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Memo

To	Neil Dixon	**Company**	Mardie Minerals Pty Ltd
From	Bruce Harvey & Duncan Storey	**Job No.**	293C
Date	4/11/2020	**Doc No.**	009b
Subject	Mardie Project – Desktop Groundwater Risk Assessment		

1. INTRODUCTION

BCI Minerals' Mardie Project is located on the Pilbara coastline of Western Australia, approximately 100km south-west of Karratha (Figure 1). The project includes the construction of extensive concentration ponds and crystallisers for the extraction of salt products from sea water.

The environmental impact assessment for the Mardie Project has identified that the understanding of the risks posed to vegetation, local groundwater and pools as a result of saline seepage from the Project's proposed concentration and crystallisation ponds should be improved. This is of particular importance due to the proximity of the culturally and environmentally significant permanent waterhole known colloquially as Mardie Pool (Figure 1) to the secondary crystallisation ponds, which will be lined with in-situ compacted clay.

The purpose of this memo report is to:

- Review and consolidate existing information and advise BCI on the significance of any knowledge gaps, critical assumptions, and inadequately described risks to the surrounding environment associated with pond seepage; and
- For priority risks, recommend the approach/es to addressing knowledge gaps and developing an adequate level of understanding, including extents and timing, of potential impacts, so that an Action Plan can be generated.

Following issue of version A of this report, scope was clarified and expanded to include investigation of risk to coastal vegetation (primarily mangrove habitat) due to possible seepage of hypersaline water from Evaporation Ponds 1-9 and Primary Crystallisers into the near-coast groundwater system.

Current project construction diagrams, relevant spatial data and reports have been provided to AQ2 by BCI, along with environmental review documentation and regulator responses to the approvals application.

2. DATA REVIEW

Documents and data relevant to the environmental assessment of the Mardie Project were reviewed as background to this desktop groundwater risk assessment, to summarise key information and findings relevant to groundwater receptors and saline seepage from crystallisation ponds. This summary is provided in Table 1.

Table 1: Data Review

Document	Key Findings
WA Dept of Water and Environmental Regulation (DWER) – Submission to Environmental Review Document (ERD)	DWER espouses the necessity for a groundwater management plan – "Categorisation of the groundwater risk as minor may not be appropriate given potential concerns around receptors such as Mardie Pool. A groundwater management plan would summarise all the commitments the proponent makes regarding groundwater, including the proposed monitoring frequency and locations, and management actions to deal with issues arising."
Australian Government – Dept of Agriculture, Water and the Environment (DAWE) – Submission to ERD	Specifications/suggestions provided for construction of groundwater monitoring bores and appropriate monitoring regime.
DFS Factual Geotechnical Report (CMW Geosciences 2020)	Soil permeability was measured via insitu falling head tests and laboratory tests on reconstituted samples. All tests measured permeability on a relatively small scale local to the bore and hence may not represent bulk soil permeability.
Seepage Model Results and Potential Environmental Impacts (Soilwater Group 2019)	Seepage modelling is based on the original Eastern Crystallisers location 250m north of Mardie Pool (since moved to 1000m east). Modelling indicates that downward seepage rate of hypersaline water could vary from 1m/2years to reaching the calcarenite aquifer in 6 months, depending on estimated permeability and seepage rate. Suggested that monitoring bores be installed and seepage capture bores may be required if seepage is detected.
Detailed flora and vegetation survey for the Mardie Project – Phoenix Environmental Services	34 significant flora species which may potentially occur within the study area: • One Threatened Flora species • 33 State-listed Priority Flora Recognised groundwater dependent species identified as associated with Mardie Pool.
Groundwater enhances above-ground growth in mangroves (Hayes et al. 2018)	Mangroves use non-saline groundwater and rainwater when available rather than saline water sources. Groundwater flows into the intertidal stimulates organic matter accumulation in above-ground biomass suggesting the availability of non-saline water sources, such as groundwater and rainfall, are important for the growth and productivity of mangrove forests.
Yannarie Solar Salt– Report and recommendations of the EPA – 2008	EPA concluded that the proposed solar salt farm is located in an area that presents unacceptably high risks of environmental harm to wetland values and unacceptable levels of uncertainty in relation to long term management of bitterns.

3. CONCEPTUAL ECOHYDROLOGICAL SYSTEM

3.1 Geology and Geomorphology

The geological model is based on published regional geological and hydrogeological reports, supplemented by recent geotechnical investigations carried out to support the Mardie Project. Soilwater Group (2019) and CMW (2020) provide differing conceptual geology models.

3.1.1 Geological Model – Soilwater Group

The geological model proposed by Soilwater Group (2019) postulates that the project area is generally underlain by a moderately to highly calcreted shelly calcarenite layer (Figure 2). According to this model, on the eastern side of the Supratidal Flats the calcarenite is unconformably overlain by Pleistocene to Holocene aeolian, alluvial and colluvial sediments forming the current surface of the Onslow Land System. The calcarenite layer dips westerly under the Supratidal Flats (corresponding to the Littoral Land System), creating an undulating surface onto which the mudflats were deposited. In areas where the calcarenite layer outcrops the mudflat surface, or where significant secondary agglomeration of calcirudite and / or calcisiltite occurs, it anchors a thin veneer of dunal sand.

The Supratidal Flats that occur extensively across the area on top of the calcarenite layer have formed by prolonged deposition of terrestrial and marine sediments. Several large creek systems, including Peter Creek (catchment area 422km^2), Gerald Creek (catchment area 153km^2), Trevarton Creek (catchment area 172km^2) and 6 Mile Creek (catchment area 164km^2), discharge directly into the Supratidal Flats. Depending on the rainfall intensity within the various creek catchments, and the distance from the discharge point, the sediments making-up the Supratidal Flats vary from heavy clays to sands to gravels, with each deposition event interfingering with the last deposition event.

In this model the secondary crystallisation ponds are located east of the supratidal flats where the calcarenite is overlain by 3 – 6m of aeolian sand (the Cane River Zone Regional Land System). Mardie pool occurs in a creek channel, incised through the aeolian sand with the invert level reaching the underlying calcarenite.

3.1.2 Geological Model – CMW Geosciences

The geological model developed by CMW Geosciences is based on recent geotechnical investigations including a large number of shallow test pits and CPT sites, combined with a small number of widely spaced deeper boreholes. The model proposes a series of six generic sub-horizontal layers, most of which are sub-divided due to varying composition or geotechnical properties. Not all units are present across the entire site. In order of depth these layers are:

Unit 1- Surficial clayey sandy gravel
Unit 2a – Sand and gravel with fines
Unit 2b – Sand with shells and gravel, medium dense to dense
Unit 3a – Clay/gravelly clay, very soft to soft
Unit 3b – Clay/ sandy clay, firm to stiff
Unit 4a – Clayey gravel/ gravelly clay, dense, cemented in places
Unit 4b – Coral with sandy clay
Unit 5 – Very low to medium strength rock with pockets of stiff soil
Unit 6a – Calcareous conglomerate/ impure calcilutite, low to high strength
Unit 6b – Impure calcilutite, high to very high strength

Interpreted distribution of these geological units across the site is described by cross sections in CMW(2020). Figure 3 provides a representative geological cross section beneath evaporation ponds (after CMW 2020). The section indicates clayey gravel/gravelly clay (Unit 4) extending to approximately 6m below ground level. Inland, sandy clay is evident at surface.

3.1.3 Geological Models – Comparison

Near the Eastern Crystalliser ponds and Mardie Pool, CMW(2020) proposes the existence of 0.5 to 1.5m of clayey sand (Units 2+3b) over clayey gravel/ gravelly clay (Unit 4). Unit 4 appears to correlate with Soilwater Group's "Calcarenite" layer (Figure 2) which is depicted to extend to basement. Generally, the two models can be considered equivalent near Mardie Pool in that there are no significant differences which may have implications for groundwater flow.

Soilwater Group (2019) proposes the calcarenite unit dipping below the sediments of the supratidal flats to the west, with interfingered alluvial layers overlying. CMW proposes that Units 4a and 5 are continuous and sub-horizontal beneath the evaporation ponds and further to the west. The CMW model is the favoured option for analysis of groundwater flow from beneath evaporation ponds towards the tidal creeks and this has not been used in the Soil Water Group modelling to date.

