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Addressing Clogging Risks When Injecting Heat-Depleted and Oxygenated Hot Springs Water: Lessons Learnt from Peninsula Hot Springs, Australia

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ABSTRACT

Peninsula Hot Springs (PHS) is Australia's premier hot springs and spa facility with over 500,000 visitors annually. It sources brackish (3 g/L salinity) geothermally heated water at 47°C from two bores targeting the Werribee aquifer (Eastern View Group) at about 640 m depth. The geothermal water is currently mixed with 15°C fresh water (< 1 g/L salinity) from a shallower aquifer to create a wide range of bathing offerings. Because of the salinity of the geothermal water, surface water discharge to the environment is problematic.

In 2010, PHS completed one injection bore (Injection Bore #1) that has faced severe clogging issues. Plans have been made to modify the system to improve injection efficiency and also to construct two replacement injection bores (Injection Bore #2 and #3) by mid-2019. Geothermal water is also considered to be cooled and used as a substitute for pool temperature regulation.

Injection of geothermal water into aquifers composed of interbedded sandstone, silty claystone and coals can be challenging. Clogging issues have impeded the development of many clastic geothermal resources globally and at PHS in particular, clogging issues have resulted in poor injection performance since the first injection bore was commissioned 2010.

The following have been cited as causes of clogging in the literature: proliferation of bacteria (biological clogging), suspended particulates, clay dispersion in aquifer matrix, gas bubbles in the water (physical clogging), chemical precipitation in the water and/or in the aquifer (geochemical clogging). While the main causes of clogging have been studied by researchers and been the subject of a number of successful pilot-scale studies for decades, particularly in the oil and gas industry, sparse published information exists in the geothermal literature regarding the key technical solutions and procedures that have guaranteed the success of injection into sandstone aquifers in modern industrial applications.

This paper focuses on the review of PHS injection scheme undertaken by the authors in 2018 and design changes that have been implemented subsequently to improve injection efficiency. Issues discussed will include clogging associated with suspended solids, bacteria induced clogging and chemical precipitation. Additionally, the key bore design and surface filtration criteria that will permit successful economic injection of heat-depleted groundwater into the Werribee Formation sandstone aquifer are discussed.

1. INTRODUCTION

Peninsula Hot Springs (PHS) is located on the Nepean Peninsula, about 4 km to the south east of Rye, approximately 65 km south west of Melbourne, Victoria in Australia (Figure 1).

A total of six bores have been drilled on the property (Figure 2):

- A narrow diameter hydrostratigraphic bore which proved the resource in 1998 but was later abandoned (WRK985891)
- Two production bores drilled in 2002 and 2013 (Production Bore #1 and #2)
- One original injection bore drilled in 2010 (Injection Bore #1)
- Two new replacement injection bores drilled in 2018 and 2019 (Injection Bore #2 and #3)

Other nearby bores include Nepean 38 (a state observation bore) about 1.6 km north west, Hilltonia Hot Springs production bore about 1.4 km north east (proposed development with additional drilling planned in the first half of 2020) and St Andrews Golf Course test hole about 2.0 km south east (other proposed development) (Figure 1).

The Nepean Peninsula is underlain by the Port Phillip sub-basin of the Otway (sedimentary) Basin (King et al. 1987) which contains a sequence of sedimentary rock of Quaternary to Tertiary age to depths ranging from about 750 m below ground level (bgl) near the property to about 1,100 m bgl at Point Nepean. The Werribee Formation is of Tertiary Age, ranging from Oligocene to Eocene Epochs. The elevation of the base of the Werribee Formation (Eastern View Group) targeted by the deep bores on the property, is about 100 m higher than the base of the Eastern View Group at the site as shown in contours relative to sea-level in Figure 1. It is unclear whether the lowermost Tertiary sediments of the Eastern View Group (Yaloak Formation below the Werribee aquifer) are conducive to groundwater flow, without further investigation. These deeper sediments are analogous to the Werribee Formation and likely to be considerably hotter but have not yet been targeted for water supply or recharge on the Peninsula. Tertiary sediments overlay undifferentiated metamorphic basement rocks.

The thickness of the Werribee Formation ranges from about 40 to 140 m (100 m on average); thickness variations are likely to relate to the terrestrial paleo flow direction and fluvial channels width at the time of deposition. Beneath PHS, the formation thickness ranges from 108 to 119 m with roughly 30 to 50% of that being conductive to groundwater flow (ie clean sandstone beds).

PHS bores (with ground elevations of about 15 m above sea level) are located about 5 km west of the Selwyn Fault. Significant displacement occurs across the fault with Older Volcanics outcropping on the up thrown (east) side (Mornington Peninsula) encountered at about 600 m below sea level on the downthrown (west) side of the fault under the property (Nepean Peninsula).

