2 February 2021

Katherine Tutt
Senior Delegated Officer
Mid West Gascoyne Region
20 Gregory Street
Geraldton WA 6530

By email: dwer@wa.gov.au

Dear Katherine

Re: Additional information required under the Rights in Water and Irrigation Act 1914.

I refer to your letter to Natalie Pethick (Pennington Scott) received on 2 December, 2020 requesting additional information on an H2 Hydrogeological Report that Pennington Scott submitted to your office on 11 November 2020, being the Lighthouse Caravan Park Redevelopment, Revision 1 on behalf of Z1Z Resorts. In your letter, you indicate that your Department has undertaken a review of the report and request that we reissue a Revision 2 of the Report, which considers the following additional points:

1. Marine wedge position and movement;
2. Piston effects within limestone cavities and voids in connection to the marine environment;
3. Marine aerosol salt deposition
4. Restricted recharge / minor catchments along the ridgeline;
5. Groundwater salt concentration stratification within the aquifer system with increased salt content with depth;
6. Potential impacts and management of the Cape Range Subterranean Waterways; and
7. Potential impacts on the Shire of Exmouth production bore located at MGA 1994 coordinate 200916 mE and 758584 mN Zone 50.

Pennington Scott will soon submit a revised copy of the report to your Department, marked as Pennington Scott (2021) H2 Hydrogeological Report for the Lighthouse Holiday Park Redevelopment Revision 2, which I shall refer to hereinafter simply as the **Report**.

The purpose of this letter is to draw your attention to how we have considered each of the points you raised in your letter of 2 December, and how and where these have been addressed in the Report.

Yours sincerely

Don Scott
Managing Director
Pennington Scott

1 Consideration of the marine wedge position and movement

The shape and position of marine wedge is referred to hereinafter as the **salt water interface** and its position can be approximated using various types of analytical or numerical solutions that can be broadly classified into either:

- **Sharp interface models**; which consider the salt water interface to be discrete material surface that separates fresh and saline water; or
- **Transitional interface model**; that use of dispersion models to simulate the salt water interface as transitional or mixing zone between totally saline and totally fresh or brackish groundwater.

Field observations of the salinity profile measured in the pilot holes at Lighthouse with depth are presented in **Figure 2-5** of the Report. Reference to this figure shows that the salt water interface on the Property is clearly a stratified transitional mixing zone; not a sharp interface. Indeed, there is no freshwater lense as such that was intersected in the borefield. The water quality about the water table is at best brackish to saline (3,000 to 14,000 mg/L), and becomes increasing more saline to the maximum drilling depth of about 20 m below the water table, where the salinity reaches up to 24,000 mg/L. None of the pilot holes was drilled deep enough to intersect the salt water interface, with sea water being measured at 33,200 mg/L.

Simulation of the transitional salt water interface with variable density numerical modelling is beyond the scope of an H2 Report; instead, the following analysis approximates the position of the salt water interface using analytical solution for a simplified "sharp" interface and the movement of the interface under pumping stress.

Analysis of the salt water interface position - Ghyben Herzberg

In the Lighthouse Borefield, the sea water interface was not actually intersected an any of the pilot holes, which were drilled to 20m below the water table. Nonetheless, the depth to the sea water interface in coastal areas can be approximated using the simplified Ghyben Herzberg approach, which is a steady-state analytical expression that gives the hydrostatic equilibrium between discretely fresh and brine waters. The approach is based on the "ice berg" principle insofar as fresh water, being lighter than sea water, floats as a freshwater lense on sea water relative sea level (0 mAHD). Thus, it is possible to calculate the depth of the salt water interface below sea level provided you know the relative densities of fresh water and sea water, plus the height of the water table above sea level.

For example, assuming fresh water (at say 1000 mg/L) over sea water (at say 40,000 mg/L), the sea water interface would be 1:40. This means if the water table at any location were 1 m above sea level; sea water interface should be 40 m below sea level.

There is limitation with the Ghyben Herzberg approach insofar as it is purely groundwater-level based; it assumes that the salt water interface intersects the sea exactly on the coastline without any allowance of seepage face for discharge of the fresh water into the ocean.

Ghyben Herzberg approach has been developed and improved over the years, with converging into two popular and well tested solutions that can now be used to predict the shape of the salt water interface in a coastal aquifer (Glover, 1964) and the upcoming of the salt water interface due to pumping (Bear and Dagan, 1968). A detailed description of the above analytical formulae can also be found, among others, in (Bouwer, 1978).