3.2 Hydrogeology

Features of the hydrogeological system at Mardie are described in detail in the following sections.

3.2.1 Groundwater Quality and Distribution

The quality of groundwater at Mardie is summarised below through several sources. Preston Consulting (2020) states:

- Groundwater within the Supratidal Flats is generally of neutral pH, whilst the groundwater in the calcarenite aquifer is more alkaline, likely reflecting the presence of the calcarenite. The majority of the alkalinity is in the form of Bicarbonate, with minor Carbonate alkalinity;
- Groundwater within the Supratidal Flats is hypersaline, with 2 – 5 times higher salinity than seawater; likely due to its low permeability and resulting evaporative concentration of salts. The groundwater in the calcarenite aquifer is brackish to saline with better quality being associated with the Mardie-pool creek line (likely to result from recharge);
- All groundwater is generally classified as NaCl type, although groundwater in the Supratidal Flats may also be considered $CaSO_4$ type, likely reflecting the formation of gypsum;
- All groundwater in the development envelopes has low to very low nutrient levels; and
- All groundwater in the development envelopes has low levels of measured metals, although some bores contain elevated Zn and minor Cd and Cu.

A landholder bore census was completed by AQ2 in November 2019 including bores relatively close to the crystallisers and Mardie Pool. Results are provided in Table 2 below. Flynn's Well and Gatecrasher Bore (those nearest to Mardie Pool) contained water which was brackish and slightly alkaline. Water in bores at the southern end of the project area and closer to the coast (Salt Bore, Surprise Well) was more saline, however still rated as brackish. New water supply bores drilled approximately 3km to the south of Mardie Pool during 2019 yielded 1-2L/s, indicating some permeability in the shallow aquifer.

Table 2: Results of Bore Census, November 2019 (AQ2 2019)

Site Name	EC (uS/cm)	pH	Approx. SWL (mbgl)	Comments
Flynn's Well	5800	8.0	8.9	EC/pH at trough.
Gatecrasher Bore	7700	8.5	-	EC/pH at trough. SWL not accessible.
Bore Near 3A Name unknown	2000	8.4	-	EC/pH from inlet. Trough higher due to evaporation? Inland within Fortescue fan.
Surprise Well	9000	8.3	-	Water into trough.
Salt Bore	10400	8.6	5.83	Water into trough.

Water quality data was acquired by BCI Minerals in April 2019 from a large number of test pits and CPT holes covering the extent of the evaporation ponds on the supratidal flats, as well as inland station bores. EC measured in station bores was similar to values presented in Table 2. Test pit sites near to tidal creeks on the western side of the proposed evaporation ponds produced groundwater in the range 50,000-80,000uS/cm. This is generally slightly higher than EC for sea water and may represent the combination of evapotranspirative concentration and some flushing.

Salinity was much higher at test pits further inland on the broad supratidal flats within the bounds of the proposed evaporation ponds. EC here was generally 3-4 times that of sea water (up to 210,000 uS/cm) presumably due to evapo-concentration of stranded sea water and the absence of regular flushing. These areas are inundated only by peak spring tides, storm surges from ocean side and by flooding during cyclonic events.

It is noted that no deep bores were available for sampling near the western side of the development envelope. Consequently, no data exists to confirm vertical salinity variations.

3.2.2 Sea Water Interface

Previous investigations at Mardie have indicated that the sea water interface (SWI) is well inland of the coast. Haig (2009) proposes, from bore water sampling, that the SWI is present east of Mardie Pool in the vicinity of the Secondary Crystalliser. Airborne EM data (Fugro 2010, AQ2 2019) indicates higher conductivity at depths greater than 10mbgl to the east of Pond 5 which coincide with the boundary of Haig (2009). It is possible that the SWI is present below and east of the evaporation ponds, however a bore installed in 2019 east of Flynn's bore to 40m depth has provided water at salinity levels suitable for camp supply.

3.2.3 Surface Water Features

Mardie Pool is noted to be the only permanent waterhole within the Mardie Project development envelope. Located 3km west of Mardie Homestead, it is seasonally 300-500m long and 1-20m wide. In the south of the development envelope, Peter Creek contains water after significant rainfall events. Surface water was sampled from these locations in February 2020. Water at Mardie Pool was found to be fresh, with EC of 370-960µS/cm. Water at Peter Creek was hypersaline, with EC of 130 000µS/cm.

3.2.4 Groundwater Levels and Flow

Groundwater level information for the site was gathered from the following sources:

- Geotechnical testing program (CMW, 2020) – shallow piezometers and test pits constructed in 2019.
- Bore Census (AQ2 2019) – landholder bores visited during water supply drilling in November 2019.
- BCI Minerals – monitoring rounds of landholder bores (latest available - April 2019).

CMW(2020) states that "… in some instances separate inflows of groundwater were noted within a single test pit" and that "the perched water is travelling through more permeable isolated horizons/lenses within the soil." AQ2 postulates that the groundwater is in fact not perched, but that the first strike of water (as reported by CMW) provides a good indication of the depth of the water table (full saturation) within strata of variable permeability. It is possible in those cases that the actual SWL was shallower, but only presented as visible flow in lenses of higher permeability.

Although taken at a range of dates, these combined water level datasets present a generalised view of water depth across the project area. Elevation data supplied by BCI Minerals was used to generate relative water level and flow gradients. Figure 4 displays simplified groundwater level contours and flow direction for the area surrounding Mardie Pool. Figure 5 provides estimated groundwater level across the entire site.

Figure 5 indicates that groundwater flow is generally towards and perpendicular to the coastline. Flow gradient is relatively steep beneath the elevated land to the west of the project. The gradient reduces significantly on the flats beneath the proposed evaporation ponds to approximately 2m in 8km, or 0.00025. Groundwater flow passing beneath evaporation ponds

Figure 6 indicates that groundwater flow from beneath the footprint of the secondary crystalliser is likely to intercept Mardie Pool, and that this groundwater may be sourced from below the closest corner of the secondary crystalliser pond (a distance of approximately 1000m).

Localised groundwater flow directions are determined by the nearby water levels, and gradients presented here are based on regional water levels. If high rates of seepage caused water mounding to occur beneath the secondary crystalliser, groundwater flow directions in the area would change. In that event direction of flow will likely become more southerly, with hypersaline water being directed towards Mardie Creek upstream of Mardie Pool. Similarly, mounding beneath the KTMS crystalliser pond has the potential to redirect flow northerly towards Mardie Pool.

Surface water in Mardie Pool is less saline than groundwater in the regional bores. It is likely that a freshwater lens exists within the pool and the adjacent unconfined aquifer, forming a zone of fresh water above the denser (saline) regional groundwater and extending up the creek valley. Water level and quality of the fresh water in Mardie Pool is probably maintained through dry seasons by base flow from the upstream alluvial valley sediments. Pressure head created by base flow has acted to prevent ingress of the surrounding denser water, counteracting the slight density difference. An increase in the salinity of the regional groundwater or a change in the groundwater level (as may be caused by seepage from the ponds) may therefore lead to changes in the fresh-saltwater interface through density equalisation; this may in turn affect the quality of the water feeding Mardie Pool.

3.2.5 Depth to Water

Figure 6 presents profiles across the secondary crystalliser ponds and Mardie Pool, displaying ground surface and SWL interpolated from the available bores and CPT sites. The profile indicates the following:

- Mardie Pool is likely to be a permanent surface water feature due to connection to the groundwater system;
- Groundwater level is approximately 6m below ground surface at the secondary crystalliser pond, increasing gradually to the east; and
- Groundwater gradient near Mardie Pool is approximately 0.5m/km (or 0.0005), falling to the west.

Beneath the evaporation ponds and primary crystalliser across the expanse of the supratidal flats the SWL is generally less than 1m below surface.

