Hydrology and hydrogeology of the Lake Mackay

Sulphate of Potash (SOP) Project, Western Australia

Agrimin Limited

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1. Introduction

1.1 Background

Agrimin Limited (Agrimin) is developing the Lake Mackay Sulphate of potash (SOP) Project. The lake hosts hypersaline brines in the sediments which are suitable for the production of Sulphate of Potash (SOP) fertilisers. The Project comprises nine Exploration Licences and two Miscellaneous Licences in Western Australia, all of which are 100% owned by Agrimin.

Lake Mackay is the largest salt lake in Western Australia, being located on the border with Northern Territory, with 75% of the lake in Western Australia. It experiences seasonal inundation associated with intense rainfall events during the wet season, after which the lake surface becomes progressively dry.

The Project currently has an Indicated Mineral Resource of 4.4 million tonnes and an Inferred Mineral Resource of 18.9 million tonnes of SOP at a potassium concentration of 3 603 mg/L in the brine. These Mineral Resources have been defined to an average depth of 24.7 m; however, the initial study proposes brine extraction from only the upper 5.5 m of the deposit.

This document provides an overview of hydrology and hydrogeology associated with Lake Mackay. The objective is to present the current understanding of the hydrological and hydrogeological regimes and processes; the connectivity between the water resources and environment; and the initial appreciation of impacts associated with the proposed trenching method. This is a summary document based on the current understanding with several work programs underway that will address knowledge gaps.

1.2 Location

The Project is located in the East Pilbara region of Western Australia, situated on the Western Australian and Northern Territory border. It is remote in the Great Sandy Desert of Central Australia being 450 km south of Halls Creek in Western Australia and 540 km northwest of Alice Springs in the Northern Territory. The nearest community is Kiwirrkurra, about 65 km southwest of the lake (Fig. 1).

The site is largely undisturbed with limited development and infrastructure. A single lane unsealed track, which traverses the western edge of Lake Mackay, connects the Project with the communities of Kiwirrkurra in the south and Balgo to the north.

1.3 Climate

The Project area is within the Great Sandy Desert Bioregion which experiences an arid tropical climate in the north, grading into a temperature-subtropical climate in the south that have dry conditions with hot summers and mild winters (Tille, 2006). There are seasonal extremes in temperature with summer temperatures commonly exceeding 50°C, while winter overnight temperatures often below zero.

The area is subjected to two distinct seasons. December to March is characterised by very hot conditions with most annual rainfall received during this period associated with thunderstorm activity. May to August is the coolest and driest period of the year, making it the ideal period for conducting exploration and feasibility activities.

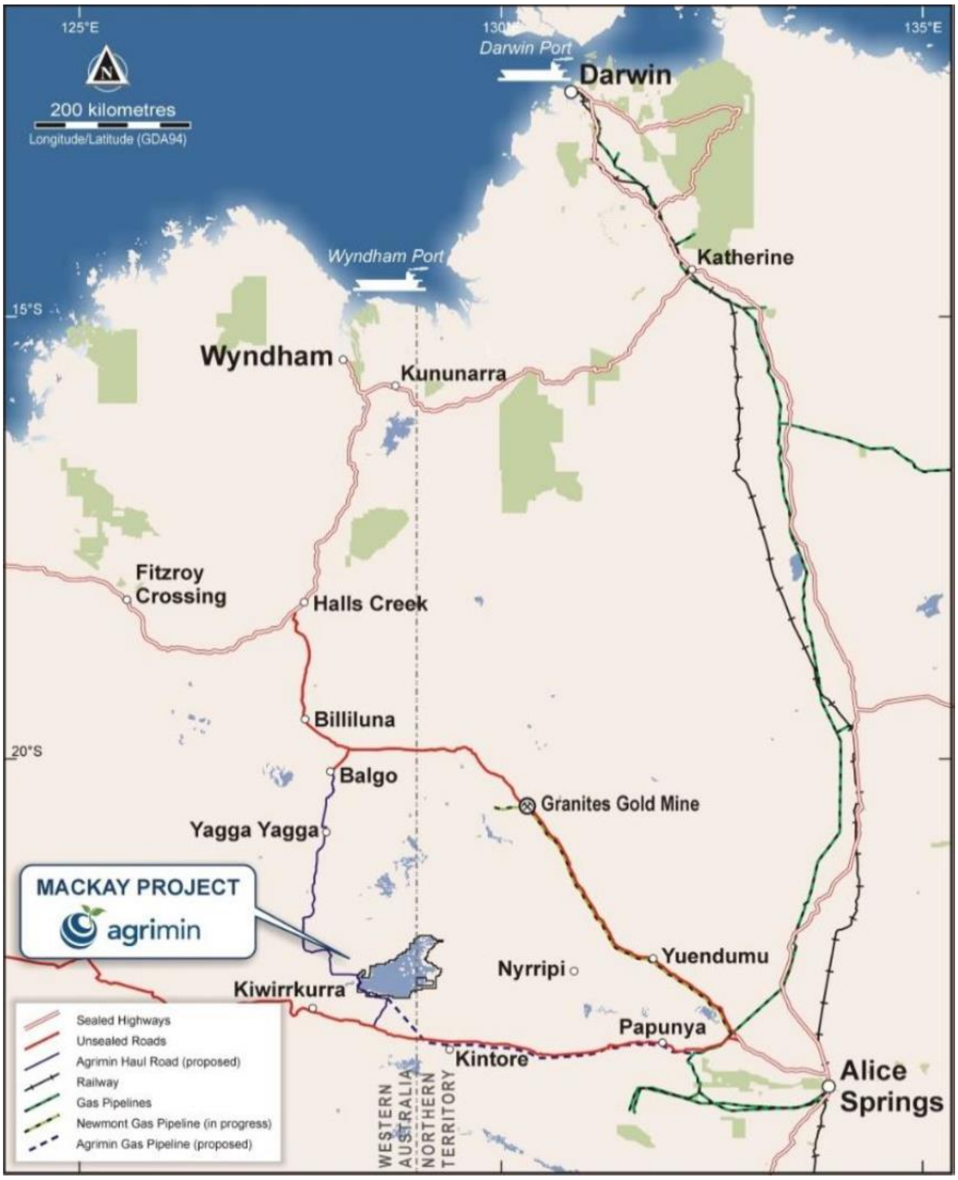

Figure 1. Location of the Mackay Project

The nearest and most relevant Bureau of Meteorology (BoM) weather station for the greater Project area is Walungurru Airport (Station No. 15664) at Kintore. It is expected that weather conditions at Kintore are similar to those at the lake. Agrimin have had a weather station in place on the lake edge since 2015.

Rainfall occurs largely during the tropical wet season that influences northern Australia. It is derived from large storm systems and cyclones that push inland from the northern coastline and generate large rainfall events between December to March. Despite the mean annual rainfall being about 306 mm, it is possible for single-storm events to exceed the annual rainfall in any month of the year; however, these events are extremely rare.

Wind is predominantly from the east and south east, which influences the formation of certain landforms associated with the lake and surrounding landscape. In addition to the solar radiation, wind is an important contributor to evaporative loss in the Project area.

There is no pan evaporation data for Walungurru Airport weather station; however, it is likely to be between 3200 and 3400 mm across the year. Evaporation will be greatest during the summer months of January and February, and lower during the winter months of June and July.

1.4 Vegetation

There have been several flora and vegetation studies undertaken between 2016 to 2018 by 360 Environmental (2017a), Ecologia (2017a) and Strategen (2018). Refer to these documents for detailed descriptions of the flora and vegetation on and surrounding Lake Mackay.

There is no vegetation on the salt lake surface, except for islands which are predominantly developed in the eastern portion of the lake. Vegetation on the islands tends to transition from salt tolerant shrubs growing on the margins of the islands toward grasses and larger shrubs in the central parts of the islands. There are frequently larger trees and shrubs up to several metres high in the centre of the larger islands.

