# Hydrogeological Study
# Harvey-Waroona Region, South West WA
# Southern Perth Basin

A Report by ODIN Reservoir Consultants

DMP/2016/3




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# Disclaimer

Information gathered for this study has been based on the assessment of published reports, unpublished reports and of government databases. No independent field verification of information has been done nor has any field data been assessed. The materials presented herein are interpretive, and provided voluntarily. The information and advice provided is made available in good faith, and derived from sources believed to be reliable and accurate at the time of release. However, the information is provided solely on the basis that readers will be responsible for making their own assessment of the matters discussed herein, and that they verify all relevant representations, statements, and information. You should not rely solely on this information when making a commercial decision.

# 1. INTRODUCTION

## 1.1 Project Understanding

Odin Reservoir Consultants Pty Ltd (Odin) was asked to provide technical hydrogeological advice on a DMP project to assess the potential of the Lower Lesueur Sandstone (Wonnerup Member) of the South Perth Basin to store carbon dioxide.

The hydrogeological study is intended to be at a high level and serve as a guidance document with recommendations for a more detailed H-3 level study to be undertaken at a later date based on the Department of Water, Government of Western Australia, Operational policy no. 5.12.

Data has been collected for the area for the greater Harvey and Waroona shires and is available in digital format.

The project (Study Project Area) Figure 1, is the area where the H3 level study is proposed. This area is where the $CO_2$ could be injected and stored. Harvey 1, 2, 3 and 4 well have been drilled here and seismic geophysical surveys have been done to increase geological knowledge.

## 2. BACKGROUND AND LOCATION

The DMP is investigating the potential of the Lower Lesueur Sandstone (Wonnerup Member) of the South Perth Basin to store carbon dioxide. The work performed to date includes 2D and 3D seismic surveys and the drilling of four wells, Harvey 1, 2 3 and 4. Reservoir modelling updates are underway but previous work suggests that the area can store around 200 million tonnes of $CO_2$ in the Lower Lesueur. This is a significant volume and thus a broad hydrogeological study of the area is to be considered to understand the implications of such injection.

Development of this infrastructure is dependent on identifying and proving a suitable underground reservoir where $CO_2$ could be injected and stored, a process called geosequestration.

The Study Project Area (Figure 1) is within the Harvey Ridge structural subdivision of the Perth Basin. The Perth Basin is a sedimentary basin filled with sedimentary rocks, mainly sands and clays, deposited between the Permian and Cretaceous geological periods (300 to 100 million years ago). The Perth Basin is separated from the Archaean granitic rocks to the east by the Darling Fault.

Studies indicate that the Harvey Ridge structural subdivision in the Project Area is one of the least prospective areas for groundwater in the Perth Basin, because of the low elevation, clay soils and unfavourable structure which result in high salinity. The Harvey Ridge area is also notable for the absence of the Yaragadee Aquifer, a primary water supply aquifer in the Perth Basin for the South West of Western Australia. Figure 2 shows the general Perth Basin Stratigraphy and the specific stratigraphy of the Study Project Area.

Groundwater use in the Study Project Area is generally restricted to shallow bores in the superficial aquifer. Most of the groundwater in the underlying confined aquifers is brackish or saline, with hypersaline groundwater at depth in the Eneabba and Lesueur aquifers considered to be stagnant and isolated from meteoric groundwater flow (Commander, 2013).

It has therefore been decided that this area is the most prospective for investigation as it will have the least impact on useable water resources.

# 3. THE HYDROLOGY AND HYDROGEOLOGY OF THE STUDY PROJECT AREA

The Study Project Area is within the Harvey Ridge structural subdivision of the Perth Basin. The Perth Basin is a sedimentary basin filled with sedimentary rocks, mainly sands and clays, deposited between the Permian and Cretaceous geological periods (300 to 100 million years ago). The Perth Basin is separated from the Archaean granitic rocks to the east by the Darling Fault.

## 3.1 Hydrology

The study area contains no major natural drainage lines, but artificial drainage lines and drains have been constructed to remove excess surface water and relieve water logging occur inside the area.

The Harvey River Main drains to the north, feeding into the Harvey River which discharges into the Harvey Estuary.

The Harvey River Diversion drains to the south of the study area. The River Diversion receives excess surface water from areas to the east and groundwater baseflow from the Superficial Aquifer and directs the water to the west to discharge into the ocean just south of Myalup.

Surface water is also removed by smaller drains in the area east of Lake Preston which discharge into the lake.

The greater area is drained by Lake Preston Flow System, a series of shallow, north-south elongate, coastal lakes (Yalgorup lakes) developed in three lines parallel to the coast within the Yalgorup Plain. The three main surface water features in the greater area are Lake Clifton, the Lake Yalgorup chain of lakes and Lake Preston which occurs west of the study area (Figure 1). The lakes are maintained by groundwater inflow and direct rainfall to the lake surfaces, with very little surface water inflow.

Figure 3 shows the surface water features included in the Conceptual Model of the Study Project Area.

Figure 4 shows the Wetland mapping areas for the Swan Coastal Plain in the greater study area.

Many of the wetlands in the Study Project Area are ephemeral, due to seasonal inundation of water during the winter months. These are known as dampland or sumpland resource enhancement areas.

The Superficial Aquifer receives recharge from some of the wetlands, mainly sumplands in the area of the Yanget Mound. The Superficial Aquifer also contributes groundwater to the wetlands in specific instances of local high groundwater levels.

# 4. HYDROGEOLOGY

## 4.1 The Superficial Aquifer

The Superficial Aquifer Formations consists of Quaternary and Late Tertiary sediments which extend from the Darling Scarp to the Coast covering the Swan Coastal Plain.

The Superficial Aquifer includes a number of formations:

- The Yoganup Formation occurs along the edge of the Darling Scarp and comprises gravel sand and clay, generally derived from erosion of the elevated granites of the scarp.

- The Guildford Clay occupies the flat eastern Pinjarra Plain. It consists mainly of clay with minor sand beds and can be up to 30m thick. It generally is a very poor aquifer with low transmissivity and storage. Figure 6 shows the extension of the Guildford Clay into the Study Project Area. The Guildford clay is associated with brackish groundwater and poor groundwater yields.

- The Bassendean Sand and Ascot Formation forms a good aquifer up to 30m thick comprising mainly sand overlying shelly, minor calcareous and peat rich sand.

- The Tamala Limestone comprises sand and limestone is up to 90m thick and forms a very good aquifer although only approximately 25m is saturated below the water table.

- The Safety Bay Sands forms the Quindalup Dune System along the coast and is a good aquifer.

In the Project Area the Superficial Aquifer thickness varies from 36-45m.

### 4.1.1 Recharge

Recharge to the superficial aquifer occurs from direct rainfall above the aquifer and from runoff from the Darling Scarp.

There are two main areas of recharge of the Superficial Aquifer in the greater area of interest, mainly the Yanget Mound and the Mialla Mound (Figure 5) (Commander 1988). These two recharge areas are separated by the Harvey River Diversion drain. Figure 10 shows the water level contours generated for the Superficial Aquifer.

The Yanget Mound falls within the Study Project Area. Rainfall infiltrates as recharge in this area causing a mound in the groundwater table and groundwater flows from these mounds generally to the west and into the underlying Leederville Aquifer.

### 4.1.2 Discharge from the Superficial Aquifer to Surface Water Bodies

The Superficial Aquifer is at its highest in the winter months and discharges to the surface as springs/swamps or areas of inundation.

Minor flows from the Yanget and Mialla Mounds occur to the east as baseflow to the Harvey River as well as local discharge to drains.

The Superficial Aquifer also discharges to Lake Preston and Lake Clifton. The groundwater evaporates in the lakes becoming saline sinks with increased concentration of salts.
Groundwater flows from the east towards Lake Preston. Low salinity groundwater discharges from the Superficial Aquifer into Lake Preston over a wedge of a hypersaline water at the base of the Superficial Aquifer. (After Commander, 2013)

## 4.2 Superficial Aquifer Discharge to Aquifers

In the Project Area, the Yanget mound discharges to the underlying Leederville Aquifer due to the height of the mounds and the increased hydraulic gradient, In the Eastern Portion of the Greater Project area there is a thick sequence of Guildford clay which acts as an aquitard and prevents the downward recharge to the Leederville aquifer. Figure 6 shows the eastern portion of the Study Project Area where the Guildford clay extends over the Leederville Aquifer.

In the area of the Darling Scarp to the east of the Project Area, where the superficial aquifer lies directly on the Cattamarra aquifer, groundwater discharges directly to the Cattamarra aquifer.

### 4.2.1 Superficial Aquifer Salinity

Groundwater salinity in the Superficial Aquifer is variable. Figure 4 shows the groundwater salinity contours for the Superficial Aquifer. The salinity is lowest in the centre of the coastal plain in the Yanget/Mialla Mounds on the Harvey Flats, where salinity is less than 0.2 ppt. The salinity tends to be highest on the eastern limit of the coastal plain. The salinity also increases from the centre of the plain towards the coast. Near the lakes and wetlands, groundwater is generally brackish, and groundwater is hypersaline at the base of the Superficial Aquifer underneath Lake Preston although there is a wedge of lower salinity groundwater which actually discharges to the Lakes.

### 4.2.2 Groundwater Use

In the Study Project Area there are 15 licensed groundwater users abstracting a volume of 2182000 kL/annum from the Superficial Aquifer (Table 2).

The Superficial Aquifer is used for domestic and stock purposes and for irrigation in the Myalup area.

## 4.3 Leederville Aquifer

The Leederville Aquifer is composed of Cretaceous Sediments. It underlies the Superficial Aquifer in the Study Area but is absent in the area of the Darling Scarp.

In the Study Project Area, the Leederville is mainly shale and contains very few aquifer horizons. It is most likely that the Leederville in this area is likely to correlate with the Marginiup Member (Lower Leederville aquifer) (Commander, 2013).

The thickness of the Leederville Aquifer varies from 108-208m thick in the Project Area based on the drilling done to date.

### 4.3.1 Recharge

Regionally recharge to the Leederville Aquifer occurs from the overlying superficial aquifer in the area of the Yanget and Mialla Groundwater Mounds.

The Leederville Aquifer has an upward discharge of groundwater into the Superficial Aquifer at Preston Beach.

In the Study Project Area, the Yanget mound, due to the height of the mound and the increased hydraulic gradient, discharges to the underlying Leederville Aquifer unless there is a thick sequence of Guildford clay which can act as an aquitard and prevent the downward recharge to the Leederville aquifer. This occurs over the eastern portion of the Study Project Area (Figure 6) where the Guildford clay extends over the Leederville Aquifer.

### 4.3.2 Water Use and Salinity

Due to a large thickness of clays and poorly developed sand beds in the Leederville, the aquifer is poorly developed in the Study Project Area. There are no licensed users of the Leederville Aquifer in the Study Project Area due to its few aquifer horizons. Groundwater salinity is assumed to be variable. One record of salinity suggests it is around 1390mg/l but it is expected to be variable dependant on whether the Guildford clay is present as an aquitard above the Leederville or not.

The Leederville more regionally is used extensively for water supply in the Kemerton / Australind area as well as supplying Preston Beach and irrigation licenses in the Myalup and Coolup areas. Table 1 shows the licensed abstraction for the Leederville aquifer in surrounding areas.

## 4.4 Cattamara Aquifer

The Cattamara Aquifer does not appear to occur in the Study Project Area based on the geology of the Harvey exploration bores.

Regionally, the Cattamara Aquifer occurs below the Leederville Aquifer. The Aquifers comprises geological units of Early Jurassic Coal Measures.

The Cattamara aquifer has small areas where it receives recharge directly from the overlying Superficial Aquifer where it is in contact with the Superficial Aquifer, along the Darling Scarp.