4. VEGETATION REVIEW – MARDIE POOL

4.1 Salinity Tolerance

Plant species have a wide range of tolerance to stress imposed by the presence of highly saline soil or by a change in the degree of soil salinity. Halophytes, such as samphires, are highly tolerant of saline conditions and can accumulate NaCl in their cell vacuoles while salt-sensitive species (glycophytes) have a more limited capacity to accumulate NaCl in this way (Lambers et al. 2008). Soils are considered saline when the electrical conductance exceeds 0.4 Siemens per metre, which corresponds to approximately 40mM NaCl (Schulze et al. 2019).

As well as inter-specific differences in salt tolerance, some species display an intra-specific variation. For example, *Eucalyptus camaldulensis* is considered to be moderately salt tolerant but this can vary according to the local conditions (or provenance) in which they occur (Marcar *et al.* 2002). In one study, seedlings were shown to have some tolerance to saline conditions in water-logged situations due to the presence of adventitious roots containing aerenchyma, but growth declined when soils were free draining (van der Moezel *et al*. 1988).

4.2 Vegetation of Mardie Pool

The vegetation of the Mardie Project development area varies from coastal communities such as samphires on saline clay substrates and mangroves on tidal mudflats, to hummock and other grasslands in dryland environments, and riparian vegetation dominated by either *Melaleuca argentea* or *Eucalyptus victrix* (Phoenix Environmental Sciences 2020). The samphire vegetation is unlikely to be affected by saline seepage to the groundwater as it already has a high tolerance to saline conditions and occurs on clay substrates. Hummock and other grasslands are not groundwater dependent and also should not be affected by alterations to the salinity of the groundwater environment (so long as the ground remains not water logged).

The main conservation concern is for Mardie Pool and associated riparian vegetation. The planned crystallizers are located on sandy substrates with connection to a calcarenite layer, which is more porous than other sedimentary layers and may be hydrologically connected to Mardie Pool. Saline discharge from the crystallizers to Mardie Pool has the potential to raise the salinity of the groundwater and/or the surface water in the Mardie Pool environment and increase stress on the plant species growing there. Modelling has shown that saline seepage may reach the pools within 1 to 2 years for some plausible seepage rates.

4.3 Individual Species Responses

The species recorded growing in and around Mardie Pool display a range in their use of water resources. Species that use soil water and never groundwater (non-phreatophytes) or only access groundwater opportunistically (facultative phreatophytes) include *Eucalyptus victrix*, *Sesbania formosa*, *Acacia ampliceps* and *Acacia synchronicia*. The Mardie Pool vegetation also includes the obligate phreatophytic *Melaleuca argentea* and the mostly aquatic species *Typha domingensis.*

Acacia ampliceps is used in rehabilitation of saline areas with a high water table in parts of Asia and is tolerant of saline, sodic and alkaline soils (Joseph *et al.* 2015), although high salinity can inhibit its growth (Ashraf *et al.* 2008). It is associated with riparian environments and coastal dunes as well as salt flats. Loomes (2010) recorded it in association with shallow groundwater levels fluctuating between 0.08 and 2.8m. below ground level.

Acacia synchronicia is considered to be moderately salt tolerant (Joseph et al. 2015) growing in lowland environments such as drainage lines and alluvial flats but is not considered to be a phreatophytic species.

The salinity tolerance of *Eucalyptus victrix* is not known but a closely related species *Eucalyptus coolabah* occurs in similar habitats and can tolerate high soil water salinities by using a mix of soil water and groundwater sources (Costelloe *et al.* 2008). It uses three strategies to tolerate saline conditions:

1. It grows in zones frequently flushed by infiltrating streamflow such as the top of stream banks;
2. Has low transpiration rates; and
3. Can extract water at very low osmotic potential.

Given the similarity in habitats, *Eucalyptus victrix* may also employ such strategies. Loomes (2010) recorded water level fluctuations for *Eucalyptus victrix* between 2.18m and <4.03m below ground level.

Sesbania formosa occurs near permanent water but is reported in the horticultural industry as having a high to moderate salt tolerance. The exact range of salt tolerance is not known, but a related species from Asia (*Sesbania grandiflora*) can accumulate and maintain nutrient concentrations in tissues under high soil salinity (Chavan & Karage 1986).

Melaleuca argentea is considered an obligate phreatophyte and is confined to where there is permanent near surface water (McLean 2014). It generally occurs where groundwater is less than 5mbgl with mean depths to groundwater in Pilbara varying throughout the year from approximately 1.15m to < 4m (up to a maximum depth of 7.71m) (Loomes 2010). There is little information on salt tolerance but given that it is generally restricted to freshwater environments, it is not likely to be tolerant of saline conditions. The species does have strategies to survive flooding and short drought periods such as moving water around the root system from moist soil to zones of dry soil (McLean 2014). This strategy may afford the species some ability to respond to changes in osmotic potential in the root zone, but is an area that needs further study.

The salt tolerance of the aquatic species *Typha domingensis* may be variable. It has been found to be intolerant of salt concentrations over approximately 7 ppt in one study (Glenn *et al.* 1995) and to have growth slightly reduced at 50mM NaCl (slightly saline) and severely reduced at 100mM NaCl (Hocking 1981). The effects of salinity may, however, be mitigated by the addition of other nutrients such as nitrogen and phosphorus (Macek & Rejmankova 2007). *Typha domingensis* can also display some plasticity in its response to salinity. Muffarege *et al.* (2011) found plants from a constructed wetland for treating industrial effluent showed had a higher salt tolerance than plants from a natural wetland. However, when plants from the constructed wetland were exposed to fresher water, growth was reduced. This suggests that the different genotypes of the species may have a narrow range of salt tolerance and any alteration in that range could have an adverse effect on growth. Therefore, *Typha domingensis* may be moderately salt tolerant under some conditions but may be adversely affected by any significant alteration to the surface water salinity.

4.4 Summary – Vegetation Salinity Tolerance

The tolerance to soil water salinity is likely to be variable among the species in the riparian zone of Mardie Pool. The two species most likely to be adversely affected by an increase in salinity in either the soil water or surface water are *Typha domingensis* and *Melaleuca argentea*. Previous studies on *Typha domingensis* indicate that the species is intolerant of large changes in the salinity regime, but the response by *Melaleuca argentea* is uncertain. To determine this would require knowledge of where and when each species is accessing their sources of water. It is also not yet known if other factors such as periodicity in water flow (e.g. seasonal flushing) may mitigate some of the effects of an increase in salinity as some species may be able to tolerate high salinity levels for short periods.

5. VEGETATION REVIEW – COASTAL AREAS

Figure 7 displays the mapped extent of mangrove species and Algal mats at Mardie (Phoenix Environmental Services 2020). Proposed ponds are positioned close to, or impinge upon, mangrove habitat at Evaporation Ponds 1 and 2 in the south, and near the primary crystalliser ponds in the north. Evaporation Ponds 3 to 8 are generally greater than 1km from mangrove areas. Ponds also are proposed to be constructed across large areas of land mapped as algal mats, with remaining areas of algal mat coverage existing to the immediate west of Ponds 2 to 8.

5.1 Mangroves

Concern has been raised by regulators regarding the possibility of hypersaline seepage from evaporation ponds impacting mangrove vegetation by interfering with upwelling fresh groundwater. Many published papers describe the importance of fresh groundwater for mangrove ecosystems. Hayes et al (2018) states that groundwater flow can reduce salinity and increase nutrient availability in the root zone, enhancing plant growth, and that mangroves use non-saline groundwater and rainwater when available. Santini et al (2014) concluded that growth of *A.marina* trees (as present at Mardie) is dependent on access to fresh water from groundwater, surface water or rainwater sources, and that the proportion of fresh water used by mangroves varies depending on seasonal availability. Trees growing in more saline environments will adapt to use the dominant water source as necessary, with preference for fresh water.

5.2 Algal Mats

Submissions by DWER in response to the ERD implies that the ecological value of algal mats on the supratidal flats is greater than specified in the ERD. DWER asserts that seepage of hypersaline water from evaporation ponds may alter the flow of groundwater towards the coast. Porada et al (2007) infers that algal or microbial mats which form in intratidal and supratidal zones in arid environments survive due to the hydraulic pressure regime of the underlying groundwater system. They state that "hydraulic upward pressure strongly contributes to the survival of mats during dry seasons, that it may trigger localised microbial growth at cracks, and that it may cause local ascent of sediment in the mat substratum." DWER implies that mounding beneath evaporation ponds may contribute to a reduction of the input of fresh water to the groundwater system which supports algal and mangrove productivity in similar settings.