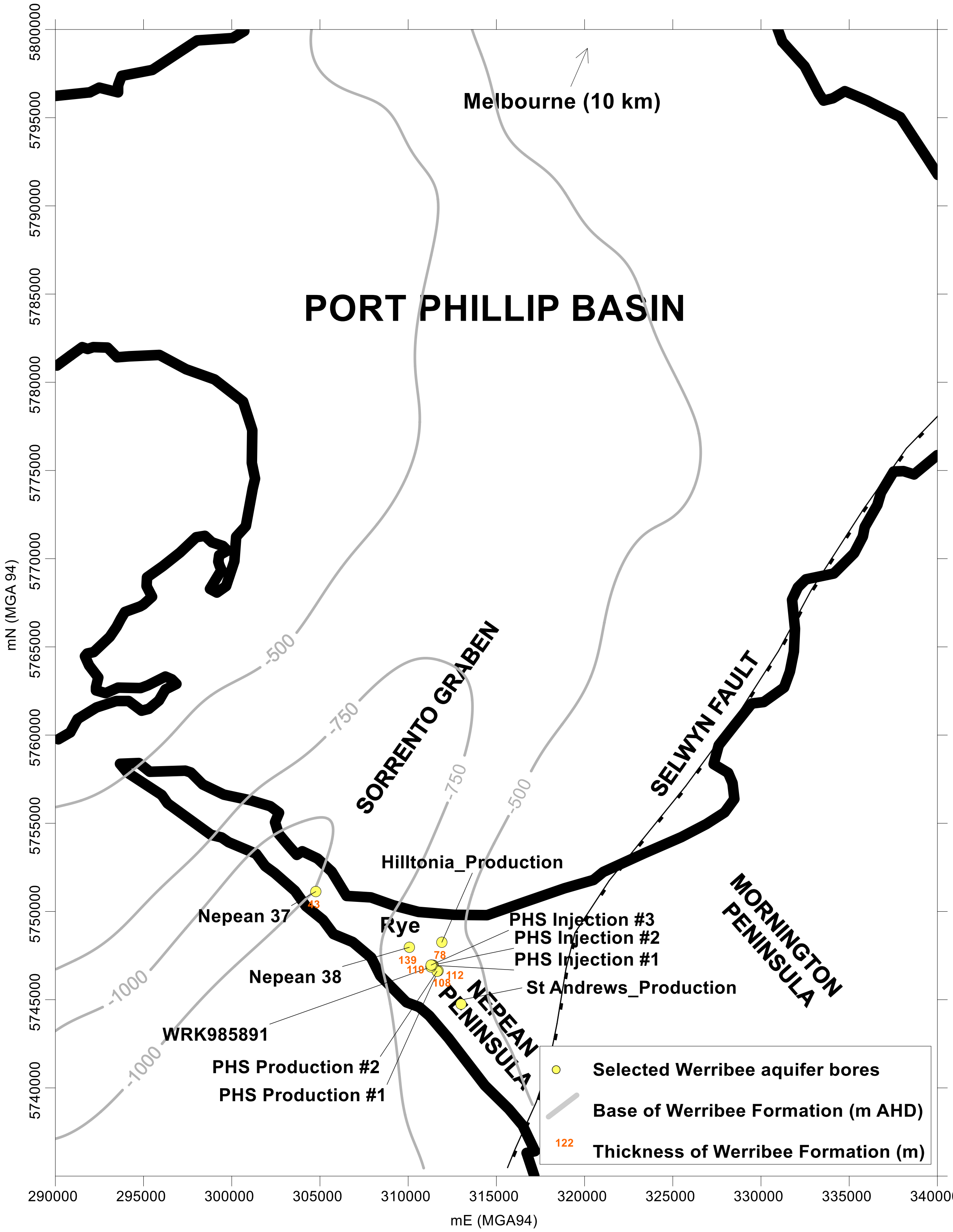

Figure 1: Locality Plan with selected Werribee aquifer bores overlain on top of the elevation of the base of the Werribee Formation in the Port Philip Basin, Victoria (Australia)

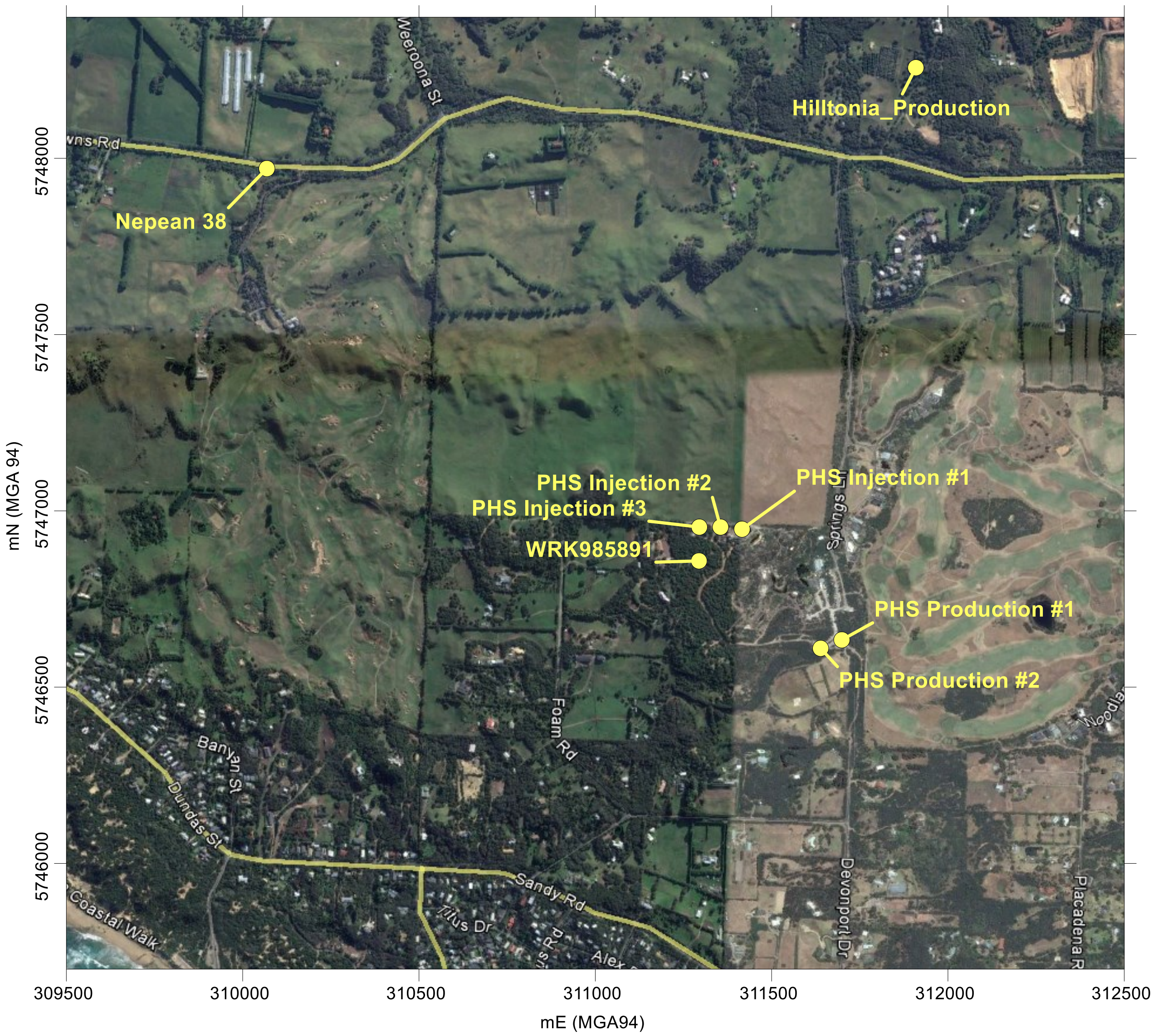

Figure 2: Site Plan showing selected Werribee aquifer bores near Peninsula Hot Springs

2. HYDROGEOLOGY OF THE WERRIBEE AQUIFER

2.1 Lithological description and depositional environment

The Werribee Formation (Eastern View Group) was laid down in a terrestrial environment of deposition and consist of interbedded sandstone, siltstone and claystone (Partridge et. al. 2001a, cited in Holdgate & Gallagher 2003).

For the purpose of this paper, the net aquifer thicknesses of sandstone beds (h) was estimated from wireline geophysics (GR, neutron, density and Nuclear Magnetic Resonance (NMR) for selected bores at the site. The net aquifer thicknesses range from 26 to 55 m for the selected bores.

2.2 Aquifer geometry

The formation is made of up to 49% sandstone in some of the studied bores and considerably less in others (down to 27%). The average net aquifer thickness estimated for the studied bores is 36% of the gross thickness.

Locally the floodplain sediments (siltstone and claystone) likely form local aquitard layers within the aquifer and can retard vertical groundwater flow between the different sandstone beds (up to eight distinct beds over the entire thickness of the aquifer). The sandstone beds range from 1 m thick near the top of the formation to over 10 m thick near the base of the formation possibly as a result of changing energy of deposition.

Coarser-grained and thicker intervals at the base of the aquifer can be correlated more or less from one bore to another over short distances consistent with the likely wider and higher energy fluvial channels at the base of the formation. Finer-grained and thinner intervals at the top of the aquifer on the other hand cannot be correlated and may not be laterally extensive.