Figure 2. Vegetation on islands and lack of vegetation on lake surface

The vegetation on the islands possibly exists due to the presence of lower salinity water that occurs in the porous gypsiferous sands that form the islands. Drilling has confirmed the presence of lower salinity shallow groundwater bodies beneath the islands that is most likely recharged by rainfall and influenced by evaporation and transpiration by the vegetation on each island. These lower salinity bodies increase in concentration back into hypersaline brine with depth.

1.5 Topography and landforms

The topography is subdued and flat on the lake, and in the immediate vicinity of the lake. The eastern portion of the lake is characterised by hundreds, perhaps thousands of small islands, of leptoscale (less than 100 m by 100 m) up to macroscale (greater than 1000 by 1000 m) with about 10 islands of more than 10 km^2 and the largest of around 30 km^2 (360 Environmental, 2017b).

The inland landforms of the Great Sandy Desert are characterised by east to west trending, linear dunes with swales opening locally onto sandplains. Some undulating plains and upland areas occur in places. Among the dunes are small claypans and isolated residual sandstone hills, as well as areas of ironstone gravels and some breakways capped by laterite duricrust (Tille 2006). Further to the east, there are more elevated areas associated with the McDonnell Range that extend through to Alice Springs.

1.6 Previous investigations

The broader Lake Mackay region has historically been explored for uranium, precious and base metal deposits. However, the lakebed itself had never been subject to exploration until 2009 by Holocene Pty Ltd, a subsidiary of Reward Minerals Ltd. Owing to the Project’s remoteness, the lake itself had been overlooked as a potential deposit of valuable salt minerals.

From 2007 to 2014, Reward Minerals held tenements covering the majority of Lake Mackay in Western Australia. In 2009, Reward Minerals conducted a vibracore sampling program across the lake. As part of this program, 24 shallow core holes were drilled to an average depth of 2.7 m. Brine samples taken from 22 of these holes returned an average of 6.83 kg of SOP (3064 mg/L of K) over the drill holes.

The Project was subsequently acquired by Agrimin in 2014, following a period of inactivity by Reward Minerals. Agrimin acquired the historical database of technical and commercial information from Reward. Throughout 2015 to 2018, Agrimin applied for additional Exploration Licences and consolidated majority control of Lake Mackay.

Agrimin has conducted extensive exploration and feasibility related works at the Project between 2015 to current date. These have included multiple programs of drilling, bore installation, trenching, aquifer testing, evaporation trials, process studies, and geotechnical assessments.

Hydrominex Geosciences Consulting and Groundwater Exploration Services (2016) provided the first description of the geological setting and hydrogeology associated with the lake sediments at Lake Mackay. This information was used to generate the first mineral resource estimates for the Project, which was supported by a numerical groundwater flow model developed by Groundwater Exploration Services (2017).

In the development of the pre-feasibility study (PFS) by Advisian (2018), Knight Piesold Consulting (2018) were engaged to undertake hydrological and hydrogeological modelling. The focus of the hydrological model was a 72-hour flood assessment of the lake, whilst the hydrogeological model was to simulate the expected groundwater regime with the proposed method of brine extraction through trenching. Based on these models, data was compiled into an infiltration model that formed the basis of a global water balance for the lake.

Since the PFS in April 2018, there have been ongoing hydrogeological studies with a focus on longer-term pumping tests of trenches on the lake. This has provided confidence in the ability of trenches to provide sufficient brine for the Project and provided information on the aquifer parameters and extent of drawdown.

2. Hydrology

The Project is located within the Mackay basin, specifically within Lake Mackay. Lake Mackay is an ephemeral hypersaline lake. The lake bed covers an area of approximately 3,500 km^2 and measures approximately 100 km east to west and 100 km north to south.

The lake is present at the topographically low point of the enormous groundwater and surface water catchment area that covers an area of 87 000 km^2. This catchment receives water from the groundwater paleochannel system and surface water runoff in times of abnormally heavy flows that generate significant surface flow. The catchment area excluding such abnormal rainfall periods is poorly defined but is possibly more localised and approximately half this size. The outlines of both variations of the catchment are shown in Figure 3.

Beneath the catchment, there is an extensive system of palaeovalleys and palaeochannels. These originate in the Northern Territory and extend west to the valley between the ranges towards Lake Mackay, which is the discharge point for water in the palaeochannels (Lycopodium, 2016).

At the margins of the lake, there are small ephemeral streams and watercourses that drain the surrounding landscape and contribute surface water runoff onto the lake during periods of extreme rainfall. These features are localised and tend to be more common in the southeast portion of the lake. There are no major stream channels that appear to reach the lake.

Lake Mackay is shallow during inundation, but depth is poorly documented. Duguid (2005) suggested the Northern Territory portion has the deepest part of the lake. It is rare for the lake to hold water or remain inundated for more than a month or two after heavy rainfall events.

2.1 Cyclic flooding of lake surface

Most recharge is derived from direct rainfall and surface runoff covering the lake and its immediate surrounds. Intermittent inundation of the lake surface typically follows seasonal rainfall during the months of December to March. Elevation modelling indicates a slight topographic gradient across the lake surface, generally sloping towards the south-east.

Observations from satellite imagery demonstrate that Lake Mackay is regularly inundated during the wet season on an annual basis. There is a high degree of variability in the frequency, extent and distribution of inundation. In addition to direct rainfall, there appears to be a component of surface water runoff from the surrounding landscape via a series of channels and streams (Lycopodium, 2016).

The inundation appears to be less common in the northern and western portion of the lake, as there is a slightly higher elevation. In contrast, there is more frequent inundation of the south eastern portion where elevation is lower and there are drainage channels that capture and move surface water runoff from the surrounding landscape onto the lake surface.

The hydroperiod being the time period from flooding to drying of the salt lake will be highly variable between inundation events. The volume and period of inundation is dependent on a wide range of factors such as duration and intensity of the rainfall event, position of the rainfall event in terms of the lake surface and catchment, time of the year (evaporative loss), etc.