The aquifer generally occurs under the shales of the Leederville Aquifer and as such it receives little recharge directly.

In the Kemerton area to the South, the Cattamara Aquifer is thought to receive fresh recharge (1000mg/l) from the Southern Yarragadee Aquifer (Commander, 2013).

### 4.4.1 Groundwater Use

In the Study Project Area there is no licensed groundwater use of the Cattamarra aquifer. In the greater Harvey–Waroona area there is no licensed groundwater use of the Cattamarra Aquifer (Table 1).

## 4.5 Eneabba Aquifer

The Early Jurassic Eneabba Aquifer occurs directly under the Leederville Aquifer in the Project Area as the Cattamarra Coal measures are absent.

The geology consists of interbedded sands and shales becoming increasingly shaley in the Eastern bores of the Harvey and Binningup Lines. The Eneabba first occurs at about 200m depth in the Study Project area. Thickness in the Project Area is highly variable from 147-677m. This is due to extensive faulting of the formation.

### 4.5.1 Salinity

The groundwater salinity in the Study Project Area was recorded in Harvey 4 bore as 70 500mg/l (Pers. Comm. Louis Stelfox). Groundwater salinities taken to date for the Eneabba, Yalgorup and Wonnerup in the study area are known to have KCL contamination however are included for relative comparison.

Groundwater salinity to the south, where the Eneabba Aquifer is thought to either have groundwater recharge from the Leederville or Southern Yaragardee, can be less than 5000mg/l.

The high salinity in the project area suggests the aquifer could be isolated by the faulting of the Formation, with water not recharged by the meteoric water cycle. Additional sampling to confirm the salinity results will be required.

### 4.5.2 Groundwater Use

In the Study Project Area, the Eneabba aquifer is not used for groundwater supply due to its depth and high salinity. There are no licensed water users in the greater project area (Table 1).

## 4.6 Lesueur Aquifer

The Lesueur consists of Late Triassic Sandstone and underlies the Project Area under the Eneabba Aquifer. It consists of two Members namely the Yalgorup Member and Wonnerup Sandstone Member.

The Lesueur Aquifer is the area targeted for $CO_2$ injection. The biggest risk in targeting this aquifer is that the $CO_2$ rich plume is able to migrate and impact on the upper aquifers of the Eneabba, Leederville and Superficial.

A study by Odin Reservoir Consultants (DMP/2016/5 - Dynamic Modelling of $CO_2$ Sequestration in the Harvey Area) shows the impact of injecting 800,000 tonnes of $CO_2$ into the Wonnerup through 9 wells (total of 24 million tonnes over 30 years). The study shows all of the $CO_2$ remains in the Wonnerup even after 1000 years. In the reference case, the $CO_2$ plume rises to a depth of ~2000 mTVDss.

## 4.7 Yalgorup Member

The Yalgorup Member, stratigraphically above the Wonnerup Member, consists of fine grained sands and siltstone beds**.** The Yalgorup has interstitial kaolin which reduces its permeability.

The Yalgorup Member in the Study project area varies from 474-810m thick due to faulting.

The Yalgorup Member salinity was measured in Harvey 4 well as 156 960 mg/l (Pers. Comm Louis Stelfox). Again the aquifer water quality will require resampling, as the analysis showed the water sample was contaminated with drilling fluid.

### 4.7.1 Water Use

Due to the Yalgorup Members aquifer depth and hypersalinity there is no water use.

## 4.8 Wonnerup Member

The Wonnerup Sandstone Member is poorly sorted and medium to coarse grained. The Wonnerup member has high porosity and permeability (Commander, 2013). The Wonnerup member is the target aquifer for injection of $CO_2$.

The Wonnerup Member in the Study Project Area varies from 908- 1428m thick due to faulting.

Rockwater, 2015 reported that on Harvey 3 well the water level stabilised at about 20 m below ground level, which is likely to be indicative of the potentiometric surface for the Wonnerup Member of the Lesueur Sandstone aquifer at this location

The Wonnerup Member salinity was measured in Harvey 4 well as 45230mg/l (Pers. Comm Louis Stelfox). ). Again the aquifer will require resampling, as the analysis showed the water sample was contaminated with drilling fluid.

The variation in TDS data between the overlying Yalgorup (156960mg/l) and Wonnerup (45230mg/l) gives an indication that there may be an aquiclude between members. Lower salinity water has a lower density and will generally “float” on higher salinity water. In the case of the Yalgorup (higher salinity than the Wonnerup Member) this has been reversed suggesting a physical barrier separating the two members of the Lesueur Formation. This is an area for future investigation.

However, with current knowledge this is positive for geosequestration as it could mean a aquiclude occurs which could stop migration of $CO_2$ rich fluid from the Wonnerup to the Yalgorup Aquifer.

# 5. GROUNDWATER ABSTRACTION

## 5.1 Groundwater Use

The Licensed Harvey Groundwater Subarea encompasses and overlaps the Study Project Area. In the Study Project Area there are 15 licensed groundwater users abstracting a volume of 2,182,000kL/annum from the Superficial Aquifer. Table 1 shows the Groundwater Subareas and the volumes being abstracted in the Study Project Area and Adjacent areas.

The Superficial Aquifer is used for domestic and stock purposes and for irrigation in the Study Project area.

Table 2 shows the Licensed Groundwater Users within the Study Project Area.

Table 1 Licensed Groundwater Abstraction Volume by Groundwater Subarea in Harvey- Waroona Area

| Groundwater Subarea | Aquifer | Licensed Volume of water being abstracted in Study Project Area | Licensed Volume of water being abstracted | No of licenses | Licenses within AOI |
|---|---|---|---|---|---|
| | | kL | kL | | |
| Harvey | Perth Superficial | 2182000 | 3531000 | 22 | 15 |
| Harvey | Perth Leederville | 0 | 0 | 0 | 0 |
| Lake Preston South | Perth Superficial | 0 | 48982180 | 42 | 0 |
| Lake Clifton | Perth-Superficial Swan | 0 | 335690 | 20 | 0 |
| Lake Preston North | Perth-Superficial Swan | 0 | 3037700 | 12 | 0 |
| Lake Preston | Perth-Leederville | 0 | 92000 | 5 | 0 |
| Coastal | Perth-Leederville | 0 | 20000 | 1 | 0 |
| Coastal | Perth-Superficial Swan | 0 | 80000 | 4 | 0 |
| Myalup | Perth-Superficial Swan | 0 | 32100750 | 51 | 0 |
| Kemerton North | Perth-Leederville | 0 | 4570000 | 13 | 0 |
| Kemerton North | Superficial | 0 | 0 | 0 | 0 |
| Karri | Perth-Superficial Swan | 0 | 0 | 0 | 0 |
| Karri | Perth-Leederville | 0 | 112850 | 36 | 0 |
| Karri | Cattamara | 0 | 0 | 0 | 0 |
| Kemerton Industrial Park I | Perth-Superficial Swan | 0 | 415900 | 3 | 0 |

## Table 2 Data for Licensed Water Users within Study Project Area

| Licence Number | Licence Type | Issue Date | Expiry Date | Licence Allocation | Groundwater Area | Sub Area | Aquifer | Licence Address |
|---|---|---|---|---|---|---|---|---|
| 157200 | Ground Water Licence | 21/04/2015 | 21/04/2025 | 692000 | South West Coastal | Harvey | Perth - Superficial Swan | Lot 5 on Plan 14927 - Volume/Folio 2076/841 - Lot 5 Goss Road Uduc |
| 157200 | Ground Water Licence | 21/04/2015 | 21/04/2025 | 692000 | South West Coastal | Harvey | Perth - Superficial Swan | Lot 8 On Plan 19981 - Volume/Folio 2091/341 - Lot 8 Goss Rd Uduc |
| 48612 | Ground Water Licence | 4/04/2013 | 31/03/2023 | 225000 | South West Coastal | Harvey | Perth - Superficial Swan | Lot 2427 on Plan 136889 |
| 48612 | Ground Water Licence | 4/04/2013 | 31/03/2023 | 225000 | South West Coastal | Harvey | Perth - Superficial Swan | Lot 14 on Plan 19981 |
| 63868 | Ground Water Licence | 16/09/2011 | 31/08/2021 | 117000 | South West Coastal | Harvey | Perth - Superficial Swan | Lot 3070 on Plan 90194 - Volume/Folio 1848/835 - Lot 3070 Riverdale Road, Cookernup |
| 53612 | Ground Water Licence | 15/03/2011 | 28/02/2021 | 52000 | South West Coastal | Harvey | Perth - Superficial Swan | Lot 2684 on Plan 135952 - Volume/Folio 1470/196 - Lot 2684 Richardson Road, Uduc |
| 104173 | Ground Water Licence | 22/05/2013 | 21/05/2023 | 45000 | South West Coastal | Harvey | Perth - Superficial Swan | Lot 2692 On Plan 136891 - Volume/Folio 1352/705 - Lot 2692 Richardson Rd Uduc |
| 95884 | Ground Water Licence | 3/04/2013 | 3/04/2023 | 40000 | South West Coastal | Harvey | Perth - Superficial Swan | Lot 7 On Diagram 78691 - Volume/Folio 1892/642 - Lot 7 Goss Rd Uduc |
| 64197 | Ground Water Licence | 23/12/2014 | 31/12/2024 | 35000 | South West Coastal | Harvey | Perth - Superficial Swan | Lot 4698 on Plan 207022 - Volume/Folio 364/74A - Lot 4698 Yarloop |
| 153200 | Ground Water Licence | 10/07/2013 | 9/07/2023 | 26000 | South West Coastal | Harvey | Perth - Superficial Swan | Lot 9 On Plan 19981 - Volume/Folio 2119/221 - Lot 9 Goss Rd Uduc |
| 57475 | Ground Water Licence | 16/11/2015 | 15/11/2025 | 18000 | South West Coastal | Harvey | Perth - Superficial Swan | Lot 4695 On Plan 207023 - Volume/Folio 341/137a - Lot 4695 Alexander Rd Yarloop |
| 100194 | Ground Water Licence | 13/06/2013 | 13/06/2023 | 8200 | South West Coastal | Harvey | Perth - Superficial Swan | Volume/Folio 1991/185 - Lot 33 Richardson Rd Uduc |
| 97794 | Ground Water Licence | 15/05/2013 | 14/05/2023 | 6800 | South West Coastal | Harvey | Perth - Superficial Swan | Lot 102 On Diagram 97478 - Volume/Folio 2192/46 - Lot 102 Stirling Rd Uduc |

# 6. CONCEPTUAL HYDROGEOLOGICAL MODEL

A conceptual hydrogeological model for the Project area has been compiled. A 3D structure has been drawn together in SCI 3D and includes all the hydrogeological units.

A summary of the relevant work done as well as data gathered and data gaps is included.

## 6.1 Properties of Hydrogeological Units in the Study Project Area

Properties of the Hydrogeological Units in the Study Project area are variable and in some cases are only estimates derived from other areas or from physical testing of core samples.

Further aquifer testing will be required to determine actual representative values within the Study Project Area.

### 6.1.1 Hydrogeological Units Thickness

Table 3 shows the thicknesses of the hydrogeological units in the Project study area. The thicknesses are highly variable in the Ennabba Formation, Yalgorup and Wonnerup Members due to faulting. These thicknesses were calculated from modelling of the well data from Harvey 1, 2, 3 and 4 and from the Harvey and Binningup Line bores. The F10 fault on the eastern part of the study area (location of Harvey 2 bore) is significant. Wells Harvey 1, 3 and 4 display greater consistency, but on a West to East downward sloping trend.