The formation is overlain by calcium carbonate clay (marl) that deposited during a widespread marine transgression during the early to middle Miocene. The formation is confined by these low permeability sediments.

The Formation is underlain by Older Volcanics that erupted across Victoria during the Palaeogene Period (Early Tertiary Age).

2.3 Mineralogy

The Werribee Formation mineralogy is primarily controlled by lithological changes with depth (ie. interbedded sandstone, siltstone and shale).

The sandstone consists primarily of quartz. Traces minerals commonly identified in cuttings include pyrite. There is general aluminosilicate enrichment and quartz is less common in finer-grained sediments and siltstones. Interbedded coal occurs at the base and top of the formation.

2.4 Particle Size Distribution

No core was acquired when drilling the two injection bores at the site in 2018 and 2019. However, laser diffraction PSD analyses were undertaken on the drill cuttings to enable the selection of the wire-wound screen aperture sizes.

As with the sandstone bed thicknesses, the formation median size (d_{50}) appears to increase towards the base of the aquifer (Figure 3 presents PSD results for Injection Bore #2 that intersected a particularly coarse sand interval within the Werribee Formation):

- Top of aquifer: moderately well sorted, medium grained sand (d_{50} = 250 to 350 microns)
- Middle of aquifer: poorly sorted, coarse grained sand (d_{50} = 650 microns)
- Base of aquifer: well sorted, very coarse grained sand (d_{50} = 1,000 microns)

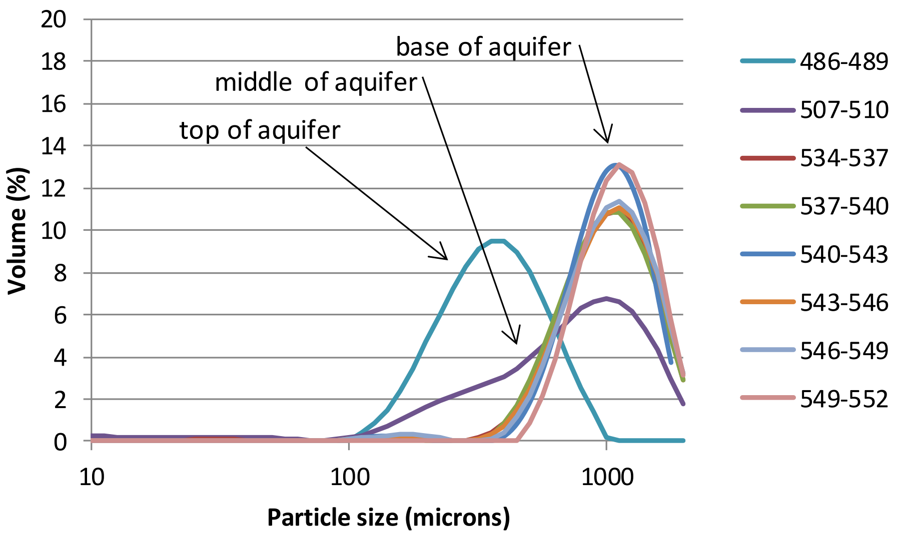

Figure 3: Laser diffraction PSD analyses of a selected Werribee aquifer bore

2.5 Porosity

The total porosity of the formation is high (37.8% on average as determined from Neutron surveys for the same bore selected for PSD analyses in Figure 2) and is characteristic of unconsolidated to weakly consolidated, coarse-to very-coarse grained sandstone (consistent with the PSD analyses above). Unconsolidated sandstone porosity values typically range from 35 to 45% and the theoretical inter-granular porosity of cubic packed spherical grains is up to 47.6%.

The average specific yield is only marginally lower than total porosity (36.4% on average as determined from Nuclear Magnetic Resonance (NMR) surveys) with nearly all the porosity made of drainable water filled porosity with the remainder consisting of the clay bound porosity.

2.6 Permeability

Leonard (1992) reports typical transmissivities of 75 to 300 m^2/d for the Werribee aquifer; equivalent to permeability thickness values of 50 to 220 Dm (Darcy × m) based on the likely groundwater density and viscosity.

Permeabilities derived from the NMR surveys for the selected bore above (Injection Bore #2) were similar (411 m^2/d for the entire aquifer and 350 m^2/d for the aquifer open to screens).

Transmissivities derived from drawdown tests of other bores at the site, some of which are not screened across the entire aquifer, range from 155 to 415 m^2/d. The net aquifer thickness open to the screens is estimated to 13 m in the original injection bore but 32 to 35 m in the two new replacement injection bores (injection Bore #2 and #3 respectively). This is consistent with relatively high permeabilities of 11.5-12.0 m/d or 8,400 to 8,800 mDarcy.

2.7 Groundwater quality

Groundwater in the Werribee aquifer is thought to reflect mixing between calcium-magnesium bicarbonate groundwater type at equilibrium in the aquifer and deep hot fluids circulating up the deep seated Selwyn Fault system (Driscoll, 2006). This is reflected in its groundwater chemistry composition which falls on a mixing line between sodium chloride groundwater type for PHS bores to increasingly sodium-calcium-magnesium bicarbonate type for Nepean 38 bore located further to the west of the Selwyn Fault.

Groundwater salinities are brackish (about 3 g L^{-1}) in bores at PHS. Total organic carbon derived from coal seams at the base of the aquifer, dissolved iron from naturally occurring pyrite minerals within the aquifer and the elevated calcium concentrations are the main element of concern with regard to clogging. Groundwater is reductive (redox potential of -220 mV). Dissolved gas is limited to small quantities of CO_2 and H_2S (bubble point measured to about 1.1-1.3 bar in the field). Degassing of dissolved gases when the geothermal water is circulated through the pools results in the pH of the water increasing from 6.2 in situ to about 6.9 to 7.1 in the dump water from the various hot springs.

Water analyses from a selected production bore at PHS are provided below.

Alk mg/L	**In-situ pH**	**Temp °C**	**EC mS/cm**	**Cl mg/L**	**Na mg/L**	**K mg/L**	**Ca mg/L**	**Mg mg/L**	**SO_4 mg/L**	**NH_3 mg/L**	**Si mg/L**	**Fe mg/L**
740	6.2	47	5.6	1500	800	70	130	95	14	2.2	21	0.05

3. PENINSULA HOT SPRINGS INJECTION SCHEME OVERVIEW

3.1 Causes of clogging

The greatest risk to the long term success of aquifer recharge is irreversible clogging of the injection bore screens and surrounding aquifer. The following causes have been cited as cause of clogging (Oolsthorn, 1982):

1. Biological clogging: proliferation of bacteria in and around the bore
2. Physical clogging:
    a) Suspended particles in the injection water
    b) Gas bubbles in the water
    c) Swelling and dispersion of clay
    d) Erosion of the aquifer structure, fine mobilisation and associated high skin losses
3. Geochemical clogging: formation of chemical precipitates in the injection water, the bore or the surrounding aquifer

Causes 1, 2b, 2c, 2d and 3 may make aquifer recharge very unreliable and have very serious consequences for the operation of the geothermal system. These risks can generally be assessed and eliminated by means of properly designed injection scheme, effective controls and in the case of PHS existing injection scheme by improving the original design.