Analysis of the salt water interface position – Glover (1964)

The conceptual model of Glover's 1964 solution for the estimation of the position (*z*) of the salt water interface at various distances (x) from the coast, in an unconfined aquifer is shown in Figure 1. It is based on the average hydraulic conductivity (K) and the horizontal flow rate (q) in the aquifer that discharges onto the ocean over a seepage face of width W.

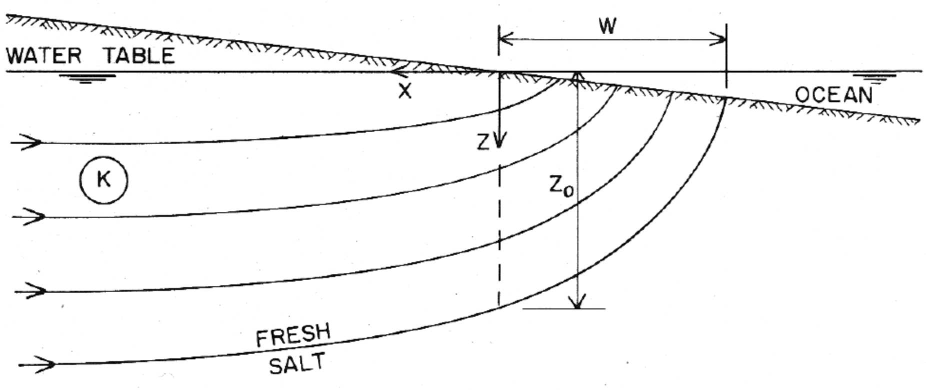

Figure 1. Conceptual model of the calculation of the position of the salt water interface in unconfined coastal aquifers based on Glover's, 1964 solution.

$$z^2 = \frac{2qx}{(\rho_s - \rho_f)K} + \frac{q^2}{(\rho_s - \rho_f)^2 K^2}$$ Equation 1

$$W = \frac{q}{2(\rho_s - \rho_f)K}$$ Equation 2

Where,

z	=	*the depth of the salt water interface (m.bsl).*
x	=	*the horizontal distance from the sea*
ρ_s, ρ_f	=	*the densities of the salt and fresh water*
K	=	*the average hydraulic conductivity,*
q	=	*the average horizontal flow rate per unit width of the aquifer, and*
W	=	*the width of seepage face onto the ocean*

Analysis of salt water up-coning due to bore abstraction – Bear and Dagan (1968)

Bear and Dagan (1968) developed an analytical solution that calculates the vertical change with time (transient state) of the position of the salt water interface under a pumping well in unconfined coastal aquifers, a process referred to as upconing. Their solution is shown in equations 3 and 4 below.

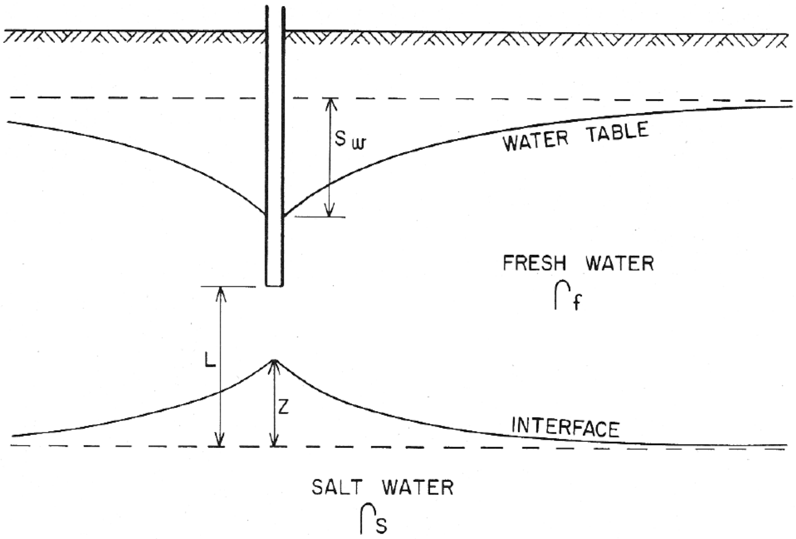

Figure 3. Conceptual model of the calculation of the movement of the salt water interface position over time based on Bear & Dagan's 1968 solution.