6. ECOLOGICAL STRESSORS

Seepage of hypersaline water from evaporation ponds and crystallisers is seen as the pre-eminent area of concern for sustainability of the groundwater system at the Mardie Project, and specifically in relation to Mardie Pool.

Soilwater Group (2019) carried out modelling of the potential for seepage to impact on groundwater receptors using infrastructure design as was available in November 2019. Since this time the proposed location of Secondary and KTMS crystalliser ponds has been adjusted to allow a greater buffer zone around Mardie Pool and Creek (proximity now 1000m compared to the previous 250m). Modelling of seepage and transport rates for possible hypersaline water plumes is still relevant, however estimated transport times from source to receptor will be significantly longer in line with the greater separation.

Soilwater Group(2019) modelling near Mardie Pool presents three scenarios for seepage from the secondary crystalliser ponds:

- Downward seepage at 10^{-9} ms^{-1} – After 2 years salinity has moved only 1m below the pond floor.
- Downward seepage at 10^{-8} ms^{-1} – Salinity reaches the Calcarenite aquifer in 1.5 years, then towards Mardie Pool at $1md^{-1}$.
- Downward seepage at 10^{-7} ms^{-1} – Salinity reaches the Calcarenite aquifer in 0.5 years, then towards Mardie Pool at $1md^{-1}$. This downward seepage rate is described as “unlikely”.

Assuming a worst case scenario of seepage from the south-western corner of the secondary crystalliser ponds at the fastest modelled seepage rate (10^{-7} ms-1), and employing the permeability for calcarenite specified in this modelling, the saline seepage would reach Mardie Pool after approximately 3.5 years.

Soilwater Group’s seepage modelling for the evaporation ponds on the supratidal flats is based on a geological model which includes the following:

- 6m of gravelly loam and clay layers overlying the Calcarenite unit.
- Separation between the groundwater system in the calcarenite and the overlying clay loam.
- The overlying clay loam is suggested to comprise a series of isolated saturated gravel lenses (i.e. perched aquifers), that where they occur, are at 2mbgl.
- The water table in the underlying calcarenite are suggested to be 6mbgl sea level (i.e. 8m lower than the ground surface at the ponds).

AQ2 analysis of available water level data indicates that the SWL is likely to be within 1m of the surface, in the gravelly clay layer (Unit 4 of Figure 3). Moreover, the evidence for hydraulic separation (from the underlying calcarenite) nor a perched water table are not clear. If this is the case then saline seepage will reach the water table much faster than modelled, and potential for mounding may be greater than stated. Moreover, the distribution of hydraulic head that will influence both the actual and modelled seepage response will be fundamentally different to that modelled to date. In particular, if there is hydraulic connection throughout the aquifer, then the propagation of pressure from the pond, through the calcarenite aquifer, may result in changes to the position of the saline interface and potential changes to freshwater “upwelling” that will be occurring over the saline water.

Based on supplied data, brine seepage from evaporation ponds may be of similar salinity to the existing groundwater as sampled from the test pits across the supratidal flats.

7. RISKS

The Environmental Review Document lists several potential impacts to groundwater at the Mardie Project:

- Potential mounding and surface expression of groundwater inland of the ponds;
- Seepage from ponds resulting in elevated salinity in underlying groundwater; and
- Changes in groundwater salinity regimes due to mounding.

Additional or associated risks evident from this review are:

- Transport of hypersaline water towards groundwater dependent ecosystems;
- Increased salinity of surface water in Mardie Pool;
- Disruption of the freshwater/saltwater interface at Mardie Pool and in the upstream creek valley;

- Morbidity of vegetation which is fully or partly dependent on fresh groundwater; and

- Possible disruption of fresh groundwater flow towards coastal ecosystems (mangrove habitat adjacent to tidal creeks, and algal mat communities on supratidal flats) due to mounding of groundwater beneath evaporation ponds.

8. DATA GAPS AND UNCERTAINTIES

All permeability testing has occurred as part of geotechnical investigations, so is therefore focussed on physical characteristics of surface and near-surface formations. No long or short-term hydrogeological testing has been carried out on constructed bores within the clay/calcrete layers. CPT investigation has been employed in the vicinity of the secondary crystallisers and Mardie Pool. Infiltration and groundwater flow assumptions made for seepage modelling are therefore based on geotechnical assessments and falling head tests at distant sites rather than in-situ local measurements.

The groundwater monitoring network currently employed by Mardie Minerals is based on station bores which are generally open hole or of unknown construction and are irregularly pumped (albeit at low rates). These bores are sparsely and randomly located in relation to the proposed project infrastructure and groundwater receptors. Estimations of SWL and groundwater flow paths in the vicinity of Mardie Pool and the crystalliser are necessarily based on limited information (spatially and temporally).

Knowledge of the salinity distribution and groundwater gradients around Mardie Pool and the crystallisers is rudimentary due to limited historical sampling and the present location of monitoring points. The nearest station bores are 350m and 3000m from Mardie Pool.

The modelling of seepage from the secondary crystalliser pond was undertaken using a 2D unsaturated zone model which showed the potential for saline seepage to reach the ponds for 2 seepage scenarios. The modelling approach did not allow quantification of the volume of seepage or the consequences for changes in the relative groundwater heads between the fresh and saline water bodies in the aquifer and the associated water quality in the pool. Specifically, regardless of seepage volume, changes in pressure head may result in a change in the saline water interface.

Modelling of seepage from evaporation ponds towards coastal receptors (including mangrove and algal mat ecosystems) appears to be based on an incorrect assumption of the groundwater level beneath the ponds. SWL was specified by Soilwater Group (2019) at 8mbgl whereas data indicates that actual groundwater level is possibly less than 1mbgl.

Literature review has shown that much research has been carried out into the dependence of coastal ecosystems on fresh groundwater inflow and upwelling for supply of nutrients and dilution of salt, however it is unclear whether the coastal groundwater regime at Mardie is similar to those examples (although this seems possible). Vertical distribution of salinity beneath the flats, and the location of the seawater interface are also undefined across much of the development envelope.

9. RECOMMENDATIONS

AQ2 recommends that further studies are required to characterise the groundwater quality and flow system around Mardie Pool, the proposed crystalliser ponds and the evaporation ponds. Knowledge of the groundwater regime is limited due to the number, location and construction of sampling points.

Further work to characterise the groundwater regime relevant to Mardie Pool could include the following:

- Detailed investigation into the true groundwater dependence of the various vegetation species surrounding Mardie Pool. The presence of *M.argentea* is suggestive of a groundwater dependent system. However, it would be beneficial to gain some indication of quality of groundwater being used by the trees and their salt-tolerance which will contribute to the development of triggers and thresholds in a groundwater management plan;

- Expansion of the monitoring network - Installation of monitoring/testing bores into the calcrete/gravel layer between the proposed crystallisation ponds and Mardie Pool. This would include locating bores within and outside the theoretical fresh water lens along Mardie Pool;
- Installation of monitoring equipment for both water level and water quality in Mardie Pool; this monitoring should be undertaken using a remote data logger;
- Using the expanded monitoring network, long-term pre-construction monitoring of groundwater levels and salinity to determine baseline water quality and gradients;
- Test pumping program to determine in-situ permeability of calcrete and potential for hypersaline seepage to be transported to Mardie Pool;
- Investigation of the salinity distribution around Mardie Pool and the crystalliser ponds, possibly through non-invasive geophysical profiling (in combination with sampling from bores drilled while expanded the monitoring network);
- The drilling and testing programme should include testing in the area between the ponds and Mardie pool where, if required, a seepage recovery system would have to be developed. The objective would be to confirm the design parameters and feasibility of saline seepage recovery;
- Completion of 3D density-dependent flow modelling to:
  - Confirm the volume of seepage that may reach the pools and changes in the relative groundwater heads that will influence the saline interface and water quality in the pools.
  - Confirm the efficacy of a saline seepage recovery or management system that may have to be developed (depending on triggers and thresholds to be developed in a groundwater management plan).