Suspended particles and associated clogging by suspended substances cannot always be avoided completely. In practice, consideration should be given to the relative merit of further pre-filtering, the construction of additional injection bores, regular bore backflush via an ASR valve and/or and more frequent de-clogging (ie re-development).

For the purpose of this paper, each of the causes of clogging was considered in a thorough review of PHS injection scheme in 2018. Design improvements were made subsequently in 2019 to reduce and eliminate key clogging mechanisms identified.

3.2 Existing filter

A comprehensive review of PHS original filter system was undertaken at the start of 2018; comprising the following elements:

- 2 × 200 m^3 pre-filter storage tanks where dump water from the various hot springs pools is collected
- A feed pump rated at 72 m^3/h drawing water from the tanks and delivering it to the filtration system
- A set of 4 off disk filters theoretically rated to remove solids particles down to 130 microns at 120 m^3/h
- 4 × 2.0 m^2 filter area × 1.05 m high filter shells filled with gravel and Granular Activated Carbon (GAC) media
- A further 2 off disk filters
- 1 × 95 m^3 post-filter tank
- A set of two injection pumps (duty/standby)

While the nameplate capacity of the existing filter was 72 m^3/h, its actual capacity has been limited to about 40 m^3/h largely insufficient to meet the peak daily volume to treat with the recent facility extension.

The daily volume to treat was 1,800 m^3/day on average and up to 2,300 m^3/day on peak days at the time of the review but has since increased to 2,050 m^3/day on average and up to 2,550 m^3/day on peak days with the continuing expansion of the facility. To meet the current requirements with some contingency, the new filter was designed to provide 144 m^3/h capacity.

In addition to the rate of filtering, another limitation with the existing filter system is that it does not appropriately mitigate clogging as demonstrated in Sections 3.2.1 to 3.2.6 below.

3.2.1 Biological clogging: proliferation of bacteria

Bacteria occur in the waste water from PHS pools and are thought to be naturally occurring in the groundwater (particularly Iron related and Manganese related bacteria). Concentrations are high (35,000 and 27,000 pac/mL respectively measured in filter backwash). Bacteria tend to further proliferate (particularly iron-related bacteria) in the areas of high flow such as in the injection bore/s were even higher concentrations were measured (140,000 and 27,000 pac/mL in the bore backflush). The microbially mediated reactions below results in the precipitation of manganese and ferric hydrates as well as production of extracellular polysaccharides or similar “slime like” organic polymers were bacteria concentrations are high and there is available organic carbon.

Reaction	**Equation**	**Bacteria associated with this reaction**
Mn (IV) reduction	$CH_2O + 2MnO_2 + 4H^+ \rightarrow 2Mn^{2+} + 3H_2O + CO_2$	*Bacillus, Clostridia*
Fe(III) reduction	$CH_2O + 8H^+ + 4Fe(OH)_3 \rightarrow 4Fe^{2+} + 11H_2O + CO_2$	*Bacillus, Aerobacter, Pseudomonas, Clostridia, Staphylococcus*

Proliferation of bacteria can lead to clogging issues when Bio-Degradable Organic Carbon (BDOC) or Total Organic Carbon (TOC) concentrations in the injected water are greater than 0.2 mg/L and 1-10 mg/L respectively. BDOC or Assimilable Organic Carbon (AOC) provide an indicator of the bio-availability of the organic carbon that may be analogous to microbial clogging of injection bores (Page et al. 2014) while TOC is the sum of organic carbon in the water and is comprised of Particulate Organic Carbon (POC), Dissolved Organic Carbon (DOC) and assimilable organic carbon (generally small chain organics in dissolved form). Granular Activated Carbon (GAC) is the conventional treatment for high DOC and BDOC/AOC concentrations prior to injection while mechanical filtration with coagulation can sometime capture POC and thus reduce the TOC.

Proliferation of bacteria in the bore can also be diminished by deoxygenation, requiring anaerobic metabolism for microorganism growth. This requires Dissolved Oxygen (DO) to be lowered to <0.3 mg/L.

The TOC concentrations in the wastewater have been reported to be as high as 6 mg/L and 3 mg/L on average and are estimated to comprise about one third DOC and two thirds colloidal POC ranging from 0.45 to 0.04 microns in size. The waste water is saturated with oxygen with DO up to 11 mg/L.

The existing filter system appears to remove about 30% of TOC and 80% of DO but residual concentrations are still conducive to proliferation of bacteria (ie approx. 2 mg/L and 3 mg/L respectively). Furthermore, there is evidence that proliferation of bacteria colonising the existing GAC filter produces biofilms. Biofilm sloughing from the GAC is contributing to the fouling problems as shown by a Modified Fouling Index (MFI) of 9.9 s/L^2 post-filter (versus 5.9 s/L^2 pre-filter and 1.3 s/L^2 at the production borehead before circulation to the pools; see Figure 3). MFI of 3 to 5 s/L^2 is the generally accepted range to minimise clogging in sandstone aquifers (Oolsthorn, 1982).

Figure 4 shows that the geothermally heated groundwater supply contains a small quantity of coal fines (contributing to the TOC levels) while the post-filter water contains suspended colloidal (> 0.45 micron) organic and biofilm particles and possibly minor inorganic carbonate scaling particles.

Figure 4: MFI testing on 0.45 micron paper of groundwater at production borehead (left) and post filter (right)

The biofilm production in the GAC is attributed to the blocking of the media by suspended solids promoting proliferation of bacteria and the inefficient backwashing (absence of an air scour). In an attempt to control biofilm after injection was first attempted in 2010, sodium hypochlorite shock dosing was trialed with only limited success. It is postulated that the elevated pH of the post-filter water (up to pH 8) limits the biocidal property of sodium hypochlorite. Furthermore, injection of Disinfection By-Products (DBPs) from sodium hypochlorite dosing is seen as a potential source of pollution to the aquifer by the regulators. UV disinfection treatment was recommended as an alternative to sodium hypochlorite dosing for the new filter and water treatment system because it was considered to be more effective with the elevated pH and it would be free of potentially harmful trihalomethanes. Chlorine dioxide is also being investigated as a potential alternative for shock dosing.

It was concluded that the filter plant was not entirely fit for purpose and contributing to the issues with injection encountered at the site. It was recommended that a new filter system be installed to reduce TOC to less than 1-2 mg/L and BODC to less than 0.2 mg/L while controlling biofilm production through adequate filter design, low pressure UV disinfection treatment and shock dosing as appropriate (using sodium hypochlorite, biodispersant or other suitable chemical). In addition, it was also recommended that an oxygen reduction trial using sodium meta-bisulphite be run to assess the impact of deoxygenation on biological clogging rates.

3.2.2 Physical clogging: suspended particles

The existing filter plant appeared to have historically been designed to remove chlorine and by-products of chlorination (trihalomethanes) from the water on the assumption that the water quality was fair to good and only required minor filtering at 130 microns prior to injection.