Equation 3 describes the change of the vertical location (z_t) of the salt water interface (upconing) with time under a pumping well, at specific values of aquifer hydraulic properties (K_x, K_y, n) and well flow discharge. **Equation 4** gives the ultimate (maximum) or equilibrium height (z_∞) of the salt water interface cone below the well center.

$$z_t = \frac{\rho_f Q}{2\pi(\rho_s - \rho_f)K_x L}\left(1 - \frac{2\rho_f n L}{2\rho_f n L + (\rho_s - \rho_f)K_z t}\right) \qquad \text{Equation 3}$$

$$z_\infty = \frac{\rho_f Q}{2\pi(\rho_s - \rho_f)K_x L} \qquad \text{Equation 4}$$

Where,

z	=	*rise of cone center at time t*
Q	=	*well discharge rate.*
L	=	*depth of the interface (salt water interface) below well bottom prior to pumping*
ρ_s, ρ_f	=	*densities of the salt and fresh water*
K_x, K_z	=	*hydraulic conductivity in the horizontal and vertical direction,*
n	=	*(effective) porosity of the aquifer, and*
t	=	*time since start of pumping*

Values of "z" calculated with the above equations agree with field measurement up to some critical cone height, which generally was 0.4 L and 0.6 L (Schmorak and Mercado, 1969, Haubold, 1975). Where the salt water interface is underlain by saltwater this equation is recommended (Bouwer, 1978) for determining the depths and pumping rates of wells (including "skimming" wells) that prevent entry of saline water into the well.

Analysis of salt water interface position at Lighthouse

The position and characteristics of the salt water interface are now in the Report in **Figure 2-3** through **Figure 2-5**. The Lighthouse borefield has some mitigating borefield design characteristics:

- there is no freshwater lense, as such, within the borefield; the better quality water is brackish to saline, ranging in salinity from 3,000 to 14,000 mg/L TDS (5 to 24 mS/cm);
- pilot hole drilling has shown the sea water interface is a broad transitional mixing zone rather than a discrete sharp boundary;
- the production water bores have been designed for groundwater sipping, and as such are only screened over the first 3 m below the water table; and
- the sea water interface was not intersected an any of the deep pilot holes, and is therefore known to be a least 15 m below base of any of the production bore screens.

  Notwithstanding these limitations, the sensitivity of the depth to sea water interface verses aquifer permeability (hydraulic conductivity) are analysed using the Glover (1964) approach with the following parameters and assumptions:

- horizontal flow rate (*q*) per unit width of the aquifer can be calculated as the equivalent recharge rate over an aquifer profile aligning with a flowline, of total length of about 4,500 m (i.e., the North-South distance through the Lighthouse borefield to the coast, coinciding with the approximate position of the groundwater divide on the Cape Range Peninsula);
- The average rainfall recharge rate in the Cape is about 10% of the total annual rainfall or 25 mm /year (6.8 x 10^{-5} m/day) which over the profile length of 4,500m gives a total flux q = 0.31 m^3/day per m width; and
- The density of the brackish water lense (ρ_f) and salt water (ρ_s) is 1.003 kg/L and 1.033 kg/L respectively.

Based on the hydraulic properties displayed in **Table 5-2,** three scenarios of aquifer hydraulic conductivities were tested, the mean value of 54 m/day, the minimum of 12 m/day and the maximum of 97 m/day. Calculated results are shown in **Figure 2** and **Table 1**