Further work to characterise the groundwater regime relevant to the evaporation ponds and coastal ecosystems could include the following:

- Re-evaluation of seepage modelling for the evaporation ponds based on a shallower SWL (<1mbgl);
- Detailed investigation into the groundwater dependence of the mangrove species existing in tidal areas to the west of the proposed ponds;
- Installation of bores to enable monitoring of the vertical distribution of salinity near mangrove stands to determine water quality and the existence (or not) of fresh groundwater flow through the root zone. This may also assist in locating the seawater interface;
- Hydraulic testing programme to determine in-situ permeability of gravelly clay layers and potential for transportation of hypersaline seepage from the evaporation ponds to the mangrove communities;
- Investigation into the dependence of algal mat communities on upwelling groundwater for moisture and nutrient supply. This may take the form of nested bore installations to quantify vertical hydraulic gradients (pressure and salinity) in areas where algal mats are present; and
- Consideration of the effects of brine salinity on modelling (density-coupled modelling) of seepage and groundwater flow.

Development of a Groundwater Management Plan is likely to be necessary for the site in line with DWER recommendations. The Groundwater Management Plan should include the following:

- Commitments for ongoing data collection, review and updates to the plan based on new data.
- The development of triggers and thresholds with respect to water quality or level. The modelling exercise will help determine what the appropriate triggers are.

- Adaptive management response when triggers and thresholds are crossed such as increased monitoring or saline seepage recovery.
- Confirmation of the feasibility of proposed management measures (i.e. that modelling shows the monitored trigger is appropriate and that proposed management options are feasible).

We trust this memo report meets your requirements. Please contact us if you have any queries.

Regards

Duncan	***Bruce***
Director / Consulting Hydrogeologist	Hydrogeologist

Attached:

Figure 1 - Mardie Project Site Layout
Figure 2 - Conceptual Geological Profile
Figure 3 - Representative Geological Cross Section Beneath Evaporation Ponds (after CMW 2020)
Figure 3 - Groundwater Levels and Flow Direction
Figure 4 - Surface Elevation and Water Level – Mardie Pool Area
Figure 5 – Mardie Project Groundwater Levels and Flow Direction
Figure 6 – Surface Elevation and Water Level – Mardie Pool Area
Figure 7 – Mardie Project Potential Coastal Groundwater Receptors

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Author: BPH, DGS, SC (3/11/20)
Checked: DGS (4/11/20)
Reviewed: DGS (4/11/20)

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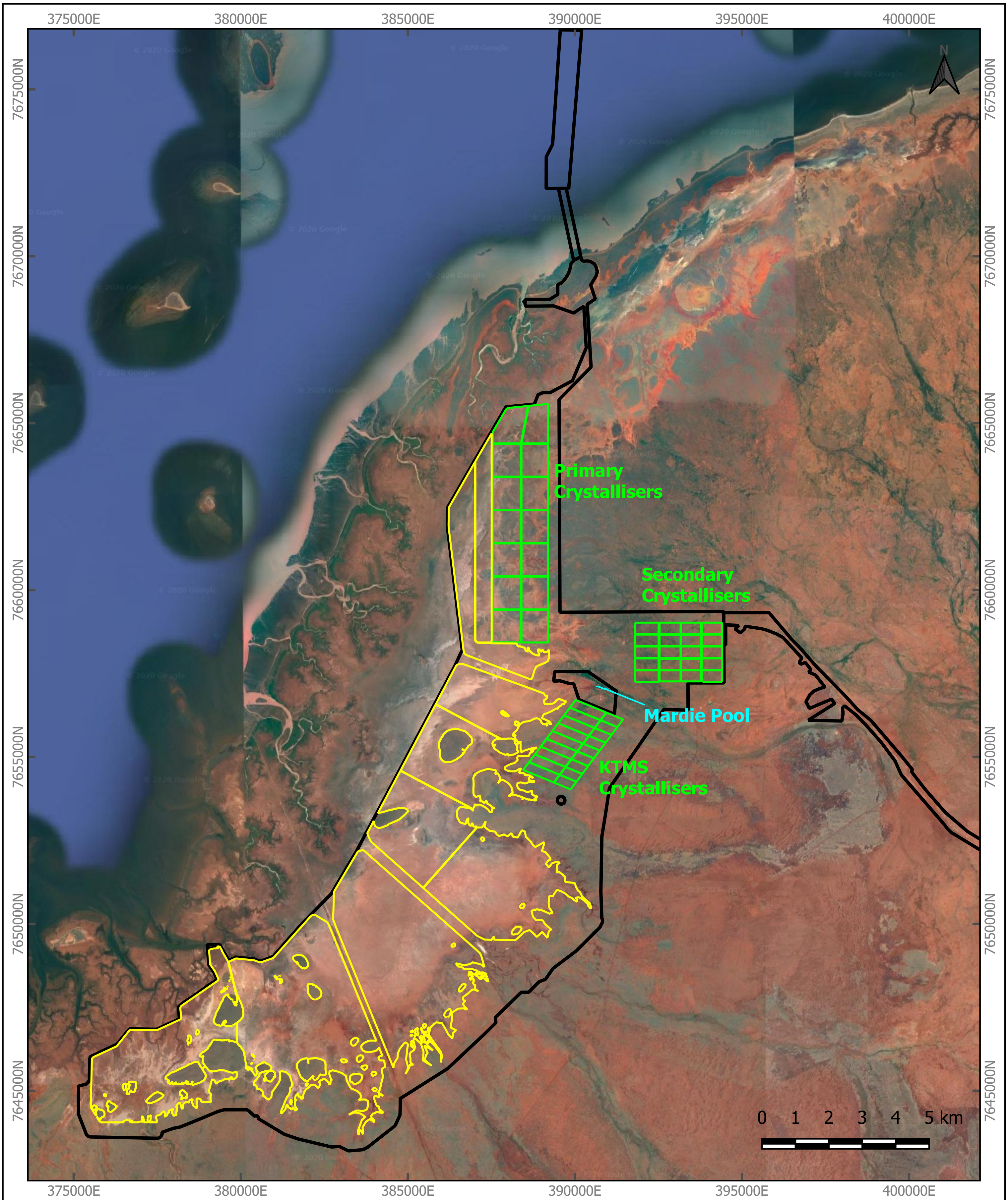