However, the Total Suspended Solids (TSS) pre filter were up to 11 mg/L reducing post filter to 2 to 4 mg/L with a median particle size of 106 microns as determined by laser diffraction PSD analyses. Perez Paricio (2000) considers that TSS greater than 1-10 mg/L may potentially cause aquifer clogging and require ongoing management while Pujol (2018) used data from operating injection bores targeting a sandstone aquifer for geothermal applications to demonstrate that TSS greater than 4 mg/L caused unacceptable clogging in bores with permeabilities greater than 1500 mD (as is the case for PHS bores).

Given the likely pore throat size of 100 microns for the Werribee aquifer and the industry accepted criteria 1/13 for free flowing particles (Saucier, 1974), it is estimated that filtering to 8-micron is necessary to prevent clogging of the aquifer matrix by suspended particles.

It was recommended that filtering be improved to achieve 5-micron effective filtration with a likely TSS less than 1 mg/L given PSD analyses of the waste water.

3.2.3 Physical clogging: gas bubbles

Syphoning and air entrainment was evident in the way the various tanks pre- and post-filtering tanks were filled.

It was recommended that tanks be filled from the bottom to avoid air entrainment and injection of gas bubbles. In addition, an injection foot valve was recommended to be installed to prevent syphoning and air entrainment when starting or stopping injection.

3.2.4 Physical clogging: clay dispersion

The Sodium Absorption Ratio (SAR) of the natural groundwater in the aquifer ranges from 15 to 16 indicating a high risk of clay swelling should lower salinity water with a low SAR be injected into the aquifer and swelling clays being present.

The SAR of the injected water was found to be 10 to 15% lower than that of the natural groundwater because of mixing with fresh water from the upper aquifer to control the hot springs pool temperatures. Without undertaking column testing it was difficult to provide a trigger salinity for the injection water to mitigate the potential for hydro-swelling of clay minerals. However, there may be potential for the brackish geothermal water to be cooled and used as a substitute for pool temperature regulation.

3.2.5 Physical clogging: erosion of the aquifer structure, fines mobilisation and associated high skin losses

The common industry accepted sandface velocity to minimise erosion of the aquifer structure during production/injection from sandstone aquifers is 1 cm/s (Ungemach, 2003) which corresponds to the transition to turbulent flow regime Reynolds number (Re) > 2000 within a typical pore throat size of 100 microns. The transition is achieved for a flow-rate of about 2 L/s / m of aquifer (7.2 m^3/h / m) in a 200 mm open hole. When analysing physical clogging in weakly cemented sandstone of the Perth Basin, Pujol (2018) found that flowrate as low as 1 L/s / m of aquifer (3.6 m^3/h / m) caused unacceptable clogging.

Using the more conservative criteria above, it was recommended that the injection flowrate target for new bores be no more than 70 to 110 m^3/h and that the two new injection bores be constructed to provide a total injection capacity sufficient to meet the current requirements with some contingency (ie 144 m^3/h).

3.2.6 Geochemical clogging: formation of chemical precipitates in the injection water, the bore or the surrounding aquifer

The geochemical modelling code PHREEQC (Parkhurst and Appelo, 1999) was used to evaluate the potential impact of injection of wastewater from the hot springs pools into the Werribee aquifer. Saturation Indices (SI) calculated by PHREEQC are discussed below (positive values indicate a potential for mineral precipitation and negative indicating a potential for mineral dissolution).

Figure 5: Dissolved Gas in groundwater degassing in flow-through sampling cell at low supply pressures (<1 bar)

Due to dissolved acidic gases (mainly CO_2 and H_2S) contained in the natural groundwater (Figure 5) and possibly the mixing with the more alkaline water of the upper aquifer, the model-calculated SI for calcite and iron oxyhydroxide were +1.2 and +0.4 respectively in the dump water from the various hot springs pools. This indicates that calcite and iron oxyhydroxides were likely to precipitate in the pools, filter plant and injection bores potentially contributing to the issues with injection encountered at the site. However, it appears that significant mineral precipitation occurs prior to injection in open air streams that carry the wastewater from the pools to the filter and splash of water in the hot springs pools themselves (scaling is evident and requires on-going cleaning of the pools) and it was concluded that mineral precipitation contribution to clogging was likely to be less than that of biological clogging.

It was recommended that the option to lower the pH of the water to that of the natural groundwater (pH 6.2) be considered to mitigate the risk of calcite precipitation, if found to be cost effective. However, laboratory testing indicates that this is unlikely to be cost-effective given the buffering capacity of the water.

3.3 Existing injection bore

3.3.1 Injectivity Index Trends

Following a comprehensive clean of the existing injection bore which included acid and sodium hypochlorite soaking, high pressure jetting, brushing and airlifting in early 2018, injection pressures and flowrates were monitored.

The gradual clogging of the screens in the injection bore, post-cleaning resulted in the injection rates declining from 85 m^3/h to less than 40 m^3/h after 200,000 m^3 were injected (≈ 6 months at 1,170 m^3/day or 60-70% of requirements at the time). The injection pressures were progressively increased from 4.2 bar after the clean to up to 8 bar to maximise injection rates while not exceeding the fracture pressure of the formation and pressure rating of the infrastructure. Despite some sodium hypochlorite dosing to prevent biologically induced clogging, the Injectivity Index could not be maintained above 10 m^3/h / bar.

The plot provided in Figure 6 shows the injectivity index (m^3/h / bar) for a six-month period post cleaning. The data, follows a trend consistent with the suspected combination of biological clogging and suspended solids clogging.