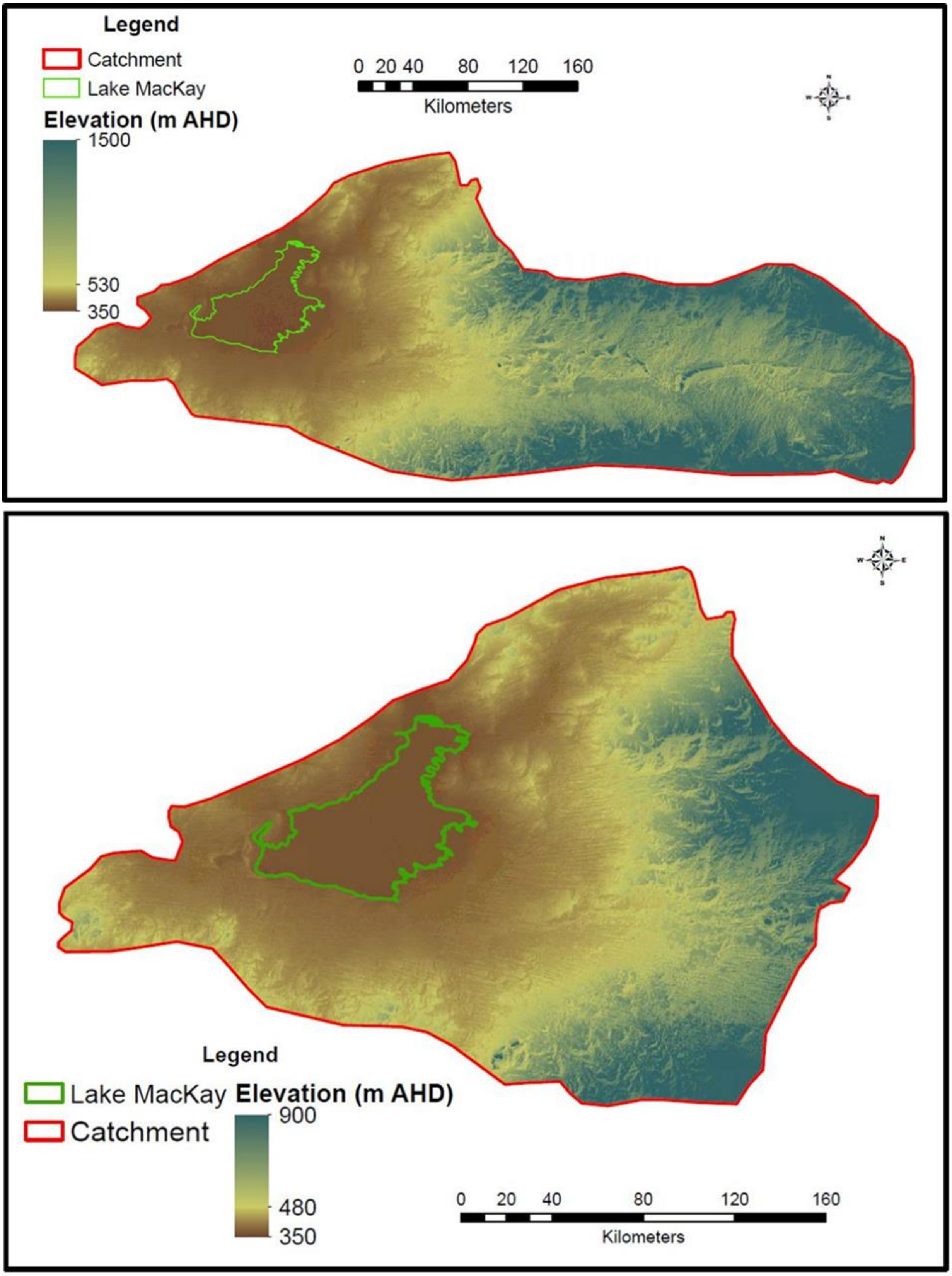

Figure 3. Lake Mackay and its associated catchment area

As the lake is a closed system, evaporation and transpiration are the only recognised forms of discharge. Evaporative loss from the lake surface is significant, which is beneficial for potash brine projects as the sun's energy is used to increase the potash concentration of the brine within large solar evaporation ponds.

2.2 Surface water movement on lake

The movement of surface water on the lake is influenced by the prevailing wind conditions and the bathymetry of the lake surface. The prevailing wind direction is from the east and southeast which pushes the water towards the west and northwest. In contrast, the lake surface elevation slopes from the west to the east and north to the south suggesting that inundation is more likely in the southeast. A combination of both wind direction and lake elevation will influence the extent, distribution and depth of the inundated water.

2.3 Fresh water claypans

There is little documentation of the claypans in the Lake Mackay region, which are typically less than 10 km from the shoreline of the lake. Google Earth imagery shows at least 30 claypans greater than 8 ha in size and hundreds to thousands of claypans less than 8 ha (360 Environmental, 2017b). It is possible that individual claypans may join forming larger wetlands during inundation events.

The claypans are most likely associated with near surface clay (Duguid, 2005) and form between sand dune swales (Fig. 4). Some of the claypans are very shallow and unvegetated, while others are deeper and well vegetated. The hydrology of each claypan is variable but it is assumed that they are filled directly from direct rainfall, and/or localised surface runoff. In general, inundated water in claypans can last from days up to months. The aggregations of claypans may be an important waterbird habitat (Duguid, 2005).

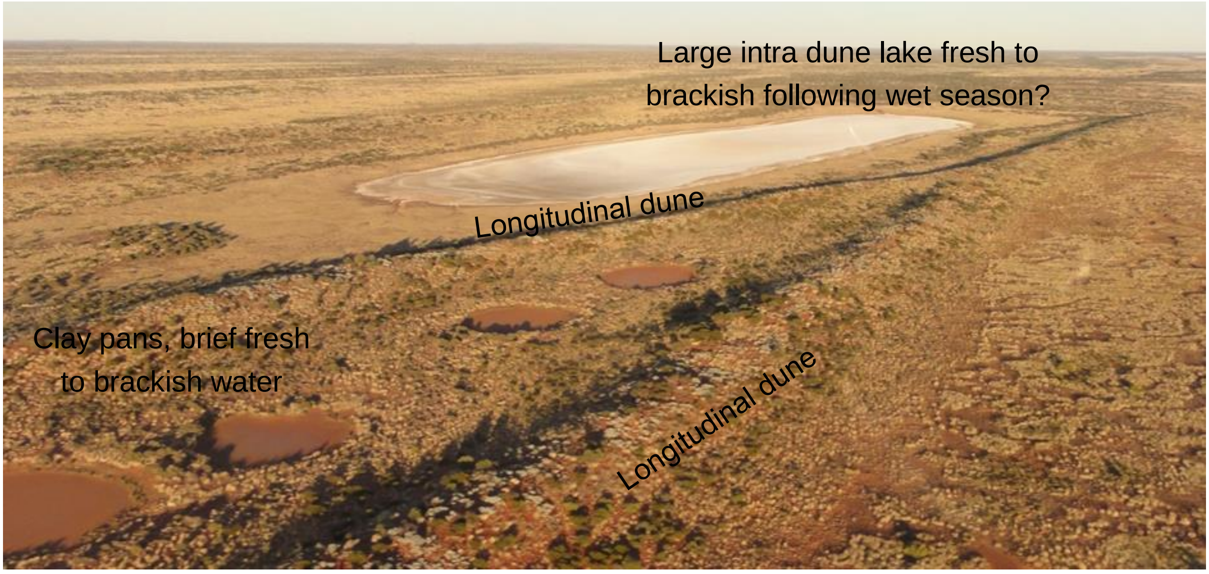

Figure 4. Clay pans and intra-dune lake in dune swales

The claypans are probably perched and it is unlikely that the claypans are in hydraulic connection with the regional groundwater watertable. The longevity and persistence of the waterbodies in the claypans may be influenced by localised discharge from the sand dunes. In order to resolve connectivity, Agrimin are installing groundwater monitoring bores with high-resolution water level monitoring in close proximity to several off-lake claypans.

2.4 Hydrological modelling

As part of the PFS, Knight Piesold (2018) completed a hydrological assessment that included a flooding assessment and the generation of an infiltration/evaporative loss model. This model was used to inform the net recharge into the lake system and provide a water balance from pre-operation and during operation of brine extraction.

Further hydrological assessment and modelling is proposed once the LiDAR data is collected. Section 8 provide more details on the objectives of these studies.

3. Salt lake geomorphology

According to the classification by Houston et al. (2011), Lake Mackay is considered an immature salar, dominated by clastic sediments, with limited thicknesses of halite. Lake Mackay and the surrounding area contains a diverse range of different landform types.

It is unknown whether Lake Mackay contains a basal coarse sediment layer, but it does comprise a coarse-grained upper gypsum sand unit (which also appears to be present in other Central Australian lakes). The lake does also not have an internal halite nucleus, surrounded by marginal deposits of carbonate and sulphate, but rather sulphate is the dominant facies. Carbonate is present; however, it is preserved as extensive calcretes surrounding the lake and in paleochannels flowing towards the lake.