Table 3 Thickness of Hydrogeological Units

| **Hydrogeological Units** | Meters to base of aquifer | Standard Deviation | Minimum meters | Maximum Meters |
|---|---|---|---|---|
| Superficial | 41 | 4.2 | 36.8 | 45.2 |
| Leederville | 158 | 50 | 108 | 208 |
| Eneabba | 412 | 265 | 147 | 677 |
| Yalgorup - Basal Eneabba | 89 | 41 | 48 | 130 |
| Lesueur -Yalgorup | 642 | 168 | 474 | 810 |
| Lesueur-Wonnerup | 1168 | 260 | 908 | 1428 |

### 6.1.2 Permeability and Hydraulic Conductivity

Permeability is the property or capacity of a porous rock or sediment for transmitting fluid (Driscoll, 1995). In hydrogeology, hydraulic conductivity is the measure of the capacity of porous medium to transmit water (Driscoll, 1995). A number of calculations of hydraulic conductivity have been undertaken for the Hydrogeological units in the project area.

Table 4 shows the hydraulic conductivities for different formations and where the values were derived from. The values shown for PHRAMS refer to the "Peel Harvey Regional Aquifer Modelling System" (PHRAMS) groundwater model that was built for the CSIRO and DoW in 2011.

Permeabilities were calculated for the Eneabba, the Yalgorup to the Basal Eneabba (possible confining unit), the Yalgorup and the Wonnerup Members. The values were taken from the average permeability from core analysis testing for Harvey 1, 2, 3 and 4 wells.

The permeabilities do not show the variation expected as they are average values for the whole hydrogeological unit. Although the permeabilities do not show a great variation between aquifer units, injection modelling of 800,000 tonnes of $CO_2$ into the Wonnerup through 9 wells (total of 24 million tonnes over 30 years) shows all of the $CO_2$ remains in the Wonnerup even after 1000 years, (Odin, 2016).

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The permeabilities were given in millidarcies (mD) and converted to Hydraulic Conductivity values. Density and temperature were factored in as they impact on conversion. Ideally aquifer tests will be done on these specific hydrogeological units, particularly the Wonnerup, to get a more accurate hydraulic conductivity.

Table 4 Hydraulic Conductivity of Hydrogeological Units

| Hydrogeological Unit | Member | Source of Data | Horizontal Conductivity m/d | Initial vertical conductivity m/d | Calibrated Horizontal Conductivity m/d | Calibrated vertical conductivity m/d |
|---|---|---|---|---|---|---|
| | | | kh | kz | kh | kz |
| Superficial | Yoganup | Phrams | 10 | 1 | 1 | 0.1 |
| Superficial | Bassendean | Phrams | 15 | 1.5 | 5 | 0.5 |
| Superficial | Tamala Limestone | Phrams | 100 | 10 | 20 | 2 |
| Superficial | Safety Bay sand | Phrams | 15 | 1.5 | 15 | 1.5 |
| Superficial | Ascot | Phrams | 8 | 0.8 | 28 | 2.8 |
| Superficial | Guildford | Phrams | 0.1 | 0.01 | 0.2 | 0.02 |
| Osborne (Aquiclude) | | Phrams | 1x10-5 | 1x10-6 | 3x10-6 | 3x10-7 |
| Leederville | Leederville | Phrams | 2 | 0.2 | 0.2 | 0.02 |
| | Base of Leederville | Phrams | 1x 10-1 | 1x10-2 | 1x10-1 | 1x10-2 |
| | | Phrams | 3 | 0.3 | 2 | 0.2 |
| Enneabba | Eneabba | Calculated | 0.235755 | | | |
| Enneabba | Yalgorup - Basal Eneabba | Calculated | 0.2401208 | | | |
| Lesueur | Yalgorup | Calculated | 0.2390293 | | | |
| Lesueur | Wonnerup | Calculated | 0.231552 | | | |

### 6.1.3 Specific Yield and Storage Coefficients of Hydrogeological Units

Specific Yield and Storage Coefficients of Hydrogeological units were taken from the PHRAMs model that covers the project area. Table 5 shows a summary of the data.

Table 5 Specific Yield and Storage Coefficients of Hydrogeological Units

| Hydrogeological Unit | Member | Source of Data | Initial Specific Yield | Initial Storage Co-efficient | Calibrated Specific Yield | Calibrated Specific |
|---|---|---|---|---|---|---|
| | | | Sy | Ss | Sy | Ss |
| Superficial | Yoganup | Phrams | 0.2 | | 0.2 | |
| Superficial | Bassendean | Phrams | 0.2 | | 0.2 | |
| Superficial | Tamala Limestone | Phrams | 0.3 | | 0.3 | |
| Superficial | Safety Bay sand | Phrams | 0.2 | | 0.2 | |
| Superficial | Ascot | Phrams | 0.2 | | 0.3 | |
| Superficial | Guildford | Phrams | 0.1 | | 0.1 | |
| Osborne (aquiclude) | | Phrams | | 1x10-5 | | 5x10-6 |
| Leederville | Leederville | Phrams | | 1x10-4 | | 5x10-5 |
| Enneabba | Eneabba | | | ? | | ? |
| Lesueur | Yalgorup | | | ? | | ? |
| Lesueur | Wonnerup | | | ? | | ? |

## 6.2 Summary on Aquifer Parameters

The Superficial Aquifer Parameters have been calibrated in PHRAMS and are believed to be reliable. During any further modelling the parameters should be recalibrated against recharge and abstraction.

The Leederville in this area is part of the Marginiup Member (Lower Leederville aquifer) (Commander, 2013) and some parameters have been calculated. Unfortunately in the project area there is limited Leederville Monitoring data so if additional monitoring bores are drilled, there should be an attempt to derive aquifer parameters from them through aquifer testing.

Below the Leederville there is limited aquifer parameter information except Permeability derived from core samples. This data has been used to calculate hydraulic conductivities. Small variation in the data values between the geological units for the permeability suggests that they are not representative of hydrogeological formations which are known to be variable. As it is essential for $CO_2$ injection to understand what the aquifer parameters of the more and less permeable areas of the underlying hydrogeological units are, additional data gathering will be required through aquifer testing.

## 6.3 Conceptual Model Structure

Data was captured and imported to a 3D modelling system in order to visualize and interpret the important hydrogeological aspects as part of the hydrogeological site investigation. This data was used to create a conceptual groundwater representation of the area.

## 6.4 Seismic Interpretations of Aquifers

Odin Reservoir Consultants used seismic data to interpret and create 3D surfaces of the aquifers and geological units in the area. These surfaces were imported as “Charisma.txt” files. These surfaces display the top elevation of the aquifer units in the study area in 3D and this includes all the interpreted faults and displacements for the study area. The aquifer top surfaces display two large vertical displacements associated with the ‘Western Fault’ and the ‘Fault 10’ fault zones. Various other faults were interpreted with smaller displacements in the area. The data was excellent for the Study Project Area and the deeper aquifers and the area surrounding it. Figure 6B shows the 3D model of the seismic data with the faults included.

## 6.5 Binningup and Harvey Lines and Harvey-1 to Harvey-4 bores

The geological drilling data for the Binningup and Harvey Lines as well as the new Harvey-1 to Harvey-4 bores were extracted from the DoW data and imported to 3D format with their associated geological logs (Figure 7A). The depth of the bores vary from 600m below surface for the shallowest bore BPL2A1 to 4565m below surface for the deepest 'Lake Preston 1' bore.

The geological units in the drilling data were used to create surfaces of the corresponding aquifer units but these surfaces are too simplified compared to the Seismic Interpreted Layer data. The Seismic Interpreted Layer data indicated that the deep aquifer surfaces were undulating and there are several fault displacements. The drilling data alone could not be used to derive the complex geometries of the aquifer surfaces.

### 6.5.1 Bore and monitoring data from the DoW

The Bore and monitoring data from the DoW were extracted as ArcMap shape files and imported and displayed for the Study Area. The bores were queried according to the aquifer that they represent in the DoW database and displayed with a colour distinction based on the representative aquifer. Most of the bores represent the shallow aquifers such as the Superficial and Leederville aquifers with a very few records for the Cockleshell Gully aquifer. Figure 7B show the shallow bores with aquifer data for the Study Project Area and surrounding areas.

### 6.5.2 Hydrology

The Major and Minor rivers were imported from the DoW online database and captured in 3D format as polygon data. The data contained various attributes such as the feature types, names and river size data. The data were then clipped to the general project area for display of the relevant surface water features for the Study area. No major rivers are flowing through the Study Area except for the Harvey Main Drain that flows into the Harvey Estuary.

The surface water features for the general project area were captured and it includes estuaries, lakes, farm dams, canals, swamps, settling ponds and watercourse Areas. The data clearly defines the important surface water features located in or close to the Study Area. The data is shown in the digital format as Figure 3.

### 6.5.3 Topographic Data

The 25m DEM data from the http://www.ga.gov.au/elvis/ web portal were transformed from ArcMAP binary grids to ASCII grids and imported into the system in order to create a realistic topographic surface. The data displays very good resolution and coverage in the project area. The topographic surface elevation varies between ~-1.5 m (MAMSL) in the west close to the coast and ~241m (MAMSL) in the east close to the Darling scarp. Figure 9 shows the Topographic data imported into the Conceptual Model 3D structure.

### 6.5.4 Guildford Clay Unit of the Superficial Aquifer

The Guildford clay unit in the Superficial Aquifer were digitised from the report “Groundwater resources of the Lesueur carbon storage project area (SW Hub) Commander (2013)”. This clay unit underlies the Study Area on the eastern side. It is expected that the Leederville aquifer underneath it may contain more saline water due to a lack of direct recharge from the Superficial Aquifer. Figure 6 shows the Guildford Clay unit extending into the Study Project Area.

### 6.5.5 PHRAMS Groundwater Model Structure

Layer and construction data from the “Peel Harvey Regional Aquifer Modelling System” (PHRAMS) groundwater model were imported and processed. The data extended from Mandurah in the north to Bunbury in the south and it was clipped to fit into the project area. This model was built for the CSIRO and DoW in 2011. It is a six layer model with very shallow vertical extent. This model was built to a depth of -87.5m below the topographic surface and it was constructed and calibrated for the Superficial and Leederville Aquifers only. The model does not contain information about the deeper aquifers underneath the Leederville or represent the hydrogeological aspects of the deeper aquifers in the project area.

### 6.5.6 Potentiometric Heads for PHRAMS

The water levels from the “Peel Harvey Regional Aquifer Modelling System” (PHRAMS) model were imported and surfaces generated for each aquifer present in the study area. The head

data reflect the expected water levels for the Superficial and Leederville aquifer from the calibrated model results. Figure 10 shows Water level contours generated for the top of the Superficial Aquifer.

### 6.5.7 Permeability Data

The “perm_facies_energy: mD” variable of the four Harvey-1 to Harvey-4 bores were processed and imported to the 3D environment. These values represent permeabilities in milliDarcy’s and a 3D grid was calculated for the data after the ‘zero’ values filtered out. This data was estimated into a grid to see if continuity could be displayed between the four holes. As there was no continuity or relationship between the data no surface of permeability could be displayed, Figure 11A shows Millidarcy information for the Harvey 1-4 bores. Figure 11B shows the unsuccessful attempt to correlate the permeability data between the Harvey 1-4 bores.

### 6.5.8 Cross Section of Hydrogeological Units

A vertical cross section from East to West was generated through all the Hydrogeological Units including the topography and it includes the Harvey-3 and Harvey-4 bores. The cross section includes the two major faults zones ‘Western Fault’ and “Fault 10” with the displacement that they caused in the deeper aquifers. Figure 12 shows the cross section which is utilised to put together a Conceptual Diagram of the Aquifer systems.

### 6.5.9 Extension of Deeper Hydrogeological Surfaces in Wonnerup, Yalgorup and Sabina

The deeper aquifer surfaces such as the Sabina, Wonnerup and Yalgorup Surface were extended in the 3D model horizontally to cover a larger area outside of the study area. The surface was extended with a built in algorithm that uses the local trends on a surface to extend it to a larger boundary. Figure 13 shows an example of the Sabina Surface extended outside the Study Project area using an algorithm. Figure 15 shows the unextended Yalgorup surface with Fault 10 and Western Fault.