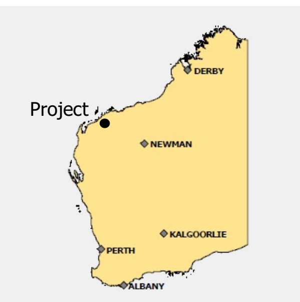

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Legend

- Evaporation Ponds
- Crystalliser Ponds
- Development Envelope

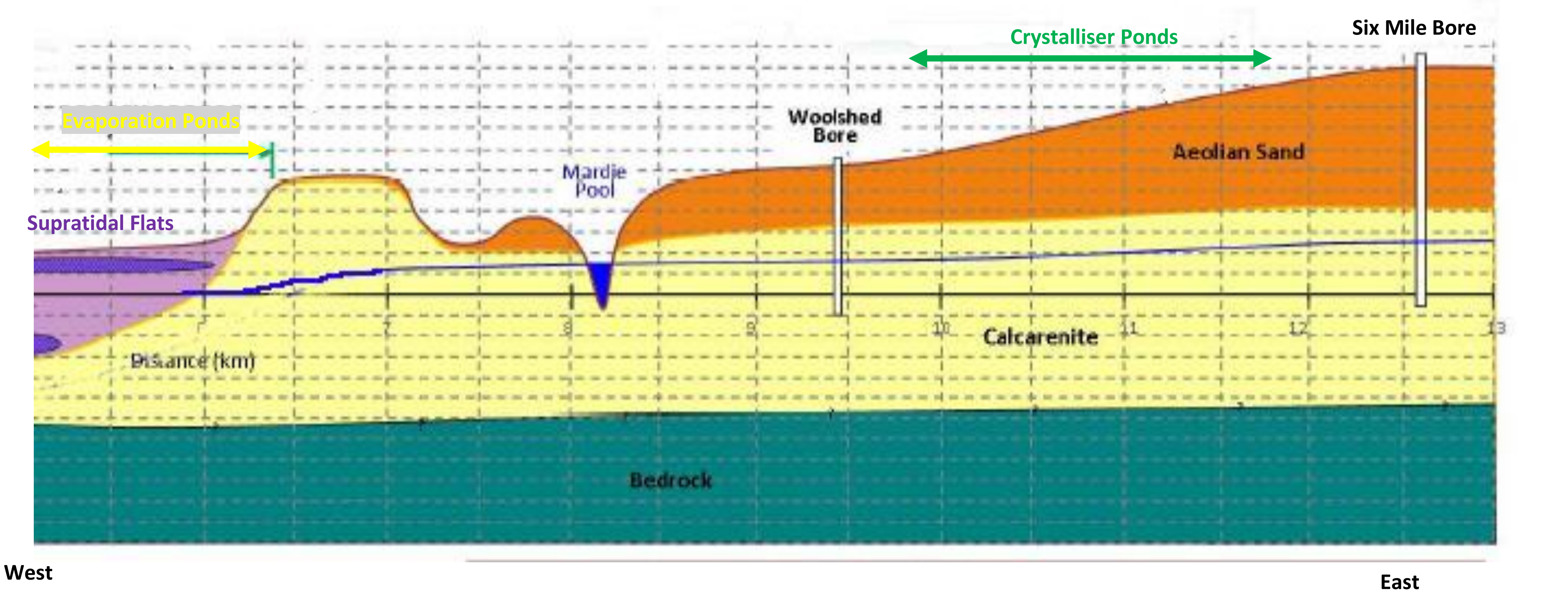
AUTHOR: BPH
DRAWN: BPH
DATE: 10/10/2020

REPORT NO: 009a
JOB No: 293
Coordinates: MGA Zone 50

Notes and Data Sources:
Background Image (C) Google
Project Infrastructure data supplied by BCI Minerals

Figure 1

Mardie Project Location and Site Layout



Not to scale

Modified from Soilwater Group (2019)

