 m). Injection pressures are generally set at 100 to 400 kPA to prevent air entrainment and provide a stable injection pressure for the inline backwash filter to operate. Although the environmental and economic sustainability of the geothermal heating systems are maximised by injecting the water back into the aquifer, a disadvantage of the method is that injection bores are susceptible to becoming clogged by fine particles contained in the injected water leading to a gradual increase in the pressure up to a trigger level (typically 700 kPA). When the injection pressures reach the trigger value, redevelopment of the injection bore is required to remove the fine particles that have partially clogged the screens or aquifer. Redevelopment will result in increased bore efficiencies, ideally to those at the time of commissioning.

For example, for St Hilda's 1020 kW geothermal project, the resulting pumping power requirement is about 48 kWe at maximum pumping rate and the COP for this system is 1020 / 48 = 21 within the range of COP values for geothermal systems in Perth (20 to 35). This demonstrates the outstanding energy efficiencies of geothermal systems for pool heating. This is obviously significantly higher than an electric air-to-water heat pump, which may have a COP of between 3 and 8 depending on the ambient and pool temperatures. A gas-fired heater has a COP of less than 1, although the heat is sourced from the combustion of natural gas.

4. FINANCIAL BENEFITS OF DIRECT USE OF GEOTHERMAL HEAT

Current electricity prices in Western Australia are about $105/MWh off-peak and $375/MWh peak. Since geothermal systems operate mostly at night when temperatures are lowest, the relevant electricity price is probably about $185/MWh. Gas costs are about $95/MWh. For example, using the typical project example presented above and a conservative capacity factor of 30%, the utility costs for the geothermal heating system are calculated to be about $18,000/year. The utility costs for an electric air-to-water heat pump would be about $115,000/year and those for a gas-fired heater up to $315,000/year. The resulting utility costs savings for the planned lifetime of the system of 30 years amount to about $3 million when compared to an electric air-to-water heat pump and up to $9 million when compared to a gas-fired heater. In addition carbon dioxide emissions over a year are estimated to 90 tons for the geothermal system example above, 600 tons for an equivalent electric air-to-water heat pump system and 900 tons for a gas-fired heater.

Although it depends on many factors the current costs to supply and install air-to-water heat pump is approximately $1,000/kW. Gas-fired heater costs are much lower and are estimated to $100/kW. This compares to costs to install a geothermal system ranging from $1,400/kW to $2,350/kW (average $1850/kW) based on project costs in Perth since 2011. However, since drilling costs typically account for 80% of the total project costs, costs for a geothermal system depend strongly on the bore design and hydrogeological context (fresh versus brackish groundwater, geothermal gradient etc…). This is reflected in costs ranging from $1,100/m in areas where warm groundwater supplies exist at shallow depth and water quality is excellent to $1,750/m in areas of lower geothermal gradients and/or where brackish and corrosive groundwater occurs. The average costs per metre are $1,450/m.

Using these indicative figures to estimate capital cost, the calculated return on investment for the geothermal system example above is 10 years when compared to air-to-water heat pump and 7 years when compared to gas-fired heater. Actual return on investment periods for systems operating in Perth are 5 to 9 years in agreement with the ranges calculated above. In practice federal grants of up to $2 million dollar are available for geothermal projects resulting in payback periods of less than 5 years.

5. DISCUSSION

Geothermal in sedimentary basins is well established at small scale (< 5 MWth) for direct use projects. While few small-scale power generation projects exists (Sanyal, 2009), it is yet to gain momentum due to the difficulty to find the right combination of aquifer temperature and quality. Large scale power generation (> 5 MWe) does not exist yet for sedimentary basins. Sanyal (2009) has demonstrated that for power generation in sedimentary basins, aquifer quality has a more significant impact on the economics than temperature which can be directly associated with the range of variation of the aquifer permeability. Historically, the development of the direct use projects in the Perth Metropolitan Area have benefited from the extensive knowledge and experience of the local groundwater community for water supply resulting in an overall lower subsurface risk than in other worldwide projects. The geothermal resource, the Upper Yarragadee aquifer, is moderately to highly permeable with excellent water quality. While the direct use surface facilities historically spans over a wide range of applications, current usage is more focused on supplying heat for leisure centres and district heating since it is one of the single highest heat requirement in Mediterranean climates such as at Perth's. Perth's geothermal projects are well established, economically viable and environmentally sustainable and they present an overall low risk profile.

Opportunities for future geothermal projects can be investigated in three key directions: diversity of the direct use applications, scaling-up to larger energy delivery at current reservoir target and exploration for hotter and deeper aquifers.

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