### 6.5.10 Water Quality

Water Analyses Results are available for all aquifers except the Sabina Aquifer. Discussion on the water qualities and their reliability is in Chapters 8, 9 and 10. Water qualities were plotted for information sake in Piper and Expanded Durov diagrams (Figures 15b and c). The Durov diagram shows Superficial and Leedervile water qualities moving along the Chebotrev sequence of natural salination where water moves from meteoric to saline water as it has longer residence time in aquifers. The three deeper water qualities are for information purposes only as there has been contamination of the samples by drilling fluid The Yalgorup Water Quality is at the end of the salination sequence. The slight shift off the Chebotrev line in the Wonnerup and Eneabba suggests possible mixing or chemical reactions.

## 6.6 Data Gaps with Conceptual Model Structure

I. DoW drilling data – the current drilling data from the DoW for the 'Greater Area of Interest' contains several bores in the area however several of them have not been marked with which aquifer is represented by the bore.

II. The PHRAMS model does not have any information for the important deeper aquifers. It was constructed to a depth of -87.5m and cannot be used to model or simulate hydraulic gradients of any of the deeper aquifers.

III. The aquifer parameters for the PHRAMS model includes only the top Superficial and second Leederville aquifer. Aquifer parameters are relatively well established for these aquifers. Aquifer parameters (hydraulic conductivity) for the deeper aquifers in the project area are based on the permeability measurements from the cores and do not seem to have much variation which suggests they could be wrong. Additional aquifer testing to establish parameters for both hydraulic conductivity and storage coefficients should be planned.

IV. The geological logs of the Binningup Line and Harvey Line bores do not contain confirmed horizon nomenclature for the deeper aquifers subdivisions. This bore data needs to be reinterpreted to and the horizons confirmed to extend the existing deeper aquifer data to a larger area outside the study area.

## 7. GROUNDWATER FLOW SYSTEMS

The conceptual flow system model diagram is included as Figure 14.

Meteoric rainfall recharges the Superficial Aquifers. Areas of surface water inundation occur largely in the western area of the Study Project Area. In these areas, recharge will be high into the Superficial Aquifer. This creates a mound in the groundwater known as the Mialla Groundwater Mound. Groundwater in the Superficial will be very recent to hundreds of years old.

Groundwater flows from the Superficial in the area of the Mialla Mound into the Leederville Aquifer in the Project area. If the Guildford Formation is present as it is in the west of the area, it does not allow recharge of the Leederville in which case the Leederville becomes increasing saline. The Leederville Aquifer in the Study Project area comprises beds of shale and poorly developed sands (Marginiup Member) and as such is a poor aquifer with no users. The Leederville has a recorded salinity of 1350mg/l. In general the Leederville will be thousands to tens of thousands of years old (Commander, 2013)

Underlying the Leederville is the Eneabba Aquifer. Generally it is separated from the Leederville Formation by the Cattamara Coal Measures, however in the Study project area these have been eroded.

The Eneabba Formation consists of poorly bedded, weakly cemented sand and shales. Recharge can occur from the Leederville into the Eneabba, however based on the salinity of the Eneabba of 70500mg/l obtained from Harvey 4 well (compared to 1350mg/l for the Leederville Formation), in the Study Project Area, the Eneabba is probably isolated to recharge from the Leederville aquifer. As discussed previously, the water quality sample for the Eneabba was contaminated so to confirm differences in salinity, a representative sample should be taken.

The underlying Lesueur Aquifer could be considered sequestered (Commander, 2013) and isolated from the other aquifers and the meteoric water cycle. It is likely that the saline groundwater in the confined aquifers of the Lesueur Sandstone has originated as sequestered seawater which could have entered the aquifers in the late Pliocene (around 2 million years ago) when the Darling Scarp was a coastline, or more likely as early as marine transgressions

in the early Cretaceous (130 million years ago), following uplift and erosion, and prior to deposition of the Leederville Formation. The evolution of the hypersaline groundwater could be through the process of ultrafiltration over a long period whereby hydrostatic pressure allows water molecules to pass through shales, leaving the larger salt molecules behind (Commander, 2013).

The isolation of the Lesueur Aquifer could be confirmed physically by conducting test pumping in the Wonnerup member of the Lesueur Aquifer and monitoring of the groundwater levels (pressure gradients) in the Yalgorup and Eneabba Aquifer and the aquifers above. Test Pumping should be properly planned. A predictive analytical/numerical groundwater model should first be constructed to determine the volume that would be required to be abstracted and time necessary for a drawdown response in the Yalgorup Member and Eneabba Aquifer assuming there is no confining/semi-confining barrier. The volumetric calculation can be used to plan for the surface saline water containment system for the abstracted water. Aquifer parameters could be calculated for the Lesueur Aquifer from the test and the test would confirm the nature of the confining layers between the aquifers. .

Thermal convection cells have been postulated for the Perth basin previously, based on work done for geothermal feasibility studies (Sheldon et al., 2012). Such systems would also be relevant for solution transport in these isolated aquifers of the Lesueur Aquifer causing very slow movement of water.

The Lesueur Aquifer could to be compartmentalised between the Yalgorup and the Wonnerup Members with an aquiclude between them. This will require further investigation. The salinity of the overlying Yalgorup is measured as 156960 mg/l in Harvey 4 whilst below in the Wonnerup Member's salinities are 45230mg/l. Unless there was a physical barrier to flow, the density difference would not allow the less saline Wonnerup aquifer to form beneath a more saline aquifer. This is important as it may mean that during $CO_2$ injection the barrier could isolate the injection fluid within the Wonnerup Member. As discussed previously, the salinity values are questionable due to drill fluid contamination of the sample so to confirm the aquiclude hypothesis, additional representative salinity analysis would be required.

In both the Lesueur and the Eneabba it could be that the ground water is possibly compartmentalised in an east- west direction due to the two major sub-vertical faults (Figure 14). The aquifer would be open in the North-South direction.

The volume of CO2 injected into the aquifer with regards to the overall Lesueur aquifer volume in the AOI in the area of the Harvey Ridge is so small it would have minimal volumetric impact to the larger Lesueur Aquifer and any fault boundary conditions would have no impact on injection.

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# 8. GEOCHEMICAL CONSIDERATIONS AND POTENTIAL IMPACTS OF INJECTION OF $CO_2$ INTO WONNERUP SANDSTONE

## 8.1 Background

Supercritical $CO_2$ is an immiscible fluid that has physical properties that are intermediate between those of a gas and a liquid. The density of supercritical $CO_2$ is highly dependent on temperature and pressure.

Existing work on the behaviour of injected $CO_2$ has found that it will rise (be less dense than brine) upon initial injection but that over time it can dissolve in water and the resulting solution becomes more dense than the formation water.

The rate of $CO_2$ dissolution in formation water depends on several factors, including trapped phase in pore spaces that will react faster than bulk phase, due to greater interfacial contact area, as well as potential convection cells that may be induced due to density and temperature changes.

Density differences that could induce flow may occur through absorption of $CO_2$ making water approximately 1% denser than initial formation water (IPCC, 2005). Thermal convection cells have been postulated for the Perth basin previously, based on work done for geothermal feasibility studies (Sheldon et al., 2012). Such systems would also be relevant for solution transport.

Under high pressure conditions, pure $CO_2$ dissolved in pure water results in a carbonic acid solution that reaches an equilibrium pH of approximately 3 compared with 5.6 under atmospheric $CO_2$ conditions, i.e. a much stronger acid. Mineral stability is also affected under high pressure conditions.

Experiments conducted by Rathnaweera et al. (2015), to simulate $CO_2$ injection into saline sandstone formations, showed substantial increases in various dissolved species from sandstone samples after the samples had been left to react under pressure, in the presence of $CO_2$ over a period of 1.5 years.

Coal fired power plant exhaust gas streams contain various gasses together with $CO_2$. Concentrations of SOx, NOx gasses are generated as a function of coal impurities and

combustion conditions and residual oxygen is also present where complete combustion occurs. During $CO_2$ separation minor amounts of these other gasses are included in the $CO_2$ stream. Although they make up a minor fraction, gases such as $SO_2$ can dramatically affect the geochemical behaviour of injected $CO_2$ in an aquifer, being much stronger acids than $CO_2$ (IPCC, 2005).

Formation of organic compounds, such as formaldehyde, can also occur through the use of amines for $CO_2$ trapping (Nelson et al., 2015).

The geochemical reactions that may occur as a result of $CO_2$ injection will therefore depend on the aquifer mineralogy, the brine composition and the gas stream composition, along with pressure and temperature.

Mineral dissolution, precipitation and / or transformation (e.g. ion exchange) reactions may occur. Co-precipitated minor and trace elements, some of which have the potential to be harmful in the biosphere, can also be mobilised through some of these reactions. Within the storage aquifer, mobilisation of minor and trace elements is not relevant unless they contribute to the formation of precipitates, since the water will not be abstracted for any useful water supply purposes. However, minor and trace element mobilisation would be an important consideration if there is any risk of stored gas escaping into overlying aquifers over time, where even relatively small concentrations could affect water quality.

The Greenhouse Gas (GHG) amendments to the *Petroleum and Geothermal Energy Legislation Amendment Bill 2013,* currently before Parliament, specify GHG as carbon dioxide, but does allow for one or more incidental GHG related substances. The level of these will form part of Regulations and licence conditions. The $CO_2$ quality will need to form part of any submission and approval process

Most minerals found in sandstone aquifers are relatively slow to react, with the exception of carbonates and sulphide minerals in the presence of acids and oxygen respectively.

Over the timescale relevant to $CO_2$ capture and storage, even silicate dissolution rates will be important. In a clean sandstone aquifer, mineral reactions that trap $CO_2$ in carbonate minerals will not be important, as can be the case in other formations with more diverse and reactive mineral assemblages.

Mineralogical changes may also occur in the low permeability sealing layers overlying the aquifer, as likely through diffusion as advection. Diffusion can occur at higher rates under high pressure than at atmospheric pressure (Iglauer, 2011). In thick confining sequences such reactions are probably slow enough to be unimportant over the timescale of interest. However, they should be evaluated from a due diligence perspective, to evaluate effects that may occur over the very long periods that may be relevant. Issues such as transport rates, reaction front composition and mineral volumetric and permeability changes should be considered.

Reaction fronts will develop where reactions are fast enough to respond to the progression of the $CO_2$, while slower reactions may affect bulk mineral stability and solute concentrations over longer periods. Where reaction fronts occur, they can promote pore blockage through precipitation of new minerals as a result of mixing and concentration of dissolved species at the reaction front. This is typical of reactive transport processes.

### 8.2 Water Quality of the Lesueur Aquifer

The water sample analyses provided for the Eneabba, the Yalgorup and the Wonnerup are affected by KCl contamination from drilling fluid. The KCl is present in variable concentrations from approximately 1% to approximately 15%. This compares with concentrations of approximately 20% KCl in the drilling mud (Rockwater, 2015 and recent Corelab fluid analyses). The presence of relatively high concentrations of Al and Si in the affected analyses also suggest that the samples were not filtered at the time of collection, or were not filtered sufficiently to remove colloidal clay particles. Consequently the analyses are not accurate reflections of geochemical equilibrium conditions in the aquifer.

The Harvey 4 water quality analyses for the Enneaba, Yalgorup and Wonnerup Formations were speciated in PHREEQC, using the phreeqc.dat thermodynamic database. In an attempt to improve the accuracy of these calculations, the K concentrations were adjusted to reflect the Na/K ratio of average sea water and $Cl^-$ was used as the charge balancing ion. A water mass correction was also made for ion dilution effects associated with the Yalgorup sample, to account for the presence of approximately 15% KCl.