Figure 2 – Conceptual Geological Profile – Mardie Pool Area

AQ2

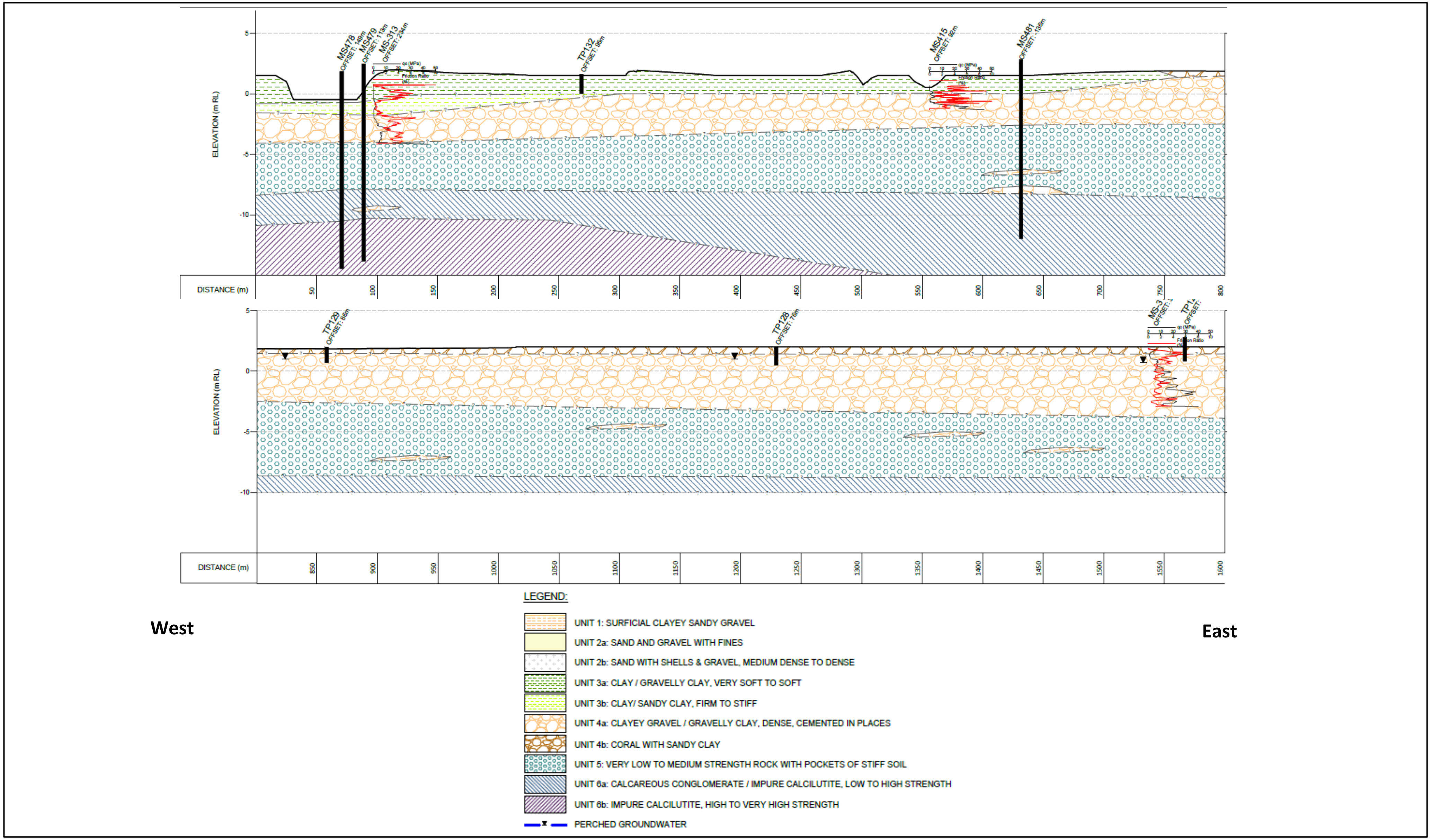


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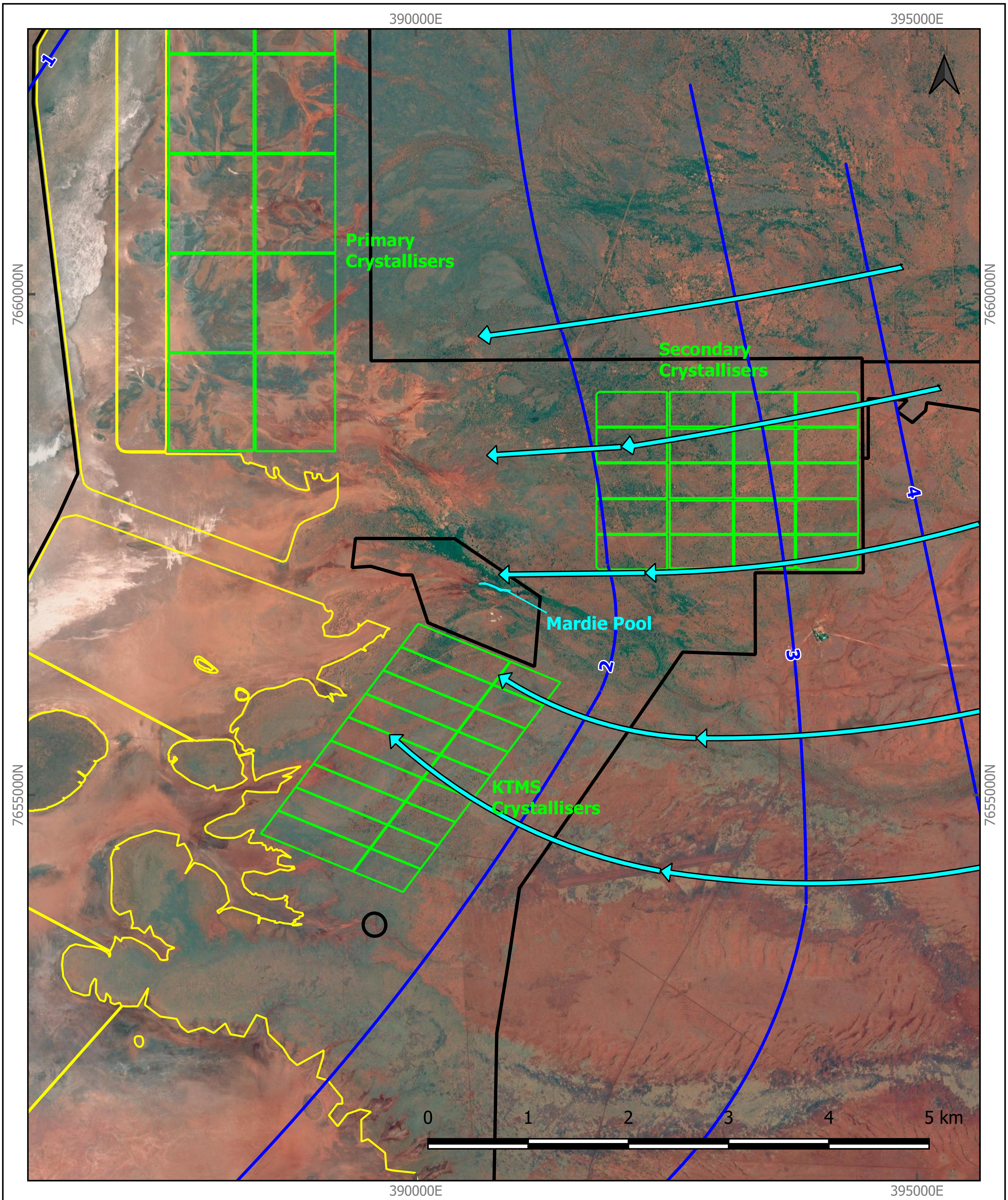
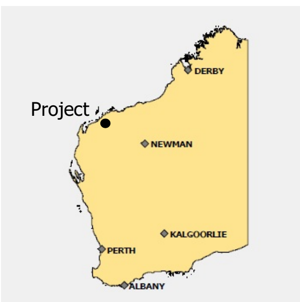
Figure 3 – Representative Geological Cross Section Beneath Evaporation Ponds (after CMW 2020)





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Legend

- Groundwater flow direction
- Groundwater Level Contour (mRL)
- Mardie_Pool
- Evaporation Ponds
- Crystalliser Ponds

AUTHOR: BPH
DRAWN: BPH
DATE: 10/10/2020

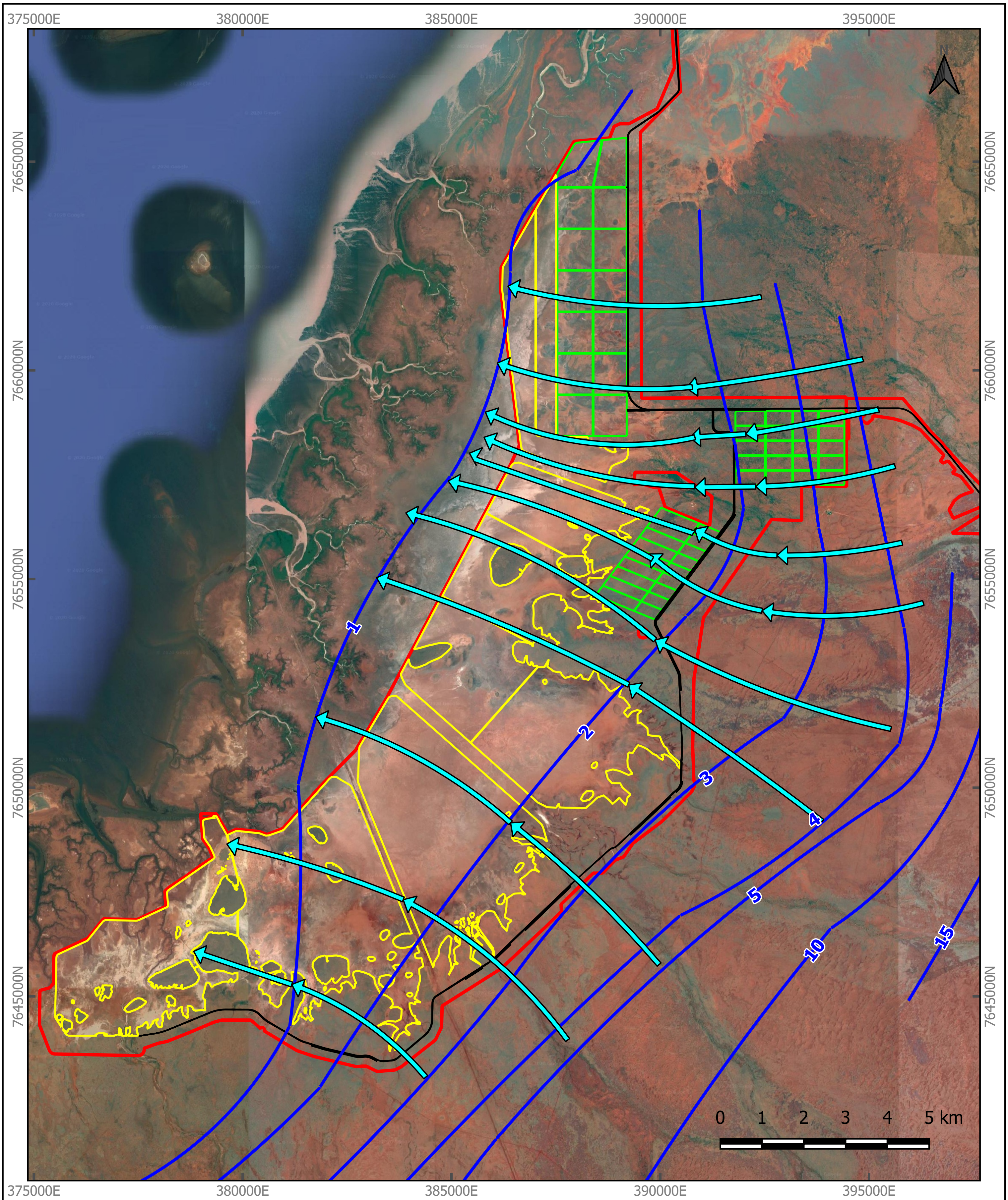
REPORT NO: 009a
JOB No: 293
Coordinates: MGA Zone 50

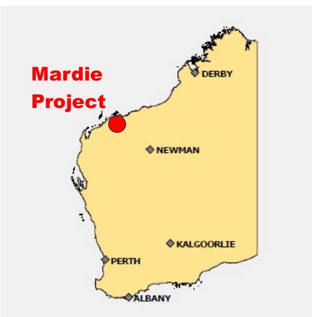
Notes and Data Sources:
Background Image (C) Google
Project Infrastructure data supplied by BCI Minerals
Water Levels based on 2019 data.