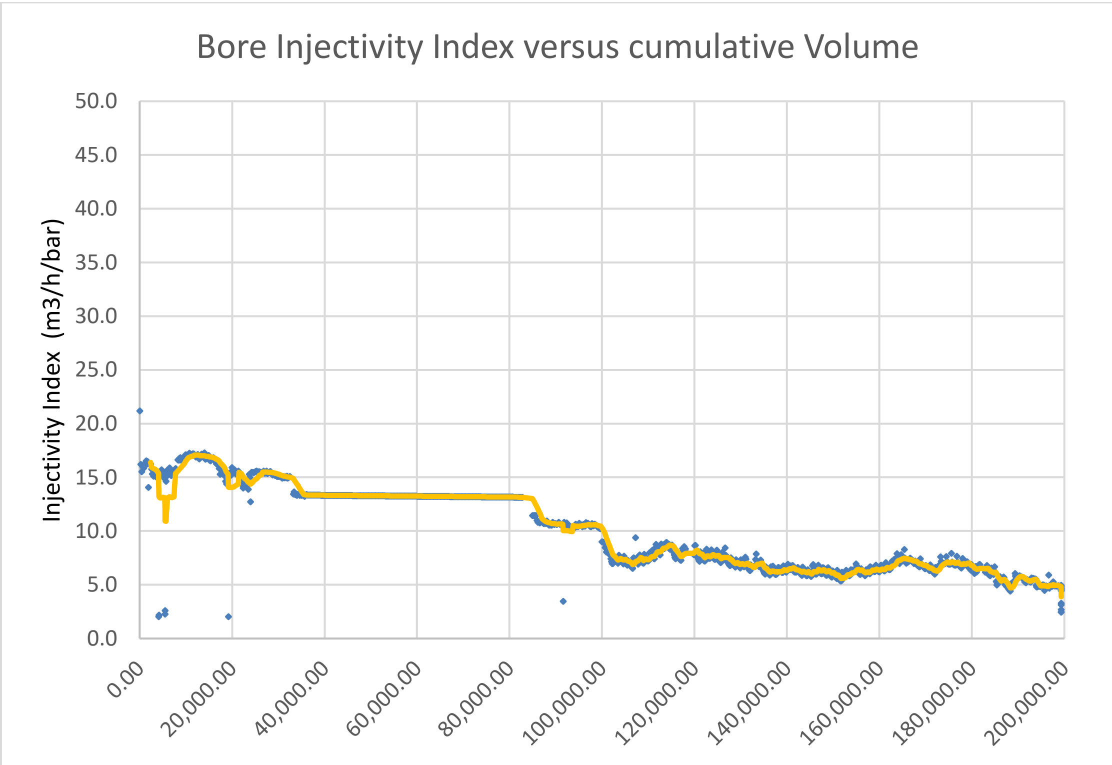

Figure 6: Clogging trend following comprehensive cleaning of existing injection bore

When the injectivity index fell below 4 m^3/h / bar at the end of 2018 (Figure 6), a simpler bore clean including chemical soaking was undertaken by pumping acid and sodium hypochlorite solutions into the bore and air-lifting the water clean on the following days.

However, with this simpler and shorter bore clean, the improvement was short-lived with the injectivity index falling further to 2 m^3/h / bar after only about 35,000 m^3 of injected water (Figure 7). It is thought that chemical soaking without high pressure jetting was only effective in breaking down biological growth on the screens but not within the natural pack on near-well zone.

It was consequently recommended that the two new replacement injection bores be equipped with downhole ASR valves and pumps to allow regular bore backflush to manage injectivity reduction and to space out the need for large workovers and cleans.

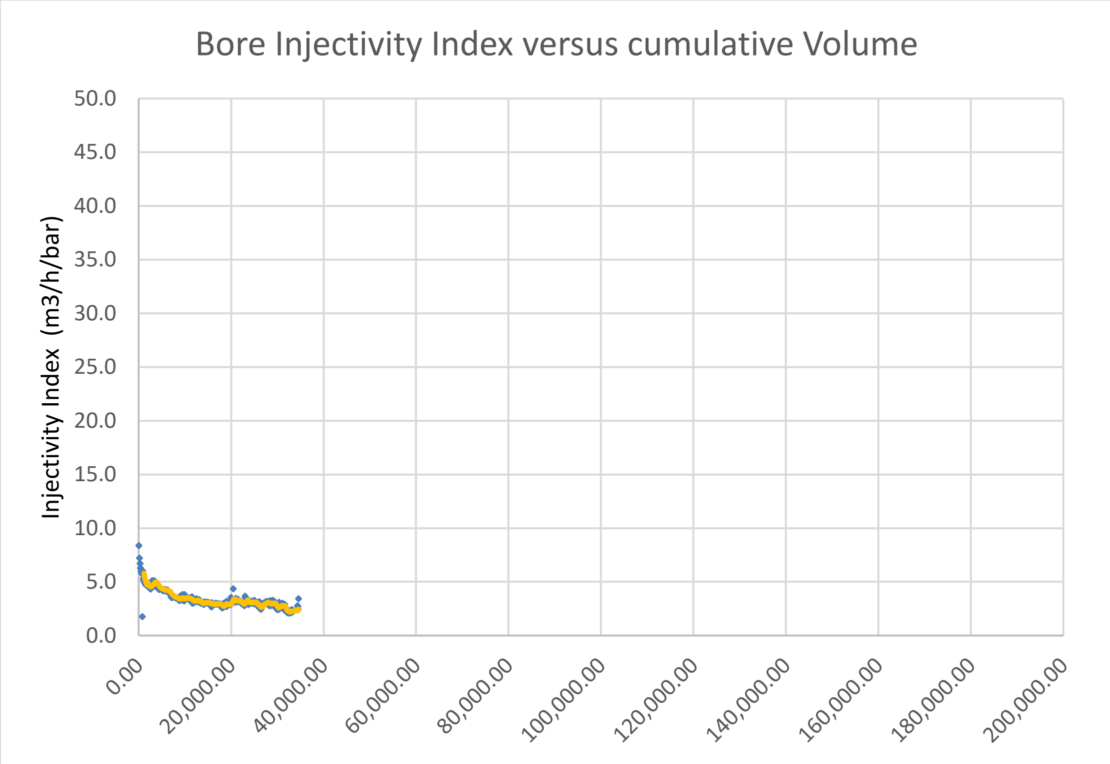

Figure 7: Clogging trend following simple cleaning of existing injection bore

3.3.2 Bore surveys

The following surveys were run in the existing injection bore:

- A Closed Circuit Camera Television (CCTV) survey
- An Optical Tele Viewer (OTV) survey
- An Acoustic Tele Viewer (ATV) survey

The surveys were undertaken in the existing injection bore to assess the bore construction and identify if clogging could be mitigated through improved bore design of two new injection bores. The findings from the surveys of the existing injection bore were;

- Because of Dog Leg Severity (DLS) of up to 5 deg/30m, the fiberglass casing was damaged during drilling and has had to be patched.
    - A DLS criteria of < 3 deg/30m was recommended for new bores to be constructed at the site.
- Non-patched sections of fiberglass casing showed up 1.5 mm depth of material loss from tools run into the bore. Furthermore, given the need for regular workover cleans further damage to the bore casing was assessed as being inevitable.
    - Stainless steel casing will be used for new bores to be constructed at the site and the existing injection bore is planned to be relined with a stainless steel sleeve.
- Considering the rod damage and burst pressure rating of the casing when new (40 bar) injection pressure had been limited to 8 bar while higher injection pressures of 12 bar would be possible given the pressure rating of the surface pipeline.
    - Higher injection pressures would be achievable for new bores to be constructed at the site.
- Friction losses in the DN150 intermediate casing are high in an encrusted scenario.
    - A DN200 intermediate casing will be considered as an alternative for future bore designs.
- A review of available geophysical surveys (GR, neutron and density) suggests that the screen length of 20 m does not provide full coverage of the net aquifer thickness.
    - Since the slot aperture of the selected screens (300 microns) would lead to sand ingress if the upper part of the Werribee aquifer was screened (with a d50 of 250 to 350 microns) it was recommended that pre-pack screens be considered as an alternative for future bore designs.
- Biofilm / organic growth inside the casing and screens was evident on CCTV survey (Figure 8).
    - This confirmed the need to address biological growth through better water treatment / filtration.

It was concluded that the existing injection bore was not entirely fit for purpose and two new higher capacity injection bores were designed for PHS.