Bowler (1986) proposed a number of salt lake types based on the relationship between the catchment and lake areas, and climatic parameters of surface water and groundwater-dominated lakes (Fig. 5). Groundwater-dominant salt lakes are characterised by irregular shorelines, common residual islands and low irregular lunettes on the downwind margin. These playas lack smooth constructional shoreline deposits, are dominated by groundwater discharge, and the water table acts as a base level for deflation of sediments and salt weathering. Lake floor sediments are disrupted by efflorescence of salts and deflated by saltation of sand-sized aggregates in the downwind direction that constructs traverse dunes (lunettes). Lake Mackay has these characteristics with an archipelago of islands formed in the east of the lake and a more homogeneous western surface.

Geoscience Australia (Mernagh, 2013) noted thick Cenozoic palaeolacustrine clays commonly underlie Australian Quaternary salt lakes being from a lacustrine, rather than a fluvial, origin. These have evolved from full, commonly overflowing, lakes to terminal lakes with no outlets, to dry terminal lakes, to groundwater lakes in which surface water is rare. These salt lakes fundamentally function as hydrologically closed entities that are dominated by groundwater discharge, regardless of where or whether there is a regional groundwater flow component within the basin.

Lunette dunes on downwind shorelines are characteristic of Australian arid-zone lakes (Mernagh, 2013). The lunette facies and lithology depend on the sedimentary conditions in the lake. Quartz-rich lunettes containing abundant biogenic carbonates occur when surface water dominates as lunettes are derived from beach foredunes. As hydrological budgets become more negative and saline groundwater dominates, lunettes become clay- and gypsum-rich (Bowler, 1973, 1983; Magee, 1991).

Lake deltas are distinctive sedimentary and hydrological environments, not only in perennial lakes, where a mix of fluvial and lacustrine processes prevail, but especially when lakes become ephemeral and contract during arid periods when new deltas form on the surface of exposed former lake beds. Delta morphologies change in response to differing regimes.

Geomorphological features that may include strandlines from former high-lake stands, terraces, spits, lagoons, islands of gypsiferous aeolian landforms, playa-fringing dunes and encroaching linear sand dunes may be indicative of such changes. These features may be combined with the impact of sporadic high magnitude run-off events that typify desert hydrological processes and the influence of the build-up of calcrete bodies around a playa. The complexity is exacerbated when contracted lakes become saline and incoming fresh fluvial waters intermix with shallow brines in the delta setting, promoting intense physical and chemical responses and reactions.

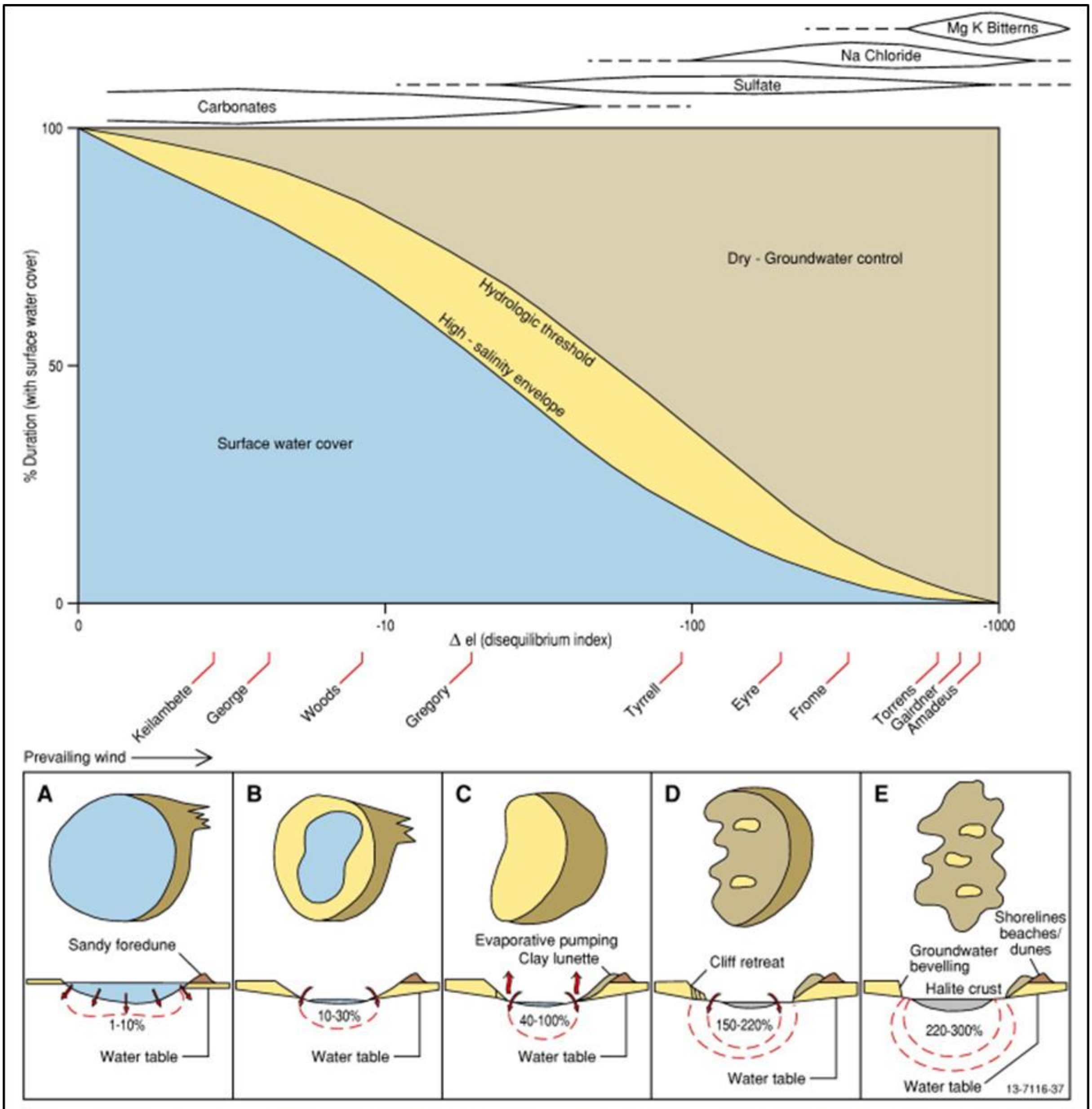

Figure 2.5 Classification of Australian lake/playa basins across a climatic gradient which extends from humid to arid conditions. Five lake/playa basin types, A to E, are differentiated by morphological and sedimentological features, which reflect successive stages in a hydrological series from surface-water to groundwater dominated systems including the evolution of a sub-playa brine pool. Figure is modified from Figures 2 and 5 of Bowler (1986a). Lake George, NSW, near Canberra, ACT, and Lake Kielembete, western Victoria, both located in the humid climate zone, are endorheic lakes, i.e., closd basins with no outflow.

Figure 5. Classification of Australian playa lakes after Bowler (1986)

4. Geological setting

4.1 Basement rocks

Lake Mackay overlies the Palaeoproterozoic Arunta Complex and Neoproterozoic Amadeus and Ngalia Basins. The Proterozoic (Adelaidean) Bitter Springs Formation of the Amadeus Basin basal sequence outcrops to the immediate south-west of Lake Mackay and may occur at shallow depth elsewhere beneath dunes of the Great Sandy Desert.

There are few areas of outcropping basement rocks in the vicinity of Lake Mackay. To the south of Lake Mackay and underlying the majority of the lake, there are isolated outcrops of the Neoproterozoic Angus Hill Formation and mixed metasediments of the Western Amadeus Basin. In the north, there are minor outcrop of Lake MacKay quartzite which comprises interbedded quartzite and quartz–mica schist. The distribution of these outcrops is shown on the update 1:250 000 geological sheet by Spaggiari (2016).

Magnetic and gravity data shows a series of prominent NE trending faults north of the lake and WNW trending probable stratigraphy and associated structures. It is not clear if any faults have controlled the development of Lake Mackay; however, it has probably contributed to the formation of the thalwegs associated with the palaeovalleys.