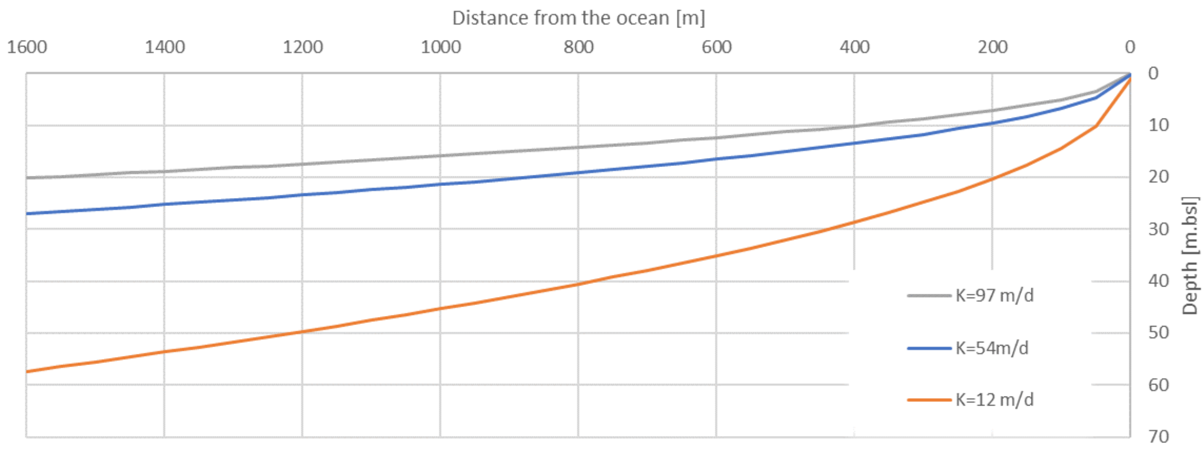

Figure 2. Calculated profiles of the salt water interface at different scenarios of hydraulic conductivities relative to sea level 0 mAHD

Table 1 Calculated profiles of the salt water interface at different hydraulic conductivities (K)

Distance from Coast [m]	**Calculated depth of the salt water interface [m.bsl]**		
	K=12 m/d	K=54m/d	K=97 m/d
0	1.03	0.23	0.13
50	10.19	4.78	3.57
100	14.37	6.76	5.04
150	17.59	8.28	6.18
200	20.30	9.56	7.13
250	22.69	10.69	7.97
300	24.85	11.71	8.73
350	26.84	12.64	9.43
400	28.69	13.52	10.08
450	30.43	14.34	10.70
500	32.07	15.11	11.27
550	33.63	15.85	11.82
600	35.13	16.55	12.35
650	36.56	17.23	12.85
700	37.94	17.88	13.34
750	39.27	18.51	13.81
800	40.56	19.11	14.26
850	41.80	19.70	14.70
900	43.02	20.27	15.13
950	44.19	20.83	15.54
1000	45.34	21.37	15.94
1050	46.46	21.90	16.34
1100	47.55	22.41	16.72
1150	48.62	22.92	17.10
1200	49.67	23.41	17.47
1250	50.69	23.89	17.83
1300	51.69	24.37	18.18
1350	52.68	24.83	18.53
1400	53.64	25.28	18.87
1450	54.59	25.73	19.20
1500	55.53	26.17	19.53
1550	56.44	26.60	19.85
1600	57.35	27.03	20.17

The above range of the estimated depths of salt water interface, especially the medium and high K scenarios, are in good agreement with salinity profiles generated from filed data shown in **Figure 2-3** through **Figure 2-5** in the Report. A deeper profile would be anticipated at low K zones as displayed in the N-S profile in **Figure 2-3**. For the purposes of this study the most likely results match with high K values of 97 m/day that yield, conservatively estimating the depth of the salt water interface to be about 20 m below sea level.

Analysis of salt water upconing risk at Lighthouse

Calculation of the vertical change of the location (z) of the salt water interface under a pumping well at different values of aquifer hydraulic conductivities for the study are presented in **Figure 4**, whereas the final maximum values are listed in **Table 1**.

The risk of up-coning the salt water interface has been calculated using Bear & Dagan (1968) approach based on the following parameters and assumptions:

- the hydraulic conductivity of the Tulki Limestone was calculated to be 100 m/day;
- the limestone has a vertical anisotropy ratio of 1 in 10;
- the effective porosity of the Tulki Limestone is 10%;
- the salt water interface is at least 10 metres below the base of the production bore screens (this is conservative considering that the pilot hole drilling results show that the salt water interface is at least 15 m below the base of the bores); and
- all production bores would be continuously pumped at 0.5 L/sec through the tourist season.

Figure 4. Calculation of the vertical change of the location of the salt water interface under a pumping well at different values of aquifer hydraulic conductivities (equation 3).

Table 1. Ultimate (maximum) equilibrium height (z_∞) of the salt water interface cone below the well centre at different values of aquifer hydraulic conductivities (equation 4)

Hydraulic Conductivity	K_x=12 m/d	K_x=54 m/d	K_x=97 m/d
Maximum upconing (z) height [m]	2.29	0.51	0.28

The results of the Bear & Dagan (1968) analysis suggest that the maximum salt water interface up-coning beneath the Lighthouse bores would be 2.3 m, giving an upconing ratio z/L is 0.23. This value is well below the threshold that Bouwer (1978) and Schmorak and Mercado, 1969 consider a threat for up-coning to occur. In other words, there is no risk that the abstraction from the Lighthouse bores would cause up-coning the salt water interface into the bores because the salt water interface is more than 10 m below the base of the wells and the bores are only screened to a maximum of 3 m below the water table.