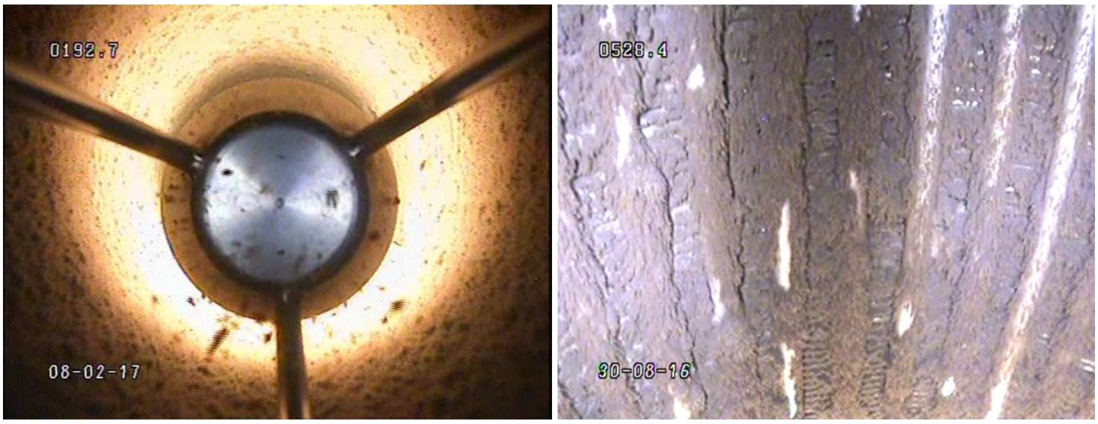

Figure 8: Example of biofilm / organic growth inside the casing (left, down-view) and screens (right, side-view)

4. CHANGES TO PENINSULA HOT SPRINGS INJECTION SCHEME

4.1 New filter system

Following on-site testing, a new filter system was designed and is planned to be installed on site in mid-2020. The following plates in (Figure 9), produced by Amiad Water Systems reveal the accumulation of biofilm at different filtration sizes.

Key filter design changes are summarised below:

- Inclusion of media pre-filtering (using Grade 1 Active Filter Media) to achieve 5-micron filtration
    - AFM glass media has surface catalytic properties and a high negative zeta potential. The surface active properties prevent colonisation by bacteria so bacteria induced bed channeling is essentially eliminated. The high negative zeta potential on AFM attracts the particles and holds them within the filter bed.
- Inclusion of air-scour for effective backwashing of the GAC filter and adequate control of biofilm
    - Vigorous air-scour is required to adequately control biofilm that will tend to colonise the GAC filter.
- Inclusion of media post-filtering (using Grade 0 Active Filter Media) to achieve a 1-micron filtration to capture any biofilm sloughing from the GAC
    - The addition of Grade 0 AFM glass media will produce water with low TSS.

At the time of writing this paper, the new filter and water treatment system had not yet been fully designed nor installed onsite. Further details will be available for discussion when the paper is presented at the 2020 WGC.

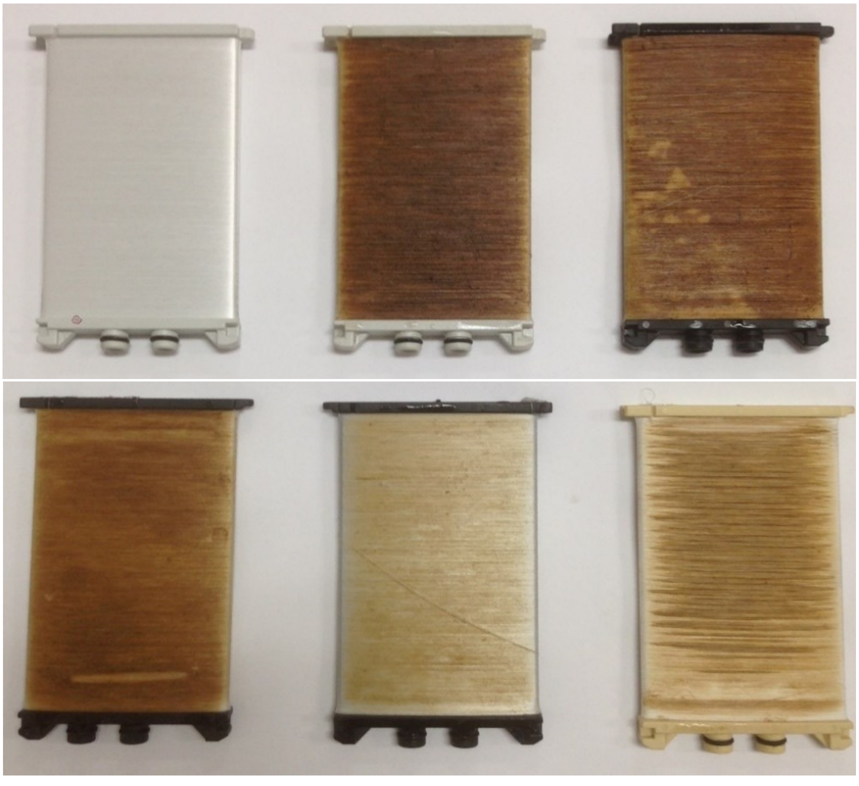

Figure 9: Testing undertaken by the filter contractor (Amiad Water Systems) using microfiber filter cassettes confirmed a minimum of 5-micron filtration and optimal of 1-micron filtration was desired (from top left to bottom right, New, 20-micron, 10-micron, 7-micron, 3-micron and 2-micron)

4.2 New bores

Two new replacement bores were constructed by mid-2019 using a 50t WEI rig (Figure 10).

While the drilling program was not without its challenges, a number of improvements from historical drilling in the area were achieved. This included better inhibition of the reactive marl, screening of the majority of clean sandstone beds within the aquifer using pre-packed screens and use of flushed threaded stainless steel casing as an alternative to fiberglass material.

Key bore design changes are summarised below:

1) Materials
   - Stainless steel bore construction (using 316 stainless flush coarse thread casing from Sharpe Engineering) as opposed to fibreglass to reduce the likelihood of damage during workovers
   - Inclusion of a DN250 pump chamber to allow an Electrical Submersible Pump (ESP) to be installed in the bore and allow bore backflush of the bore via an ASR valve from AGE Developments
   - Use of a DN200 intermediate casing instead of DN150 to minimise friction losses and maximise injectivity
   - Use of Johnson pre-pack screens (900 to 1,100 microns' pre-pack silica beads) with 700 microns' slot screens to capture the entire aquifer interval

2) Drilling fluids
   - Use of fresh drilling fluids for drilling the aquifer interval (low solids, no bentonite)
   - Use of a tailored chemical soaking development program to break down residual polymer in the formation and pre-pack screens

3) Drilling engineering
   - Rather than drilling a pilot hole across varying lithologies (calcarenite, marl and sandstone), new bores be drilled and cased in sections (superficial, intermediate and aquifer) allowing fit for purpose drilling fluids and bottom hole assemblies (BHA)
   - Directional drilling of the intermediate section with a motor to allow spreading injection over a larger area of the aquifer

The new bores (Injection Bore #2 and #3) were sited near the existing injection bore (injection Bore #1) about 60 and 120 m away respectively (Figure 2) but were drilled using directional drilling techniques to maximise the spread of the heat-depleted bubble in the aquifer and the distance to the production bores. The latter resulted in a horizontal distance between the new injection bores and the production bores of more than 500 m and no thermal breakthrough after 20 years of continuous operation (Figure 11). The vertical separation at the aquifer level between all PHS bores is negligible.