Convergence could only be obtained in PHREEQC speciation calculations if Al was eliminated from the calculations, which is consistent with the presence of Al in colloidal form, rather than as a dissolved species.

Reaction temperatures and pressures were set at the measured Harvey 4 field values, reported with the Corelab fluid analyses. Silica concentrations were found to be close to saturation for amorphous silica for the Enneaba and Yalgorup samples and with quartz for the Wonnerup sample. All the PHREEQC speciated solutions indicated super saturation of calcite, dolomite and siderite, with the exception of the Wonnerup sample that was undersaturated in siderite. This is an indication that $CO_2$ degassing occurred prior to measurement of alkalinity and pH.

PHREEQC analyses were recalculated by adjusting $CO_2$ concentrations to obtain calcite saturation indices of approximately 0. Through this method, it was found that initial pH values were probably around 6.5 for the Enneaba and Yalgorup Formations and around 6.2 for the Wonnerup Formation, assuming that formation water is in equilibrium with calcite. Corresponding $CO_2$ partial pressures were 0.02 atm, 0.05 atm and 0.11 atm respectively.

Barite and Hydroxyapatite are supersaturated in speciated solutions, although the reason cannot be established with any certainty without additional data. Several Iron minerals are shown to be near saturated, with siderite being the closest to saturation in the Enneaba and Yalgorup Formations and siderite and goethite being near saturated in the Wonnerup Formation.

In summary, the PHREEQC speciation indicates the presence of minerals that would generally be expected in a sandstone lithology, with the exception of the aluminium containing minerals (such as clays) that had to be ignored.

It should be noted that the effects of contamination on sample composition are uncertain. Although corrected sample compositions provide reasonable speciation results, they are not reliable without further confirmation. Multiple samples should be used for comparison and speciation data should be compared with mineralogical data to ensure consistency.

Under high pressure conditions it is important to take in-situ measurements, or to preserve samples under ambient pressure conditions. One of the main reasons for this is that degassing through depressurisation, especially of $CO_2$, can rapidly change sample pH and any mineral

stabilities that depend on it. The pH is a critical parameter in correctly predicting mineral speciation and carbonate minerals are particularly sensitive. In a deep borehole, sampling through pumping causes depressurisation over a long transport path, potentially making it difficult to obtain an accurate pH at surface, even using a flow cell.

A pressurised sample may be needed or, if suitable equipment is available, in-situ measurements should be taken.

### 8.3 Recommendations for future hydrogeochemical work

The following work is specified based on supplied information. Some of it may already have been done. The recommended work is to obtain an adequate understanding of the geochemical conditions at the study site, focussing on the Lesueur sandstones and overlying stratigraphy. Work should be scoped with a view to following a risk based approach, with the following tasks envisaged:

#### 8.3.1 Water sampling

If accurate water quality analyses are required, a new borehole may have to be drilled to obtain them, unless sampling can take place from existing drill sites. The drilling method and drilling fluid that is used should be assessed carefully beforehand, to minimise the contamination of the aquifer. KCl is highly soluble and is likely to infiltrate the aquifer for some distance around the bore. This makes it very difficult to obtain a representative sample from the aquifer if the borehole cannot be pumped clean through displacement of several bore volumes prior to sampling. Borehole purging is difficult at Harvey due to the poor water analyses, which requires careful consideration of this aspect before drilling occurs.

A sample of any drilling fluid that is used should be kept for analysis, in case corrections need to be made for residual contamination, as was done for Harvey 4.

For geochemical modelling it is imperative that a filtered sample be collected for analysis. As a minimum, fresh sub-samples of acidified and un-acidified water should be collected prior to analysis to ensure accurate determination of soluble ions and metals / metalloids. Standard groundwater sampling and monitoring equipment is normally unsuitable for use at the high pressures that occur at the depths of interest. Specialised equipment (possibly custom made or developed for the oil industry) may therefore be necessary. Sampling should therefore be planned in detail prior to finalising a work plan.

Physico-chemical parameters, especially pH should be measured on a pressurised sample if possible. Unless a multi-parameter probe can be obtained that can operate at the pressures in question it may be necessary to collect a pressurised sample to achieve this. Multi-parameter probes generally operate to maximum depths of the order of 100 m to 200 m.
Ideally oxidation reduction potential (ORP) should also be measured and Fe speciation should be measured to facilitate calculation of the correct redox potential (since ORP tends to be inaccurate in the presence of dissolved Fe).

If a fully pressurised sample cannot be collected, sampling equipment should allow for headspace gas volume and pressure to be calculated, as well as for the gas composition to be analysed. This will enable back calculations of gas sensitive parameters to be done more accurately, if necessary.

Ideally, several samples (at least 5) should be collected and tested from different depths for each major geological unit, to obtain an indication of variability.

### 8.3.2 Rock Sampling

Samples of drill cuttings or core material should be collected for geochemical testing. They should include the Wonnerup Formation and overlying confining strata, as well as any potential water supply aquifers that may be affected above or nearby the storage compartment. The following tests should be carried out, as a minimum:

Leaching tests to evaluate the influence of $CO_2$ and mixtures of $CO_2$ and $SO^2$ on mineral solubility and element mobilisation. This will be necessary to predict possible reactive transport impacts associated with the injection process. Leach testing may be done according to standard leach methods if a suitable geochemical model can be constructed to justify such an approach, but more accurate results will be obtained if samples are tested under representative conditions of pressure, temperature and gas composition.

Basic Acid Sulphate Soil tests should be included, since the presence of sulphides may have an important geochemical influence if any oxygen is included in the injection stream.
Several samples (at least 5) should be collected from each major geological unit at different depth to evaluate variability.

## 8.4 Aquifer Parameters

Measured Aquifer Parameters (Hydraulic Conductivity), for the different Yalgorup and Wonnerup Members are required for geochemical modelling and volumetric estimates of $CO_2$.

## 8.5 Modelling

If a suitable range of gas composition is not available for the likely injection stream, a model should be developed that is specific to the gas stream that will be treated. This can be done using a stochastic model based on mass balance and chemical partitioning principles, unless an accurate deterministic model can be developed based on existing information.

Relevant transport pathways and processes should be identified and geochemical speciation and transport models should be developed based on the available data. As a starting point, models should be developed to facilitate risk assessment of specific scenarios. In such cases, simple geochemical speciation and 1D reactive transport models should be sufficient to evaluate specific transport pathways. Several software packages are capable of such simulations, however, the relevant software should be selected carefully to ensure that it is suitable for simulating the salinity, temperature, pressure and important mineral phases that are present or could form. Many thermodynamic databases that are commonly used for geochemical modelling are unsuitable, so they should not be used without an understanding of their limitations.

Geochemical modelling software continues to be refined and developed for conditions that diverge from ideality and standard temperature and pressure. Hence the modelling environment should be selected by the geochemist at the time the work commences.

If required, a more detailed 3D model can be developed to simulate multiphase reactive transport processes that would occur through the injection of the $CO_2$ stream into the Wonnerup Formation. Such a model will only be representative and useful if an accurate geological-stratigraphic model and associated mineralogical and water composition is available, along with hydrogeological parameters. Also, such a model will probably only be useful if preliminary 1D and 2D reactive transport models indicate that more detailed modelling is required to evaluate specific geochemical processes. The use of a 3D model will be the only way to simulate injection plume spreading and associated geochemical reactions with reasonable accuracy. Long-term impacts and their anticipated timeframes will also be more

easily demonstrated using such a model, although key processes could be quantified more simply.

### 8.6 Approximate costs

Estimated costs for the geochemical assessment, pertaining to data processing, modelling and reporting are included in Table 7. Drilling, sampling and testing costs, as well as associated fees, are excluded, since they would need to be established in detail for the prevailing site conditions and desired outcomes. Project liaison and management fees are also excluded, since they would depend on the project reporting structure and requirements.

No cost is provided at this stage for a 3D reactive transport model, since it will depend on which software is used, as well as the available information that can be input to the model. In any event, such a model should only be attempted once preliminary work, which can be used to facilitate scope development, has been completed.

Cost calculations in Table 7 are estimated based on professional fees for the geochemist at a rate of $200 per hour.

Table 6 Estimated costs for geochemical evaluation inputs

| Cost item | Cost (Excl. GST) |
|---|---|
| Literature and data review | $10,000 |
| Injection gas composition, based on site-specific assumptions and available data and literature. This will be done using a stochastic model constructed with GoldSim software. | $15,000 |
| Identification of relevant transport pathways and exploratory modelling of speciation and 1D or 2D reactive transport processes for the Wonnerup and Yalgorup Formations, and other relevant geological units. Models will be based on the mineralogical, water quality and gas compositional data to be collected. | $40,000 |
| Reporting | $15,000 |
| **Total** | **$80,000** |

# 9. RECOMMENDATION TOWARDS DEVELOPMENT OF A CONCEPTUAL BASELINE MONITORING PROGRAM

Groundwater monitoring is required for the development of a conceptual baseline groundwater quality, levels and piezometric pressure monitoring for the existing aquifers. In a water monitoring program any impact on bore yields, groundwater levels, groundwater quality (e.g. saline interface), other users , the environment or aquifers needs to be monitored according to Operation policy no 5.12 (Hydrogeological reporting associated with a groundwater well licence).

The proposed groundwater monitoring program is provided to monitor the impacts of ongoing groundwater abstraction and $CO_2$ injection prior to and upon commencement of operations. Existing Department of Water observation bores may be suitable for ongoing monitoring however they only monitor the Superficial Aquifers in this area and may be required closer to the $C0_2$ injection sites prior to injection to establish baselines. The Department of Water bores in the Project Area only appear to be monitoring groundwater levels not chemistry at present.

Groundwater modelling particle tracking should be done to show the movement of any possible groundwater contaminants and additional monitoring bores should be placed up and down the hydraulic gradient of the potential flow paths.

## 9.1 Establishment of Monitoring Network

### 9.1.1 Superficial Aquifer

The Superficial Aquifer has the only licensed abstraction within the project area.

There are 15 recorded Department of Water monitoring sites within the Project area. A site assessment of the current status of these bores is proposed to determine their ability to provide representative monitoring data. If additional bores are required a costing for these is provided. The Department of Water monitoring bores only appear to be used to monitor groundwater levels at present and this could be due to their construction/present condition. As groundwater chemistry would be required for ongoing monitoring, it is proposed to assess the Department of Waters bores current status to determine whether they are able to be utilised for the

groundwater monitoring program. If not costs are included to drill additional bores in the Capital Costs section of Table 10.

### 9.1.2 Leederville

There are no licensed users of the Leederville aquifer. There is also no Department of Water Leederville monitoring bores within the Study Project Area.

It is proposed an up hydraulic gradient and two down hydraulic gradient monitoring bores be constructed in each aquifer in the vicinity of any proposed $C0_2$ injection site to monitor background water quality and water levels piezometric pressure and hydraulic gradients. The actual positions can be determined from the groundwater modelling particle tracking of possible contaminants in the aquifers once the groundwater model is constructed. Costs are included to drill monitoring bores in the Capital Costs Section of Table 10.

### 9.1.3 Eneabba Aquifer

There are no licensed users of the Eneabba aquifer within the Study Project Area. There are also no Department of Water monitoring bores. Monitoring within the Eneabba could be useful as it could show any changes in water chemistry before the changes impact the Leederville and the aquifer is still fairly accessible being around 250m depth at its deepest.

It is proposed an up hydraulic gradient and two down hydraulic gradient monitoring bores be constructed in each aquifer in the vicinity of any proposed $C0_2$ injection site to monitor background water quality and water levels/ piezometric pressure and hydraulic gradients. The actual positions can be determined from the groundwater modelling particle tracking of possible contaminants in the aquifers once the groundwater model is constructed. Costs are included to drill monitoring bores in the Capital Costs Section of Table 10.