AQ2

Figure 4

Mardie Project Groundwater Levels and Flow Direction - Mardie Pool Area





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Legend

- Groundwater flow direction
- Water Level (mRL)
- Road/Track
- Evaporation Pond
- Crystalliser Pond
- Development Envelope

AUTHOR: BPH	REPORT NO: 009b	Notes and Data Sources:
DRAWN: BPH	JOB No: 293C	Background image (C) Google Maps Approximate groundwater level contours based on level measurements from several periods in 2019.
DATE: 3/11/2020	Coordinates: MGA Zone 50	

Figure 5

Mardie Project Groundwater Levels and Flow Direction

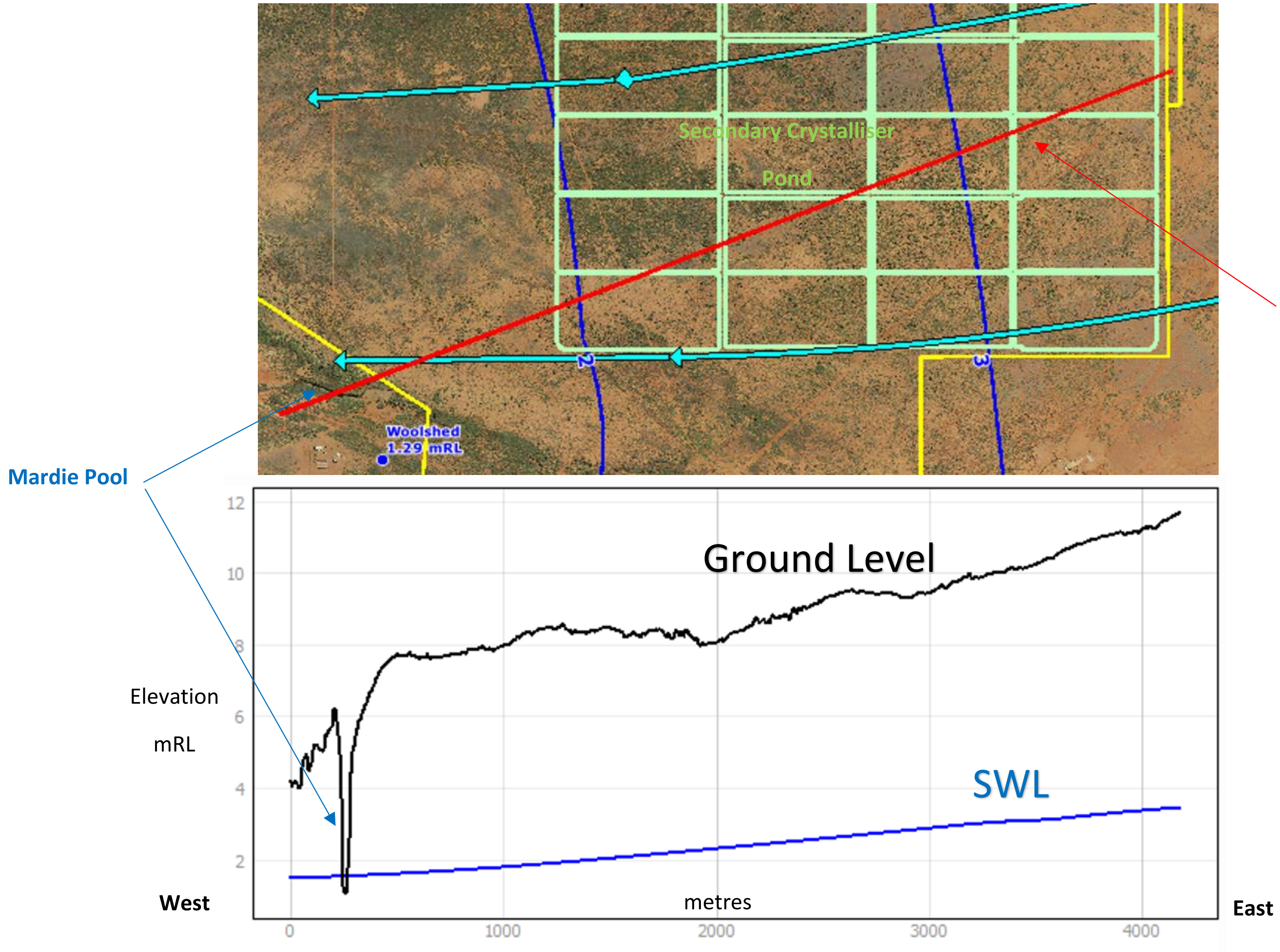
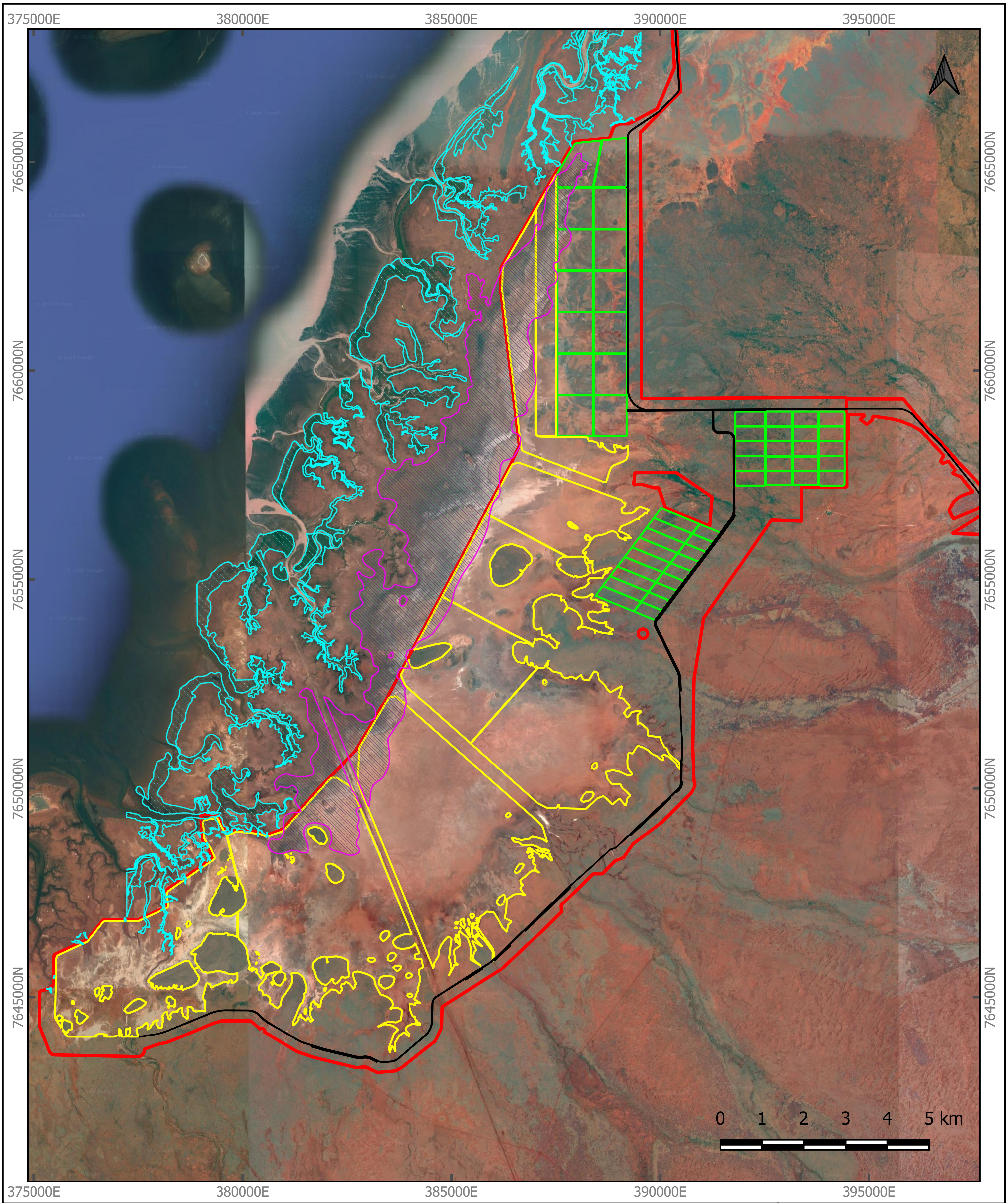
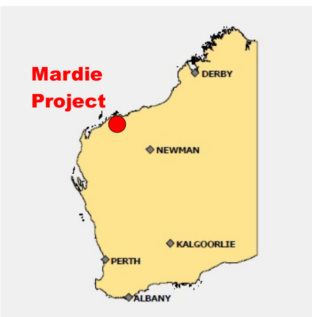


Figure 6 – Surface Elevation and Water Level – Mardie Pool Area





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Legend

- Algal mat
- Mangrove
- Road/Track
- Evaporation Pond
- Crystalliser Pond
- Development Envelope

AQ2

Figure 7

Mardie Project Potential Coastal Groundwater Receptors

AUTHOR: BPH	REPORT NO: 009b	Notes and Data Sources:
DRAWN: BPH	JOB No: 293C	Background image (C) Google Maps
DATE: 3/11/2020	Coordinates: MGA Zone 50	Approximate groundwater level contours based on level measurements from several periods in 2019.