Geoscience Australia (2012) suggest there may be some tectonic control of the lake basin, as active faults are widespread and seismic activity is significant. Tectonism during the Cenozoic has greatly contributed to the shaping of the landscape that now contains the present-day array of salt lakes. Many of the faults are ancient in origin, associated with major orogenies of the Precambrian and Phanerozoic, and have been reactivated during the Cenozoic. The Wilkinkarra paleovalley study suggests the regional hydraulic gradient was previously to the east, but is now towards the west, ending in Lake Mackay.

4.2 Palaeochannel sediments

The Wilkinkarra and Kintore palaeovalleys are incised meandering palaeoriver systems that were formed during previous wetter climates of the Early to Mid Cenozoic. The stratigraphy in the Wilkinkarra palaeovalley comprises an upper layer of calcrete, underlying units of sandy sediments with internal clay units that overlie weathered basement of the Arunta Complex and Ngalia Basin. In contrast the stratigraphy in the Kintore palaeovalley has no near-surface calcrete with aeolian sand at the surface, which overlies clay-dominated lithologies of the Currinya and Mount Wedge Clay members.

The presence of sand horizons is poorly resolved in these palaeovalleys. Woodgate et al. (2012) suggested that based on the Kintore palaeovalley, there is potential for coarse sediments to be present and widespread. These sand horizons are important aquifers for groundwater resource development.

A passive seismic geophysical survey was conducted to map the basement contact over a significant area beneath the central part of the lake. This work has suggested basement contact depths vary between 80 m to 200 m from surface with depths appearing to increase towards the east. The survey identified the presence of several palaeochannels beneath the present-day lake surface. Drilling investigations are proposed in late 2018 to confirm the extent and nature of the palaeochannel sediments beneath the lake.

4.3 Calcrete

There are extensive tracts of calcrete comprising massive, nodular and cavernous sandy limestone of Tertiary age that occur in the catchment surrounding Lake Mackay where they are formed as palaeovalley infill deposits. Secondary silicification of these deposits locally results in incomplete replacement by a vuggy, opaline silica caprock. Quaternary aeolian deposits often overlie these calcrete deposits.

4.4 Lake sediments

Salt lake deposits have been evaluated by drilling aircore holes to a maximum of 30 metres deep, trenching to 6 m deep and by power hand auger holes to 1.5 m deep. There is a reasonably consistent stratigraphy beneath Lake Mackay. The key lithological units are mentioned below from top to bottom of the sequence. Drilling has demonstrated that the lake sediments are up to 30 metres thick.

4.4.1 Surficial halite

Surficial halite is generally only 5 mm or a single salt crystal thick. In the west of the lake, this crust takes on a different, less porous form than in the east of the lake, where it is intermixed with gypsum in small mounts with internal vugs and void spaces. The halite is interpreted to dissolve each wet season and reprecipitate when waters evaporate.

4.4.2 Organic silt horizons

An upper organic layer, up to several cm thick, occurs at surface or within 5 cm of surface and is commonly exposed as patches within the salt lake where surficial halite is not present. It is unclear whether this represents a recent inundation that carried a significant volume into the lake sediments, or whether it is reworked at the surface of the lake, similar to the halite crust. Typically, a cm or several cm thick in the west of the lake, this horizon appears to thicken to the east and may be correlated with a silt unit tens of cm thick in the upper metre of sediments.

4.4.3 Friable gypsum sand

Friable gypsum sand has been encountered from surface, where it is interbedded with the silt and clay. It varies from a fine to coarse gypsum sand and grit, which has a maximum thickness of approximately 1.5 m to 2 m in the east. The grit-like gypsum changes below approximately 0.5 m to finer grained gypsum with interbedded layers of clay. The exact thickness of this unit appears to be variable.

4.4.4 Red brown to brown clay

Below the clayey sands, a red-brown clay with intermittent bands of crystalline gypsum and sand across the lake is present. This is the dominant salt lake lithology, beginning within 1 m of surface in the west of the lake to as deep as 2.5 m in the east.

The clay shows some variation in colour from medium brown to red brown but is overall homogeneous, completely lacking in internal structure or bedding, with minor gypsum sand grain content. In places the clay unit is paler and can be described more as olive green to grey, rather than red, reflecting a distinct period in the clay deposition; however, this change cannot be correlated across the lake. In other lakes, this represents more reducing conditions (deeper water) rather than oxidizing non-permanent water cover or surficial conditions. The green intervals commonly occur between 5 and 24 m below surface.

There appears to be a distinct difference in lithology of the lake sediments between the western and eastern sides of Lake Mackay. The western side of the lake appears to host a lower energy zone, with predominantly higher clay content. In contrast, the eastern side of the lake contains a higher sand and silt content. This is possibly the effect of different depositional environments.

The sediments within Lake Mackay thicken from a shallowest point of 21 m in the south-west corner to beyond 30 m (the maximum investigated depth) in the east. The lake bed sediments are unconformably underlain by highly-weathered sandstone, siltstone and metasediments.

4.4.5 Consolidated gypsum sand layers

Within the red brown clay unit, there are horizons of gypsum sand with grains typically up to 1 mm or smaller, which form consolidated layers. They are texturally distinct from the friable gypsum sand but may represent similar surfaces where the gypsum has recrystallized. It is unclear as to the lateral continuity of these layers; however, it is assumed that continuity is poor. The consolidated layers are more common below 9 m depth in central and eastern parts of the lake, but there are some layers present close to the surface at about 3 m depth. These layers often encountered significant flows of brine.

4.5 Gypsum islands

In the east of Lake Mackay, there are a large number of islands ranging from tens of square metres to several square kilometres. These islands reach a height of several metres above the lake surface and appear to be entirely composed of gypsum grains. The gypsum is deposited in layers with different textures. The islands support significant communities of grasses, scrubs and trees which are interpreted to survive exploiting lower salinity groundwater that has infiltrated the gypsum layers from rainfall.

4.6 Aeolian deposits

Aeolian deposits, comprising sand and clayey sand, are present as flat to undulating sand plains and extensive seif (longitudinal) dunes have formed adjacent to Lake Mackay. Sand plain deposits also occur as discontinuous, shallow relief areas within the extent of Lake Mackay.

Both within and fringing the lake bed sequence, locally throughout the extent of Lake Mackay, is a series of discontinuous aeolian deposits comprising silty to clayey sands composed of loose to partially consolidated crystalline gypsum and quartz. These deposits intermittently extend to the surface as eroded dune ‘islands’ throughout the extent of the salt lake.

5. Hydrogeology

There has been little to no development of groundwater resources in the region, prior to the investigations by Agrimin and others. At a distance from the lake, there are groundwater bores for the Kiwirrkurra Community located 60 km southwest of the lake and several water supply bores by the Main Road Department located about 70 km northwest of the lake.

A major focus of the Project has been understanding the hydrogeology of the lake sediments within Lake Mackay. There are also investigations underway in the palaeochannels beneath the lake and in the surrounding catchment to provide lower-salinity process water. The drilling will confirm depth to basement for correlating with geophysical data; understand the presence of palaeochannels beneath the lake including lithologies, water levels and water quality; and install Vibrating Wire piezometers (VWP) for better understanding of hydraulic regime and processes. This new information will provide a better understanding of the overall lake model and influences on the shallow aquifer.

5.1 Regional setting

Lake Mackay hosts hypersaline brine within the lake bed sediments. Potassium and other elements dissolved in the brine are derived from weathering of rocks within the catchment area. The sediments consist of essentially two flat-lying hydrostratigraphic units: an upper zone comprising coarse gypsum sand, with an approximate thickness of 1 m grading downward into sandy and silty clay, and discrete sand and crystalline gypsum units, to depths beyond 6 m; and a lower zone comprising a largely massive clay interfingered with sands and silts, and interbedded layers of granular and crystalline gypsum.