### 9.1.4 Lesueur Aquifer (Yalgorup / Wonnerup)

The Wonnerup Member of the Lower Lesueur Aquifer is the aquifer targeted for $C0_2$ injection.

Monitoring of the Lower Lesueur would be essential although difficult. Ideally there should be three monitoring points for each aquifer.

Possible recommendations based on the status of the existing wells are as follows.

Harvey 3 is cased to the top of the Wonnerup Member. The casing could be slotted in the area of the Yalgorup formation by an oilfield wireline setup. The plug at the base of the Harvey 3 well could be drilled out and drilled deeper (if this is done before the Yalgorup Member is slotted a pump test could be done on the Wonnerup open hole). Slotted monitoring conduits (nested piezometers slotted over the injection area of the Wonnerup and above the base of the Yalgorup Members) could be gravel packed and cement grouted in grout raises to separate the members.

Harvey 4 could be similarly have slotted casing installed at the positions of the base of the Yalgorup and near the injection area in the Wonnerup Member or at the top of the Wonnerup to assess change in chemistry as injection proceeds. These slotted sections could be gravel packed and separated by cement grout.

These piezometers could then be developed and provide both water qualities and piezometric heads over the slotted portion of the deeper members. It is recommended that instead of traditional slotted and blank uPVC, 100mm polypipe could be considered as piezometers, as the joints would be much further apart and could be poly welded and it would be simpler to install with less chance of failure or issues with pressure damaging uPVC at depth. The existing well casing would provide some protection if polypipe or traditional uPVC was used.

Future Harvey wells may be perforated to provide measurements for water quality and levels as well as for hydraulic conductivity assessments. It is envisaged that these wells would become the deepest monitoring network for the Lesueur.

Another possible option would be to have fully grouted Vibrating Wire Piezometers in the Wonnerup and Yalgorup and at their interface and possibly in the Leederville and Superficial all installed in one well. The only issue with these is if they stop working there is no possibility of replacing them and water quality cannot be measured.

If the Lesueur Aquifer has test pumping undertaken a flow gauge should be installed to record cumulative volumes and flow rates.

### 9.1.5 Surface Water Quality Monitoring

Potentially large volume of saline water could be discharged to the surface and although it will be managed and contained, as a precaution, a surface water monitoring plan is required.

As there is no natural drainage features but rather areas of seasonal inundation it will be difficult to be specific about where these monitoring sites should be. It is recommended they could be installed in any constructed drains running through the project area that could be impacted by a surface spillage of saline water. In general they would measure the chemistry of the surface water (specifically salinity) rather than the volume. This could be done by installing a datalogger that measures specifically salinity.

### 9.1.6 Requirements for Groundwater Chemistry

The Department of Water will inform applicants/licensees of the analysis suite required. If particular chemicals or compounds are required outside of the standard suites provided, the department will inform the applicant/licensee, or may include them in the licence conditions (Operation Policy 5.12).

## 9.2 Comprehensive Analysis

A comprehensive water quality analysis (Operation Policy 5.12) is recommended by Department of Water for activities with the potential to contaminate groundwater.

Field analysis and laboratory analysis is required as a minimum for the analytes specified in Table 7 9:

Groundwater sampling should be undertaken in accordance with the Australian Standard (AS/NZS 5667, 1998) and wherever possible, a NATA-registered laboratory should undertake the analyses, using NATA-accredited analysis methods.

Table 7 Comprehensive water quality analysis analytes (Operation Policy 5.12) as recommended by Department of Water

| **Field Analysis** | **Physico-chemical** | **Ions (mg/l)** | **Metals (mg/L)** | **Nutrients** |
|---|---|---|---|---|
| | | | **(Filter and acidify samples in field)** | |
| Temperature (°C) | pH | Calcium Ca | Aluminium Al | Total Kjeldahl nitrogen TKN |
| pH | Conductivity | Magnesium Mg | Arsenic As | Total phosphorus TP |
| Eh | Total dissolved solids (calculated @ 180 C) | Sodium Na | Cadmium Cd | |
| Conductivity (compensated to 25°C) | Total hardness (as CaCO3) | Potassium K | Chromium Cr | |
| Dissolved oxygen | Total alkalinity (as CaCO3) | Ammonia NH3 | Iron Fe2+ | |
| Bicarbonate (HCO3) | | Phosphate PO4 | Lead Pb | |
| | | Carbonate CO3 | Manganese Mn | |
| | | Bicarbonate HCO3 | Mercury Hg | |
| | | Chloride Cl | Selenium Se | |
| | | Sulphate SO4 | Zinc Zn | |
| | | Nitrate NO3 | | |
| | | Nitrite NO2 | | |
| | | Silica SiO2 | | |

## 9.3 Cost of Monitoring Program

The groundwater monitoring program has been costed for the establishment of the monitoring network and the quarterly sampling that will have to occur as part of the Licence Conditions. Table 8 shows a breakdown of groundwater monitoring costs adjusted for CPI. (**http://www.abs.gov.au/ausstats/abs@.nsf/mf/6401.0**)

Table 8 Estimated Cost of Groundwater Monitoring Program

| **Proposed Monitoring Program** | **Description** | **Cost Each ($)** (Excl GST) | **Number** | **Cumulative Cost ($)** (Excl GST) |
|---|---|---|---|---|
| **Capital Costs for Establishment of Shallow Monitoring Network** | | | | |
| Superficial Aquifer | Site assessment of 15 DoW Monitoring bores to assess current status and ability to provide representative data | 6400 | 1 | 6,400 |
| Superficial Aquifer | Construction of three monitoring bores 100mm diameter (one up hydraulic gradient and two down hydraulic gradient) (40m depth) | 6400 | 3 | 19,200 |
| Leederville Aquifer | Construction of three monitoring bores 100mm diameter (one up hydraulic gradient and two down hydraulic gradient) (150m depth) | 30000 | 3 | 90,000 |
| Eneabba Aquifer | Construction of three monitoring bores (100mm diameter)(one up hydraulic gradient and two down hydraulic gradient) (250m depth) | 60000 | 3 | 180,000 |
| | | 1000 | 15 | 15,000 |
| Consulting Cost | Cost To manage construction of nine bores in shallow network | 1500 | 90 | 135,000 |
| | | | | |
| **Establishment of Lesueur Monitoring Network** | | | | |
| Wonnerup/Yalgorup | Nested Piezometers (100mm) installed in existing wells (2) in Wonnerup and Yalgorup (excludes drill costs) | 70000 | 2 | 140,000 |

| | | | | |
|---|---|---|---|---|
| Test Pumping to Establish Aquifer Parameters in Wonnerup/Yalgorup | Aquifer testing (using inflatable straddle packers) to establish hydraulic conductivity and storativity of aquifers before installation of Nested Piezometers | 30000 | 4 | 120,000 |
| Consulting Cost | Consulting costs to manage the nested piezometer installation and aquifer testing | 1500 | 30 | 45,000 |
| | **Monitoring Network Establishment Total Cost (excl. GST)** | | | **750,600** |
| | | | | |
| **Site Sampling (Annual Cost)** | | | | |
| All Aquifers | Data loggers (measuring piezometric head and temperature) | *1000 | 15 | 15,000 |
| Water Quality and Piezometric Sampling (consultant) | Sampling of water quality (see section 9.3.1 for details) and downloading data logger data (quarterly) | 1500 | 15 | 22,500 |
| Surface Water Monitoring | Data loggers (measuring salinity) | *1600 | 4 | 6,400 |
| Surface Water Sampling (consultant) | Sampling of runoff water quality and downloading data logger data (quarterly) Estimated 4 sites | 1500 | 1 | 1,500 |
| Water Quality Analysis | Laboratory Water Analysis (Ground and surface water biannual) | 900 | 76 | 68,400 |
| Data Interpretation and Reporting | Hydrogeological reporting associated with a water well licence | 20000 | 1 | 20,000 |
| | | | | |
| | | | **Total** | **133800** |
| **Annual Adjustment for CPI (March 2016)** | | 1.30% | | 135539.4 |
| | Jun-17 | 1.30% | | 137301.4122 |
| | Jun-18 | 1.30% | | 139086.3306 |
| | Jun-19 | 1.30% | | 140894.4529 |
| | Jun-20 | 1.30% | | 142726.0807 |
| | Jun-21 | 1.30% | | 144581.5198 |
| | Jun-22 | 1.30% | | 146461.0795 |
| | Jun-23 | 1.30% | | 148365.0736 |
| | Jun-24 | 1.30% | | 150293.8195 |
| | Jun-25 | 1.30% | | 152247.6392 |
| | Jun-26 | 1.30% | | 154226.8585 |
| | Jun-27 | 1.30% | | 156231.8077 |
| | Jun-28 | 1.30% | | 158262.8212 |

*Assumptions are:

- Data loggers are replaced annually,
- water quality is sampled biannaually,
- costs are derived from discussion with DDH1 Drilling,
- CPI remains at 1.3%.
- No cost has been calculated for specialised sampling equipment as discussed in Section 9.3.1.

# 10. RISKS AND RECOMMENDATIONS

1. Available information has been compiled in SCI-3D software as a 3D model for the structure, lithology and permeability of the hydrogeological units. For the shallower units of the Superficial Aquifer and Leederville Aquifer parameters and structure and lithology are well defined. The structure and lithology is well defined in the Study Project Area. Licensed groundwater abstractions, hydrogeological units exploited and abstraction rates have also been compiled for all units. A conceptual model showing flow lines and hydraulic linkages between geological units has also been compiled. The Harvey and Binningup lines should have the deeper geology redefined as per the present understanding of the geology and the aquifers. The geology should be extrapolated to join up with the geology from the seismic study in the Study Project area and will provide a better understanding of the deeper geology and hydrogeology outside of the Study Project area. The Eneabba Formation, Yalgorup and Wonnerup members' aquifer parameters require further investigation.

   If the salinity differences between the aquifers are confirmed, the Eneabba and the underlying Lesueur Aquifer could be considered stagnant and isolated from each other and the meteoric water cycle. The could also be confirmed by conducting test pumping in the Lesueur Aquifer and monitoring of the groundwater levels response (pressure gradients) in the Eneabba Aquifer (see Section 7). The test pumping would also provide aquifer parameters for the pumped aquifers.

   In both the Lesueur and the Eneabba it could be that the ground water is possibly further compartmentalised in an east -west direction due to the two major faults. The aquifer in north south direction appears to be open. Fault boundary conditions would have no impact on injection volumes because the volume of CO2 injected into the aquifer with regards to the total Lesueur aquifer volume the AOI of the Harvey Ridge is very small and would have minimal volumetric impact to the larger Lesueur Aquifer.

2. The different water salinities within the Eneabba Formation, Yalgorup and Wonnerup members aquifers suggest the aquifers may be isolated from one another which could be beneficial for injection. The samples have been contaminated by drilling fluid and

poor sampling techniques. Proper development of the bores before sampling and correct sampling procedures are required to ensure samples are representative.

3. Changes in water quality and mass transport through $CO_2$ injection can be modelled, however this requires representative aquifer parameters as well as reliable geochemistry of the geology as well as good water quality data. Representative samples are required and information on how these should be taken is included in section 9.1. Preliminary 1D and 2D reactive transport models are recommended to guide more detailed modelling which is required to evaluate specific geochemical processes. A cost has also been compiled to provide a1D and 2D reactive transport model.

4. Recommendations toward development of a conceptual baseline groundwater quality, levels and piezometric pressure monitoring program and development of approximate costs accounting for CPI have been developed. The monitoring program has been designed to the level of an H3 assessment as required for a 5C licence.