The position of the salt water interface is considered in **Section 2.4.4** of the Report, while the risk of up-coning the salt water interface in the borefield is considered in **Section 7.4** of the Report.

2 Consideration of piston effects within limestone cavities and voids in connection to the marine environment

The host formation of the hydrogeological environment is the Tulki Limestone. **Section 2.3** of the Report describes the Tulki as a calcarenite, which is a granular type of limestone composed predominantly of detrital (transported) sand-size, carbonate grains. The aquifer permeability in the Tulki may be derived from a combination of primary granular permeability/porosity over the more fossiliferous clay free units and through karstic (dissolution) cavities.

The presence of karstic or more permeable granular limestone was reported by loss of circulation of drilling mud reported in Melanie 1 from 73 m (Lane, 1998). Drilling of the Lighthouse borefield production bores did not experience loss of circulation, suggesting that they had not reached the karstic or high permeability features, which would be expected to a maximum depth of 51 m. The main water bearing zone in the Lighthouse bores was loose to moderately cemented medium to coarse sand; not karsts.

Based on the above aquifer characteristics there is no evidence to suggest the occurrence of discrete fractures or other similar features (e.g., fault zones) that could provide favourable zones of preferential flow or piston flow effects. Hence, for the needs of this study, regardless of the occurrence of unknow local fractures and solution channels, the whole hydrogeological environment is treated as an "equivalent porous medium" with average hydraulic properties.

The Report has not been updated to discuss piston flow mechanisms because there is no evidence that piston flow is a relevant flow mechanism within the non-karstic granular Tulki Limestone aquifer encountered in the Lighthouse Borefield.

3 Consideration of marine aerosol salt deposition

Hingston and Gailitis (1976) have studied the transport and distribution of atmospheric marine salt deposition in rainfall across Western Australia. While accepting that that marine salt is transported in sea spray, particularly during heavy seas, and distributed over the land surface, there are no published data or reports to quantify the proportion of “dryfall” marine aerosol salt deposition on the Exmouth Peninsula. However, Hingston and Gailitis (1976) found that the average dryfall salt accumulation (i.e. rainfall and sea spray) across the Port Hedland, Onslow and Carnarvon during 1973 was 92 kg/ha.

Section 2.4.4 of the Report has been updated to discuss relevant observed groundwater salinities and profiles in the lighthouse borefield area.

Section 2.1 of the Report has been updated to specifically discuss dryfall salt deposition.

4 Consideration of restricted recharge / minor catchments along the ridgeline

Rainfall recharge to the aquifer must percolate downward through 40 m of unsaturated and heterogeneous Tulki Limestone before it reaches the watertable. There are no surface hydrology features (i.e., rivers, creeks) of significance on the Property that would have a greater impact on the mixing and distribution of recharge to the aquifer, or the position of the position of the sea water interface.

Since the development of the Project would have no impact on recharge surface catchments, the Report does specifically include consideration of minor catchment recharge mechanisms.

5 Consideration of groundwater salt concentration stratification within the aquifer system with increased salt content with depth

Section 2.4.4 of the Report is dedicated to groundwater salinity. **Figures 2-3** through **Figure 2-5** have been added to the Report to address this consideration.

6 Consideration of potential impacts and management of the Cape Range Subterranean Waterways

Bennelongia has been engaged specifically to address subterranean fauna issues with the borefield. Bennelongia undertook a desktop review on the Project in December 2020 and a subterranean fauna survey of bores on the Property in January 2021.

In particular, Bennelongia have considered the Project in the context of the Cape Range Subterranean Water ways.

A copy of the Bennelongia Report is included as **Appendix B** of the Report and is discussed in **Section 7** of the Report.

7 Consideration of potential impacts on the Shire of Exmouth production bore located at MGA 1994 coordinate 200916 mE and 758584 mN Zone 50

The shire of Exmouth production water bore is located well outside the radius of influence from the Proponent's borefield. Furthermore, the Shire Bore is within a few hundred metres of the coast and would be heavily influenced by the sea level and salinity.

The Project borefield could have no potential impact on the Shire of Exmouth production bore.

This is included in **Section 7.2** of the Report.

8 References

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