The lake is the low point of a vast catchment that extends hundreds of kilometres east from the lake. It is surrounded by higher sand dunes and forms a major regional groundwater sink or a discharge area. The lake is occasionally inundated after rain. The occurrence and accumulation of hypersaline brine in the sediments is due to evapo-concentration, as evaporation exceeds rainfall.

Most recharge is derived from direct rainfall and surface runoff covering the lake and its immediate surrounds. Intermittent inundation of the lake surface typically follows seasonal rainfall during the months of December to March. Elevation modelling indicates a slight topographic gradient across the lake surface with a gentle slope towards the south-east, which results in extended periods of ponding and inundation in this part of the lake.

Groundwater levels are generally close to the surface between 0.1 to 0.4 m bgl across the lake and have a very shallow gradient. In paired monitoring bores, there are higher hydraulic heads in the deep bores suggesting upward heads and discharge towards the lake surface.

Groundwater inflow from the perimeter of the lake is expected to be limited due to the clayey lake sediments. Recharge from the more-elevated sand dunes surrounding the lake is still to be fully resolved. Recharge to the lake is predominately from direct rainfall and surface runoff from the large catchment. Direct rainfall and possibly upward leakage are the primary recharge mechanisms, whilst groundwater discharge is solely from evaporation of the lake surface and evapotranspiration from fringing vegetation.

Hydraulic connection between the lake sediment and underlying palaeochannels is poorly resolved. Investigations in the Wilkinkarra palaeovalley system, east of Lake Mackay, suggested that the palaeochannel aquifer thins significantly before the lake; however, groundwater flow along the palaeochannel is towards Lake Mackay. There are possible palaeochannels associated with the Kintore palaeovalley system beneath the lake; however, there is little known about the presence and distribution of palaeochannel aquifers.

5.2 Aquifer description

5.2.1 Basement fractured-rock

There is limited outcropping basement rocks near Lake Mackay with most basement rocks being concealed by surficial sediments. They are likely to form fractured-rock aquifers characterised by secondary porosity and permeability associated with complex fracturing systems being enhanced by chemical dissolution along fracture lines.

Local geological structure is the dominant feature controlling the occurrence of fractured-rock aquifers, with the lithology of the rocks having limited influence and affecting only the extent of structural development. These aquifers often have an associated weathering profile of variable thickness and extent that is in hydraulic connection with the underlying fractured rocks.

The weathering profile is likely to be low yielding owing to its high clay content. Larger groundwater supplies may be obtainable from regional fault zones, lithological contacts, and where there is brittle deformation of the Lake Mackay quartzite in the north.

The fractured-rock aquifer is not considered significant for the hydrogeology of the lake; however, it may be in hydraulic connection with the palaeochannels that underlie the salt lake and other parts of the larger catchment. They are recharged infrequently by rainfall and runoff from ephemeral drainages into open fractures and weathered zones; hence, recharge is likely to be small. They often contribute groundwater inflow towards palaeochannels associated with abstraction and aquifer depressurisation.

Groundwater salinity will be variable dependent on proximity to the salt lake. There will be hypersaline groundwater beneath and immediately adjacent to the lake, becoming less saline away from the lake and fresh to brackish towards the catchment divides.

5.2.2 Palaeochannel aquifer

In other palaeochannels throughout Western Australia, there is a basal palaeochannel sand aquifer that can provide significant brine and groundwater supplies. The presence of this sand aquifer is poorly resolved beneath and in the palaeovalleys that contribute to Lake Mackay. Further investigations are currently underway to understand the potential of the palaeochannel aquifer both beneath the salt lake and in the surrounding catchments for low salinity process water.

Ground-based geophysical techniques have been used to map the contact between the less-dense palaeochannel sediments and the basement rocks. The initial interpretation suggests the presence of palaeochannel features beneath the central portion of the lake that previously flowed to the northwest and formed part of the Kintore palaeovalley system. An on-lake drilling program is planned for late 2018 to understand the stratigraphy and groundwater potential associated with these palaeochannels.

To the east of Lake Mackay, Geosciences Australia undertook groundwater investigations into the Wilkinkarra palaeovalley system (Woodgate et al., 2012). The hydrostratigraphy comprises an upper layer of calcrete that overlies sandy sediments with internal clay horizons that are incised into a weathered basement of the Arunta Region and Ngalia Basin. The stratigraphy thins near Lake Mackay with the basement rocks at the base of the palaeochannel becoming shallower from the east towards the lake.

Groundwater flow within the palaeochannel is towards Lake Mackay. The elevation of the palaeovalley floor rises towards the west, although the surface elevation declines westward. This suggests that the drainage flow directions of the past may have been different to modern drainage directions, and Lake Mackay may not have always been the major depocentre of the regional drainage network.

The alluvial sequence is a vertically interconnected hydrogeological system (Woodgate et al., 2012). Aquifer porosity is similar throughout the downhole profile and there are no significant confining layers suggesting that the aquifer is an unconfined system. Some of the clay and silt-rich beds of the alluvial sequence may impede groundwater flow (at least to some degree), and areas of relatively elevated basement rocks may act as groundwater divides, which could compartmentalise zones of the aquifer.

Groundwater is abundant in both the Kintore and Wilkinkarra Palaeovalleys with the water table at relatively shallow depths below the surface (generally 3 to 5 m). The entire palaeovalley sediment sequence forms a moderate to good quality aquifer with average bore yields at between 5 and 10 L/s (Woodgate et al., 2012).

Water quality is variably fresh to saline, with salinity generally increasing down-gradient along the groundwater flow path. Modern recharge to these palaeovalley aquifers is episodic, as indicated by time-series data collected over the course of an unusually wet period (2010-2011). The presence of fresh groundwater in this arid environment suggests that there is modern recharge, mostly via diffuse infiltration, into these palaeovalleys. The karstic nature of the near-surface calcrete zones may also provide preferential pathways for groundwater recharge.

5.2.3 Calcrete

The modern palaeovalley system associated with the Kintore and Wilkinkarra Palaeovalleys is defined at the surface by extensive calcrete deposits. Owing to its well-developed secondary porosity and high permeability, calcrete may form a locally high-yielding aquifer. Calcrete occurs low in the drainage systems where the watertable is generally shallow, less than 5 m below ground level, and saturated thickness is mostly between 5 and 10 m. Bore yields are likely to be highly variable depending on the nature and extent of karstic development.

Groundwater in the calcrete is commonly brackish to saline, between 2000 and 6000 mg/L TDS, because of its position in the lower reaches of drainages. There may be, however, small fresh supplies where the calcrete receives enhanced groundwater recharge via direct rainfall infiltration, and more particularly inundation from surface runoff surrounding catchments during intense rainfall events.

There may be increased infiltration through sheet flooding and streamflow that occurs after intense rainfall events. Infiltration will be very rapid into the calcrete via solution cavities, although this process of recharge probably only occurs during sheet flooding.

5.2.4 Lake sediments

There are broadly two flat-lying hydrostratigraphic units with an upper zone comprised of coarse gypsum sand, with an approximate thickness of 1 m grading downward into sandy and silty clay, with discrete sand and crystalline gypsum units, to depths beyond 6 m, and a lower zone comprised predominantly clay that is intermixed with sands and silts, and interbedded layers of granular and crystalline gypsum.

There appears to be a distinct difference in lithology of the lake sediments between the western and eastern sides of Lake Mackay. The western side of the lake appears to host a lower energy zone, with predominantly higher clay content; whereas, the eastern side of the lake contains a higher sand and silt content. Generally, high brine flows into excavated trenches are encountered in the eastern side which is reflective of the higher sand content and crystalline gypsum zones.