   A 5C licence is a licence to take groundwater. This may not be required for investigation of the aquifers. A 26D licence to drill an exploratory bore will be granted under section 26D of the Rights in Water and Irrigation Act 1914. This licence allows the required bore(s) to be constructed by a licensed driller, and test pumped, in order to complete a hydrogeological assessment. This may be all that is required in the investigation stages and should be followed up with Department of Water for clarification.

5. Appendix 1 contains a preliminary costing for groundwater modelling, using the geological structure obtained from the Sci-3D model. This model would provide information necessary to complete the H3 groundwater assessment for a 5C license to abstract.

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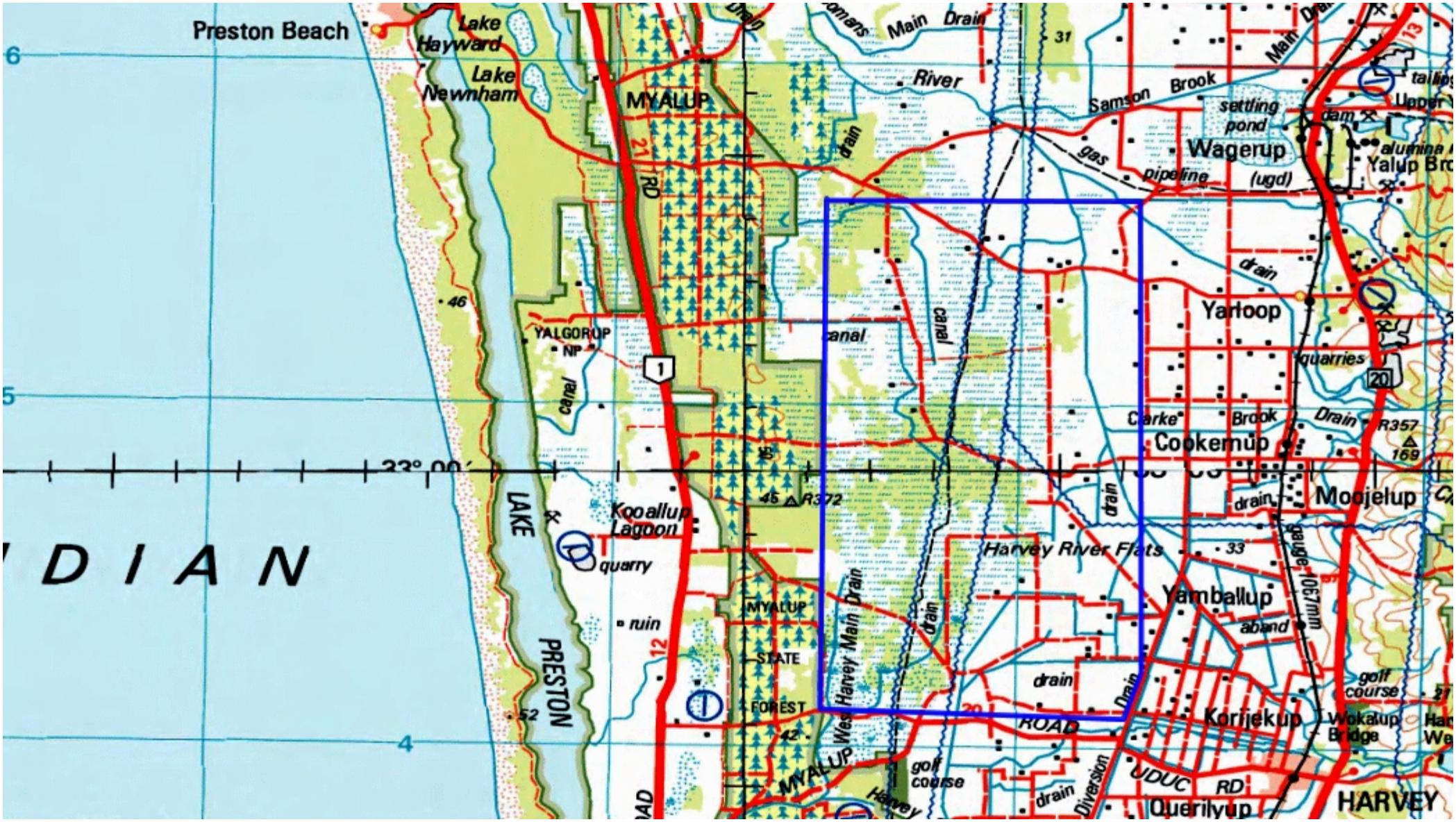
Links

https://www.dpaw.wa.gov.au/management/wetlands/mapping-and-monitoring/227-wetland-mapping-on-the-wa-atlas

# Appendix 1

Costing for Groundwater Model to obtain H3 licence.

| # | Item | Rate | | Time | Total $ |
|---|---|---|---|---|---|
| 1 | Review of existing geological data and importing of data | $165.00 | | 24 | $3 960.00 |
| | *Collecting and reviewing data* | | | | |
| | *Importing data and setup with information* | | | | |
| | *Create GIS and 3D database* | | | | |
| 2 | Definition of Hydrogeological Conceptual Model | $165.00 | | 36 | $5 940.00 |
| | *Reviewing Groundwater Investigations* | | | | |
| | *Hydrogeological Setting & Recharge calculations* | | | | |
| | *Geological Data Inputs* | | | | |
| | *Aquifer parameters* | | | | |
| 3 | Hydrogeological Modelling | $165.00 | | 280 | $46 200.00 |
| | *Numerical Model Construction* | | | | |
| | *Model Calibration* | | | | |
| | *Sensitivity Analyses* | | | | |
| 4 | Model Predictions and Outputs | $165.00 | | 45 | $7 425.00 |
| | *Impact predictions* | | | | |
| | *Best & Worst Case Scenarios* | | | | |
| | *Conclusions* | | | | |
| | *Recommendations* | | | | |
| 5 | Reporting Results | $165.00 | | 56 | $9 240.00 |
| | *Groundwater Reporting & Presentations* | | | | |
| | | | | | |
| | **Total Budget in Australian Dollars** | | | **441** | **$72 765.00** |




Department of Mines and Petroleum

Geological Survey of Western Australia

GOVERNMENT OF WESTERN AUSTRALIA

5

Kilometers

NOTE: Scale is calculated at the centre of the map. Scale representative fraction will vary in a North South direction.



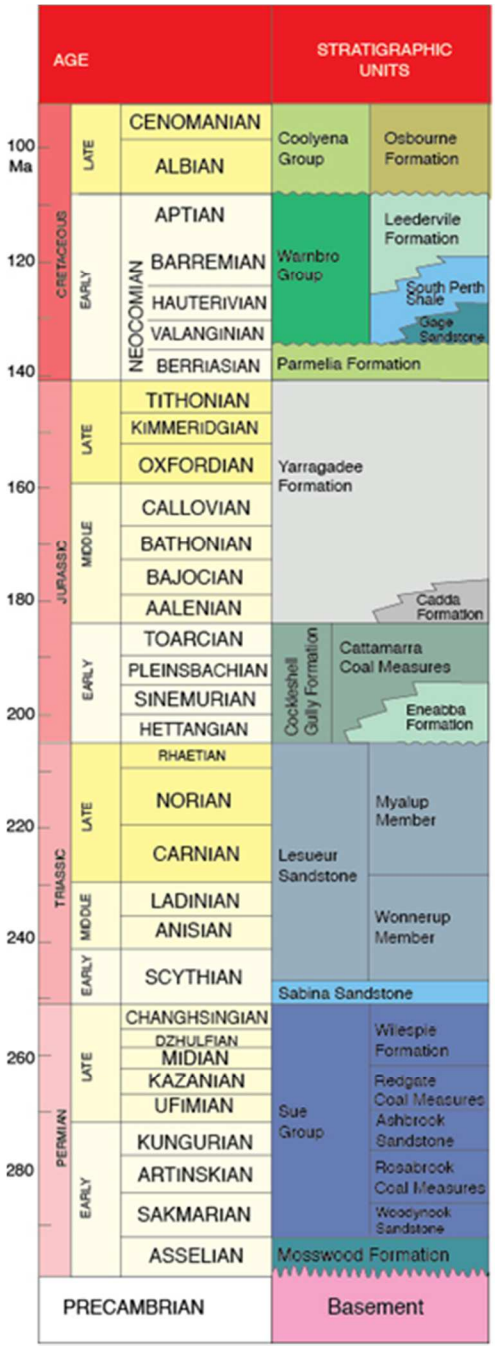
Recommend Reference for this map is: Geological Survey of Western Australia 2016, Locality of Project Area extracted from GeoVIEW.WA. on 24/05/2016 Perth, Western Australia: Department of Mines and Petroleum.

The data presented herein are interpreted, and made available in good faith and derived from sources believed to be reliable and accurate at the time of release. You should not solely rely on this information when making a commercial decision.

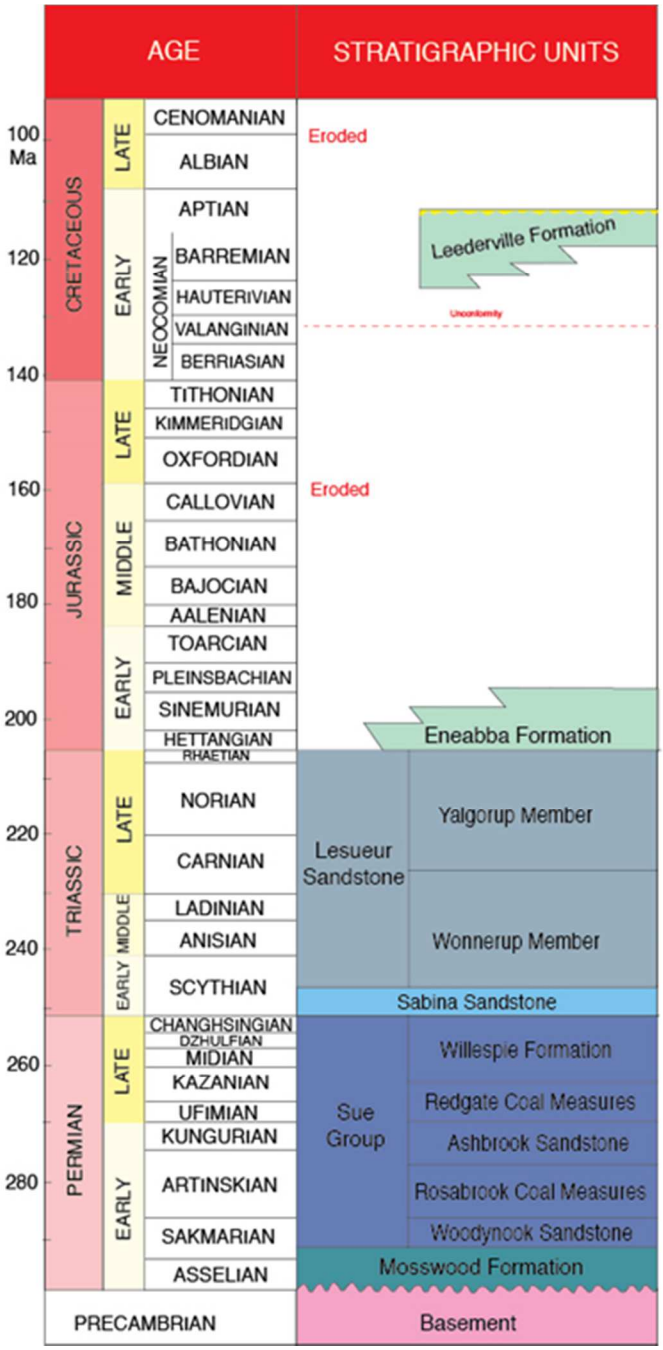
Legend

**Study Project Area**

Geological Survey of Western Australia.