Figure 10: Aerial photo of drilling of Injection Bore #3 during geophysical logging of the aquifer section

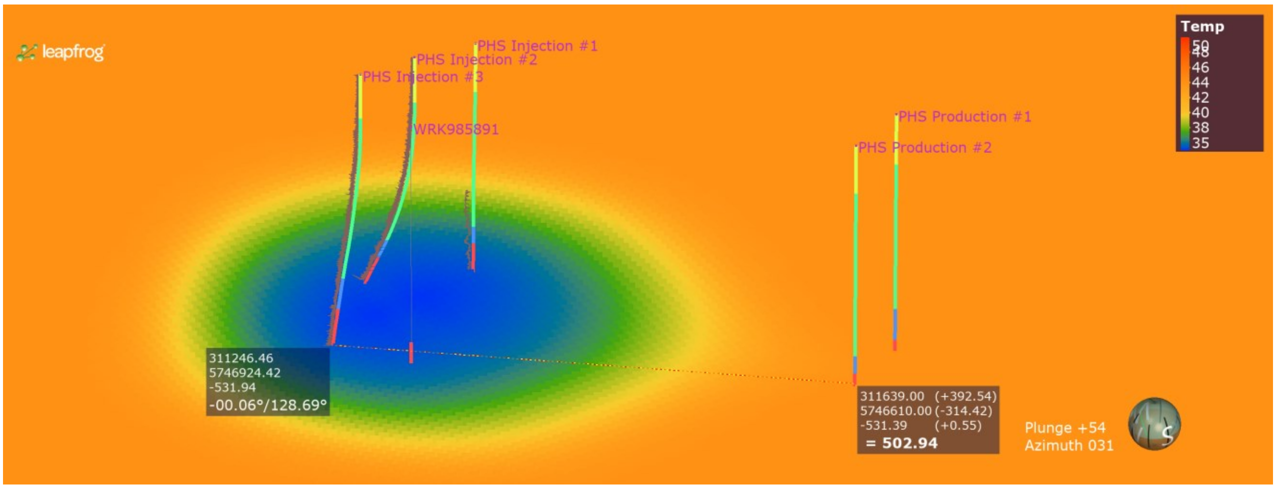

Figure 11: Bores drilled at Peninsula Hot Springs with modelled heat-depleted plume in Werribee aquifer after 20 years

At the time of writing this paper, the new bores had been commissionned and a 6-month injection test had just been completed with a temporary pipeline and temporary filter but without UV treatment, without complete TOC removal and without continuous sodium hypochlorite dosing as was undertaken in the past (Figure 6 and 7). The injectivity index was managed by initiating a 30 min bore backflush using the downhole ASR valve and pump whenever the injectivity approached 10 m^3/h / bar. A total of eight bore backflush events were required over the 6-month injection test. The first four backflush relied solely on the mechanical cleaning action while the remainder (and most efficient) backflushes were preceded by chlorine soaking to deactivate bacteria and break biofilm ahead of the mechanical backflush. Residual chlorine was removed from the aquifer and bore by backflush. The 6-month injection test results indicated that Injection Bore #2 was capable of injecting more than 50 m^3/h at no more than 4-5 bar over-pressure and 72-100 m^3/h at less than 10 bar over-pressure (ie an injectivity index of about 10 to more than 50 m^3/h / bar; Figure 11) which is a significant improvement from historical injection performances (i.e. injectivity index of 2 to 16 m^3/h / bar; see Figures 6 and 7).

The permanent filter system is scheduled to become available in mid-2020. In the meantime, injection will continue with the temporary filter system. In the absence of complete TOC removal, UV treatment or continuous chlorination dosing, and despite the good overall injectivity performances of Injection Bore #2, some clogging may still occur with the temporary filter system. Further details will be available for discussion when the paper is presented at the 2020 WGC. In particular, long-term performances of the temporary and final filtration systems, dosing prior to bore backflush and the optimal frequency and duration of bore backflush to manage clogging and maximise the injection efficiency of the borefield will be discussed.

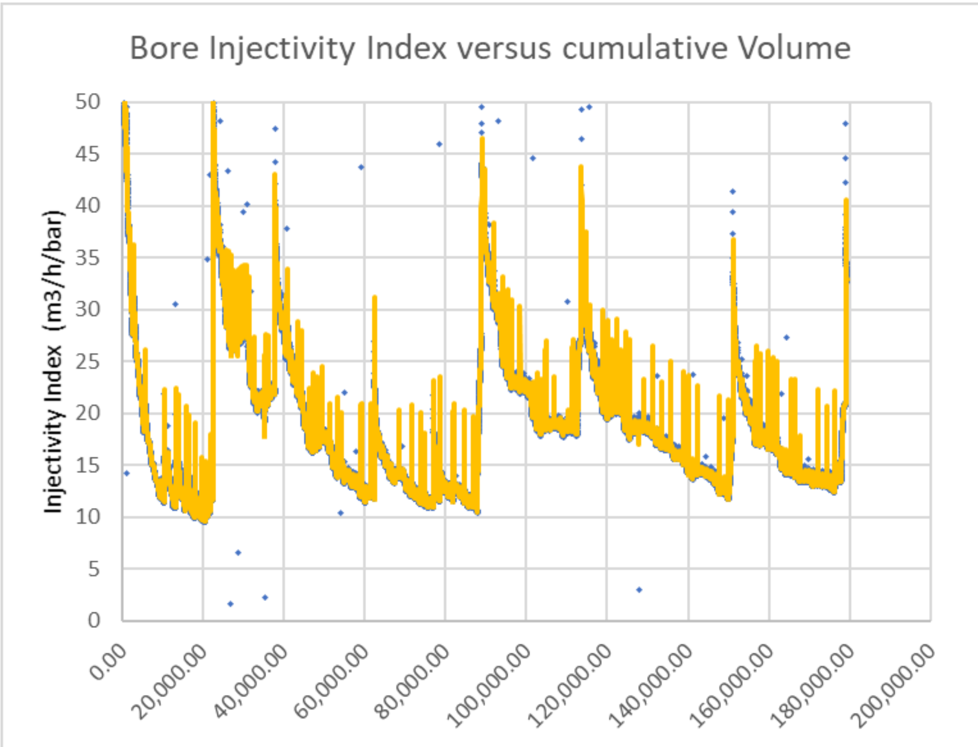

Figure 12: 6-month injection test of Injection Bore #2 with a temporary pipeline, filter and downhole ASR injection valve.

5. CONCLUSION

This paper summarises a comprehensive review of PHS injection scheme undertaken by the authors in 2018 and describes design changes that have been implemented since, to improve injection efficiency.

At the time of writing this paper, a 6-month injection test of one of the two new deviated injection bores (Injection Bore #2) had just been completed using a temporary pipeline and filtration plant and indicated higher injectivity than previously achieved was available from the bore. The new filter plant is scheduled to be commissioned in mid-2020. Data from the performance testing of the plant will be presented at the 2020 WGC and actual performances of the new PHS injection scheme will be compared to historical performances.

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