Groundwater levels are generally close to the surface between 0.1 to 0.4 m bgl across the lake and have a very shallow gradient. The watertable will slope towards the southeast in line with changes in the lake surface topography. In paired monitoring bores, there are higher hydraulic heads in the deep bores suggesting upward heads and discharge towards the lake surface.

When the lake surface is dry, evaporative processes dominate with substantial discharge of groundwater. This discharge is reduced when the surface is inundated with flood water.

5.2.5 Island sediments

Islands that rise several metres above the lake surface are present in the east of the lake, becoming progressively less common to the west across the lake and are absent in the western third of the lake. The gypsum islands are often present as distinct elongated east-west dunes with a barchan dune geometry that have a broader sloped eastern side and a compact shorter western side. The barchan geometry suggests that predominant wind direction has been important in the formation of these islands. On occasions, there are small cliffs that are several metres high on the western edge of the islands.

In 2016, auger core holes were drilled on several of the islands and this confirmed they are surficial features, with the sand forming the islands grading downward into sandy clay and clay. The islands themselves are composed of gypsum that is friable or cemented.

There is lower salinity water that occurs in the porous gypsiferous sands that form the islands. Drilling has confirmed the presence of these low salinity groundwater bodies beneath the islands that is most likely recharged by rainfall, perched on top of the brine water, and influenced by evaporation and transpiration by the vegetation on each island.

5.3 Conceptual hydrogeological model

The conceptual hydrogeological model is presented in Figure 6. This conceptualisation was provided in the PFS and represented in the numerical groundwater model undertaken by Knight Piesold (2018). The general water regime is as follows:

Rainfall and recharge:

- Direct infiltration through the lake surface during seasonal rainfall events;
- Runoff – inundation of the lake from rainfall within the catchment, flowing into Lake Mackay as the low point in the drainage resulting in inundation in the east and south of the lake. Only likely with associated high rainfall events such as storms or cyclones; and
- Interflow – rainfall infiltrating into the upper soil profile and flowing to the lake, evaporating on the lake margins.

Groundwater flows:

- Palaeovalley interpreted to connect to Lake Mackay, bringing water from the Northern Territory, which discharge into the lake in the east and along the southern boundary;
- Evaporation of surface water from rain and inundation of the lake surface;
- Evaporation and transpiration loss;
- Evaporation within the 1 m of the lake sediments where capillary forces allow evaporation;
- Transpiration of water from plants that are accessing fresh to brackish water derived from incident rainfall as it percolates through the gypsiferous island sediments; and
- Possible upward hydraulic connection with deep palaeovalley sequence beneath the lake bed sediments.

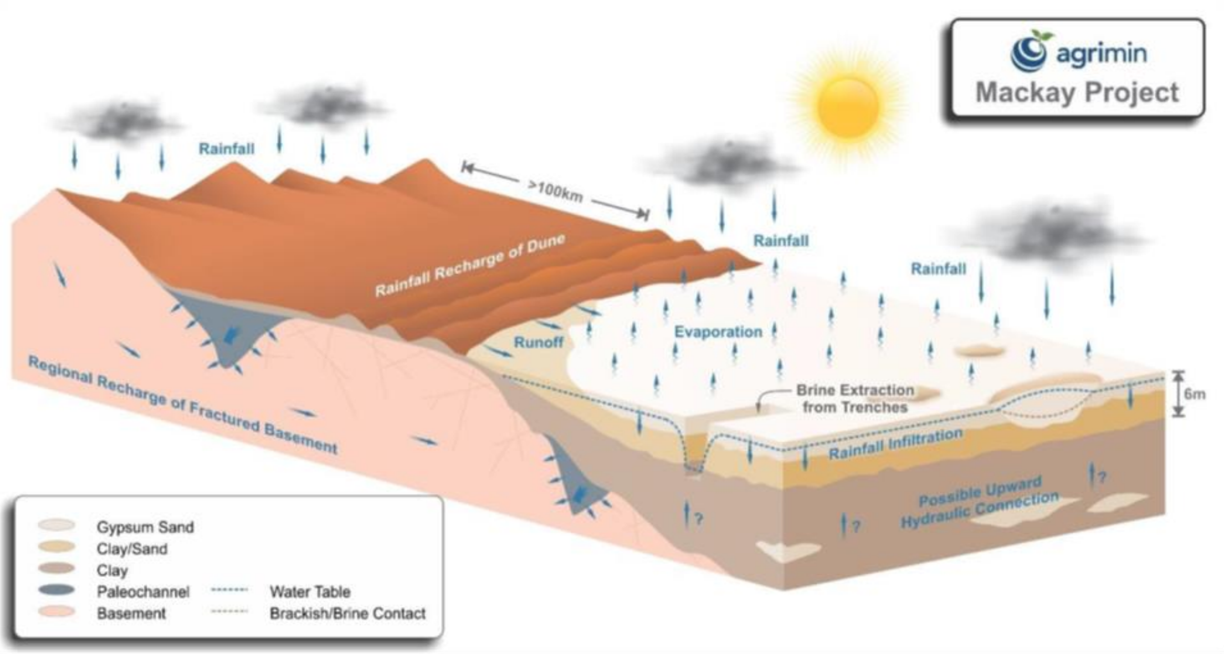

Figure 6. Conceptual hydrogeological model

6. Hydrogeological connectivity with the environment

6.1 Salt lake

The lake surface on Lake Mackay is largely devoid of vegetation except for vegetated gypsum islands that are more common in the eastern part of the lake. The lake is a major discharge feature of both surface water and groundwater that results in the creation of hypersaline brines through the significant evaporative losses.

The water table is very close beneath the lake surface. Any salt-tolerant vegetation in the fringing lake surface may have some dependency on the shallow water table. There may also be some dependency of vegetation on the fresher, less dense recharge surface water that floats on the hypersaline groundwater.

It will be important to understand whether there will be any repopulation of vegetation associated with the abstraction from the trenches. The reduction in water levels may increase the zone of unsaturation and provide an opportunity for vegetation types to recolonise areas that were previously saturated with brine.

6.2 Islands on lake

The islands on the lake are composed of gypsum sand, which is porous in places and allows for infiltration of rainwater. An important portion of the annual rainfall is likely to infiltrate into the gypsum sand, forming a lens of fresh water grading deeper to brackish water and overlying the brine beneath the lake. The groundwater lens is in a dynamic equilibrium with the rainfall and evaporation.

Abstraction of the brine from the trenches and possibly bore has potential to influence and possibly destabilize the water lenses beneath the islands (which are topographically higher than the lake brine). There is a high likelihood that the freshwater lens is in hydraulically connection with the brine underlying the islands.

Any modification of the hydrology from brine abstraction near the islands has potential to influence these ecosystems. These impacts may include reduction of the watertable beneath the islands and movement of the fresh to brine water interface from the lake margins towards the trenches. Despite flora studies suggesting the island vegetation is not dependent on the lens of fresher water but instead sustained by intermittent seasonal rainfall, it will be necessary to assess whether there will be any potential impacts on changes to vegetation distribution and repopulation of the lake surface.

6.3 Fresh water claypans

The claypans are most likely associated with near surface clay (Duguid, 2005) and form between sand dune swales. Some of the claypans are very shallow and unvegetated, while others are deeper and well vegetated. The hydrology of each claypan is variable but it is assumed that they are filled directly from direct rainfall, and/or localised surface runoff. In general, inundated water in claypans can last for months. The aggregations of claypans may be important for waterbirds, as they consume the fresher water (Duguid, 2005).

The claypans are probably perched and it is unlikely that the claypans are in hydraulic connection with the regional groundwater watertable. There will be need for further investigations to demonstrate the hydraulic connectivity.

6.4 Subterranean fauna habitat

Lake Mackay is east of the main known habitat areas for subterranean fauna in Western Australia, namely the Pilbara and Yilgarn regions (Halse et al., 2014), but stygofauna have been found in the adjacent Ngalia basin in the Northern Territory (Balke et al., 2004). As part of the initial risk assessment, it was assumed that stygofauna could be expected to occur in calcrete and alluvial aquifers at Lake Mackay assuming that the salinity is suitable (Ecologia, 2017b).

Pilot and Phase 1 preliminary surveys have been undertaken by Invertebrate Solutions (2017 and 2018) to determine the presence of stygofauna and troglofauna communities at Lake Mackay. These documents should be referred for a more detailed taxonomic description.

6.4.1 Calcrete

The initial risk assessment by Ecologia (2017b) highlighted a high likelihood of stygofauna owing to the presence of calcrete and alluvial formations, and there is also a high likelihood of troglofauna associated with the calcrete formations. Invertebrate Solutions (2017 and 2018) have completed surveys that confirmed the presence of stygofauna in the calcrete aquifer to the south of Lake Mackay; however, this area is no longer being considered for process water supply. As groundwater investigations are now focused in the palaeovalley to the east of the lake, the presence of a near-surface calcrete aquifer will require further surveys to confirm the stygofauna and troglofauna communities.

6.4.2 Underlying alluvium

The deeper alluvial aquifer currently presents an environment unfavourable to stygofauna and preliminary sampling of this aquifer has recorded no stygofauna. Invertebrate Solutions (2018) recommended that additional surveys were required before a final assessment regarding the presence or absence of stygofauna within this aquifer can be undertaken.

6.4.3 Islands

Ecologia (2017b) suggested that it was possible for styglophilic species with widespread surface populations, such as cyclopid copepods, to occur in the low-salinity water lenses under the islands. It was felt these fresher systems are too small (and too ephemeral in a geological sense) to support large stygofauna communities; however, there is some potential for troglofauna to be present. Invertebrate Solutions (2018) recommended ongoing surveys to assess the stygofauna present and the potential for impacts associated with the trenching operations.

6.4.4 Lake sediments

The initial risk assessment by Ecologia (2017b) suggested that no stygofauna and almost no species of invertebrate will persist at salinities around 200 000 mg/L. In combination with the clayey nature of the lake sediments, it is unlikely that there will be any subterranean fauna beneath the lake surface.

7. Potential impacts

7.1 Groundwater abstraction

The brine (hypersaline groundwater) will be abstracted via an approximately 540 km long trench network. It is expected that 66.5 GL of hypersaline groundwater will be abstracted per year. Initial groundwater modelling has been undertaken to understand the likely radius of drawdown from the proposed abstraction.

It is estimated that 3.3 GL of fresh water per year will be required to support the process plant and other uses for the Project. This groundwater is proposed to be abstracted from a borefield located more than 100 km east of the proposed plant site. The proposed borefield is remote and distant to lake bed. Based on this distance, it is unlikely that the radius of watertable drawdown from the borefield will impact on the Lake Mackay sediments.

7.1.1 Trenching

Groundwater modelling by Knight Piesold (2018), as part of the prefeasibility study, suggested that about 540 km of trench network would be required to meet the brine requirements for the proposed SOP Project. This may be supplemented by bores positioned into the underlying palaeochannel aquifer; however, the groundwater modelling has suggested that trenching will be adequate to provide a target inflow rate of 2.18 m^3/s.

The extent of drawdown over the proposed 20-year mine life will be highly dependent on a range of factors such as aquifer capacity, sustainability of brine supply, recharge contribution, etc. A numerical groundwater model was developed to provide confidence that the lake sediments would be capable of meeting the brine requirements; however, it did provide some insight into the extent of drawdown. The drawdown around each trench was relatively localised. Further testing and modelling will be required to determine an indicative buffer for trench distance away from islands. Based on the aquifer testing of the trenches and hydrogeological modelling, a 500 m buffer is required around the islands.

Further work is currently underway to confirm the rates and extent of drawdown, as well as the sustainability of brine supply. The hydraulic testing of the test trenches in 2018 will provide useful information on the actual water level drawdowns associated with abstraction – these results are being compiled at the present and will be useful for determining the permissible trench distance from the islands.

7.1.2 On-lake bores

Investigations are underway in late 2018 to confirm the nature and brine potential of palaeochannel aquifers beneath the lake. Drilling investigations to date have only been shallow; however, it is possible with the support of ground-based geophysics to assess the thalweg (deepest part) of the palaeochannel. The thalweg has the highest potential for encountering the basal sand aquifer.

Dependent on the results of the drilling investigations, there may be suitable and prospective aquifers that could be developed to provide a supplementary brine source for the trenches. The installation of test production bores will provide a measure of the indicative bore yields, likely drawdown extent and connectivity with the lake sediments. The presence of the thick clay horizon in the upper palaeochannel will have a semi-confined and confined aquifer response with limited vertical connectivity.

7.1.3 Borefield for process water

Groundwater investigations comprising two 150 mm production bores, five 50 mm monitoring bores and a 72 hr aquifer test have been undertaken on the palaeovalley to the south of Lake Mackay to locate a process water supply. The presence of hypersaline groundwater was not considered ideal for the process water requirement; hence, investigations have moved to exploring the Kintore palaeovalley system in the Northern Territory to the south east of the lake.

There are other potential groundwater resources that may be considered. These include the Angus Hills Formation between the lake and Kiwirrkurra to the south, and the Liveringa Formation of the Canning Basin which is located about 80 km to the northwest of the lake. Further studies are planned in 2019 to understand groundwater resource potential, drawdown extents and any likely impacts on ecosystems.

7.2 Impact on surface water movement

The flood assessment modelling by Knight Piesold (2018) suggested that the southern extents of the trench system may require more than the nominal 1 m high bunds. Bunds in selected areas may be required to be up to 2 m in height. The extent of the increase will be determined in detail when more accurate topography is provided as part of the next phase of design.

The trenching network and its associated bunding has potential to impact on surface water movement on the lake. Additional modelling using LiDAR data is proposed to demonstrate that the altered surface water hydrology is acceptable. There is also the possibility that engineering measures, such as culverts, could be installed to minimise impacts on surface water flow.

8. Future investigations

8.1 Hydrology

There is a need for further work on the hydrology of Lake Mackay. Most information to date has been general and conceptual in nature. The collection of new LiDAR data in 2018 will provide an improved bathymetric resolution supporting the undertaking of more detailed hydrological studies and modelling. The key studies that should be undertaken are:

- the relationship between rainfall events and flood inundation;
- the impact of trenches and bunds on surface water movement on the lake and associated ecosystems; and
- the influence of lake inundation on sediment generation, turbidity and potential erodibility of these landforms.

The completion of these studies will support the planning of mine infrastructure and a full consideration of impacts. Through hydrological modelling, it will be necessary to demonstrate that any impacts can be managed through considered design and/or scheduling of the trenching plan.

8.2 Hydrogeology

There is a large range of groundwater studies to be undertaken by Agrimin over the 2018/19 wet season. Combined with long-term aquifer testing undertaken in 2018, there will be a detailed appreciation of the hydrogeology of the lake sediments and their brine yielding potential. The key areas that warrant further studies and consideration include:

- assessment of the pumping tests of the trenches to understand actual drawdown extents;
- determining the most acceptable distances of trenches from islands;
- demonstrate connectivity between clay pans and groundwater resources, which will be integrated with the hydrology studies looking at flood durations, etc;
- detailed lake infiltration and recharge testing;
- salt water balance modelling to understand the changes and possible migration of salt back into the lake; and
- hydrogeological modelling to predict the development of the drawdown cone, determine the optimum distance between trenches, and impacts associated with a changed regime.

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