Perth Basin Stratigraphy

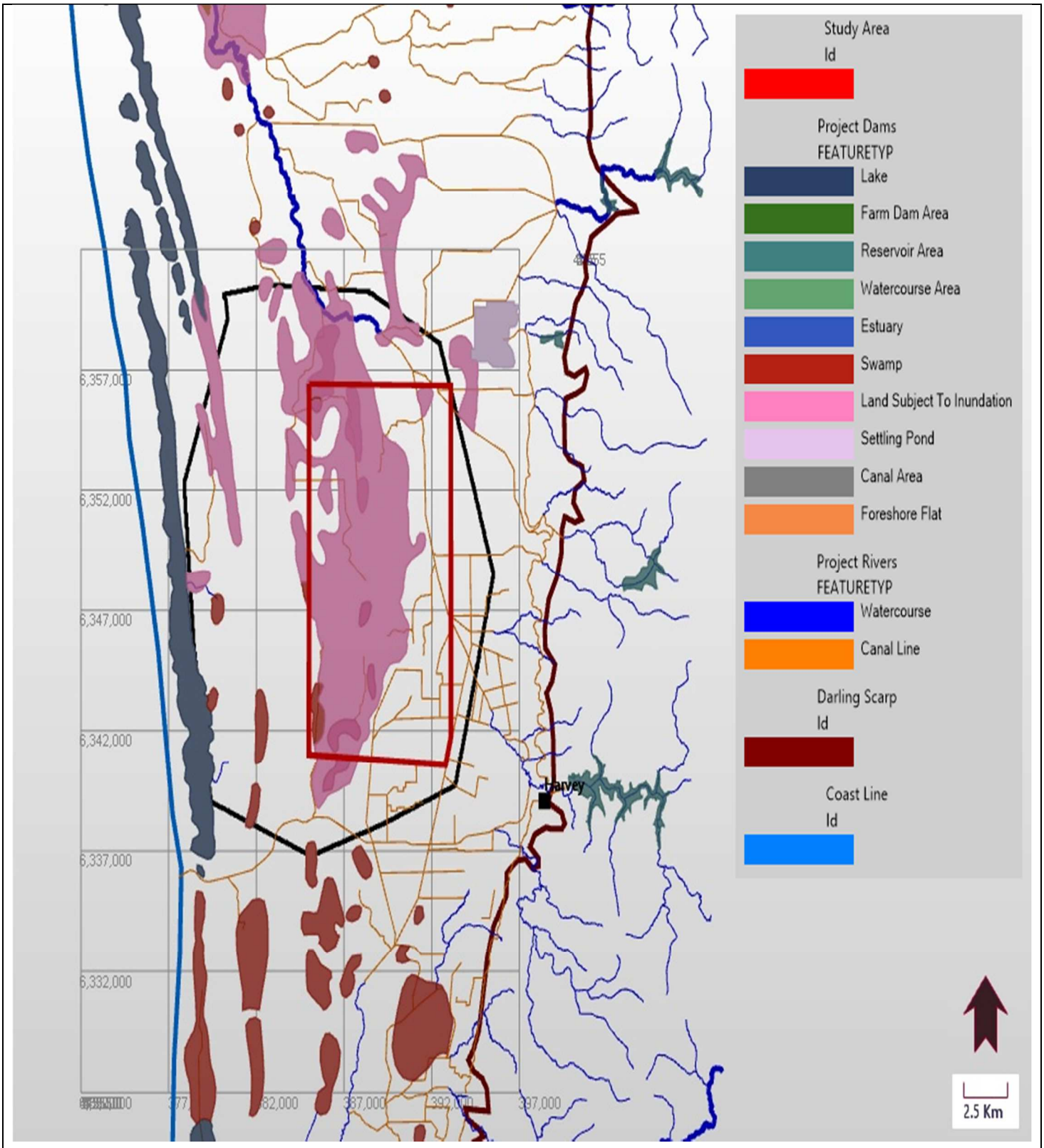



Study Project Area Stratigraphy

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**Perth Basin Stratigraphy with Project Area Stratigraphy**

**Figure 2 Stratigraphy of Study Area**

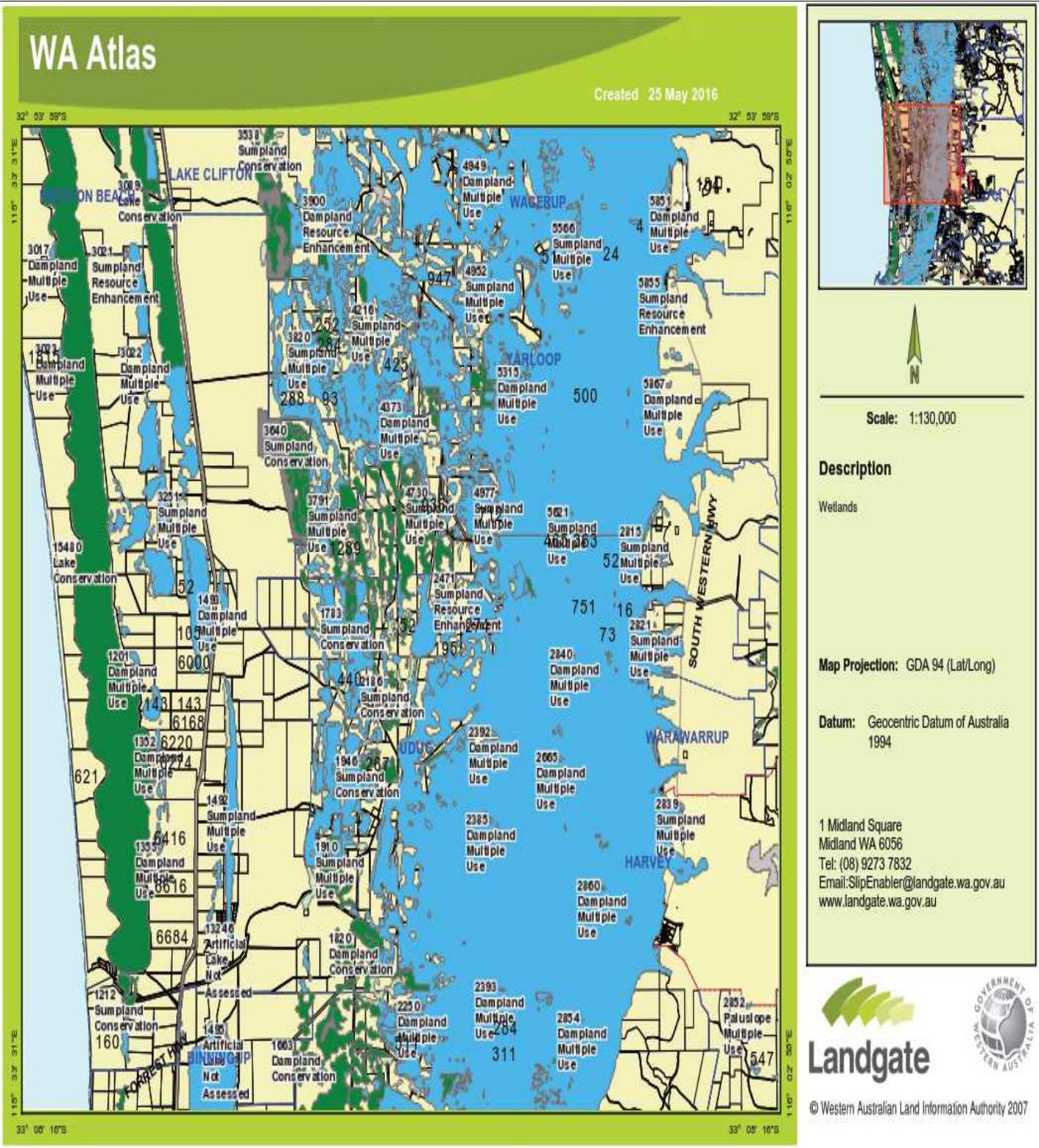



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**Southern Perth Basin**

**Figure 3 Digitised Surface Water Features in Greater Harvey-Waroona Region**

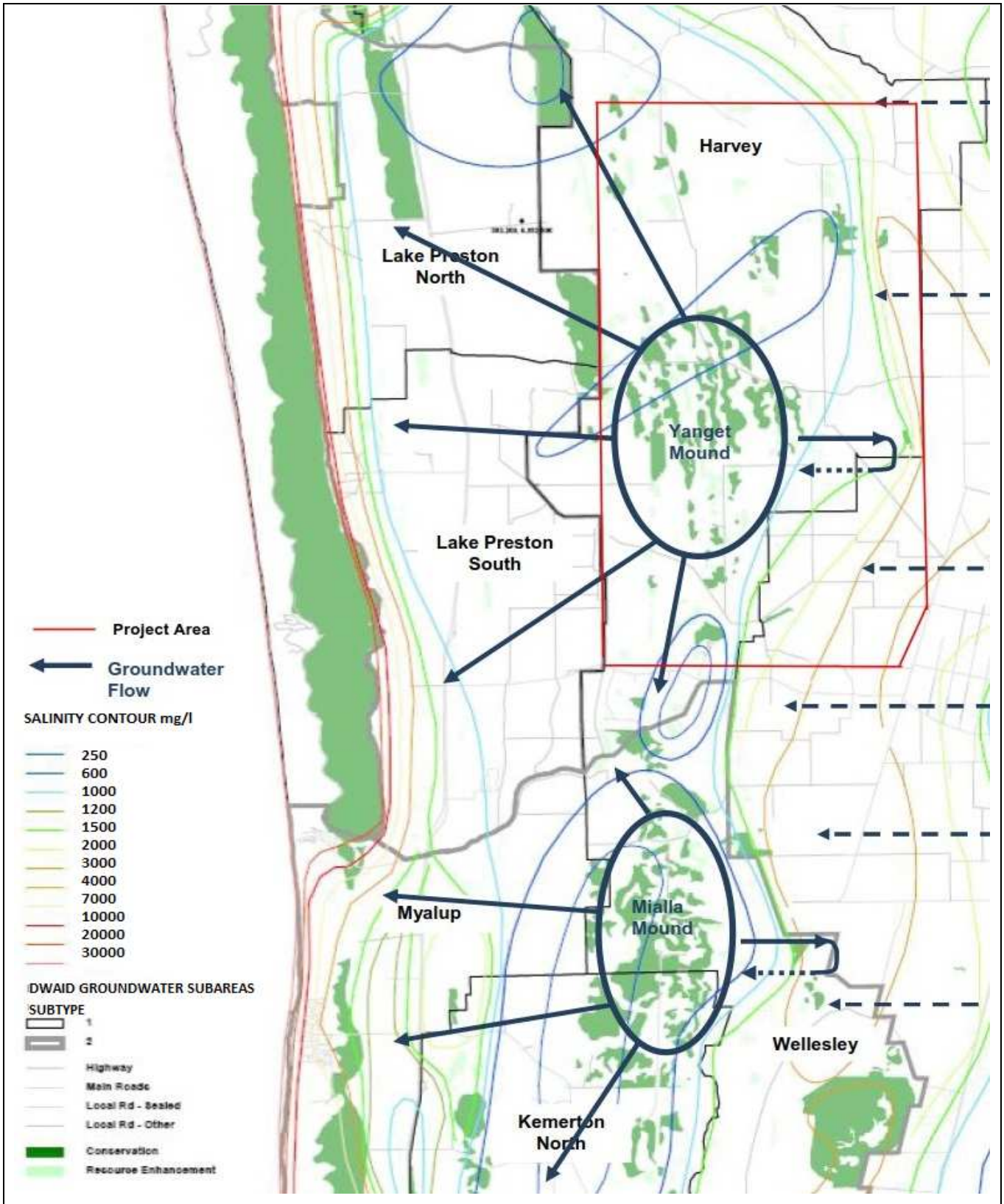



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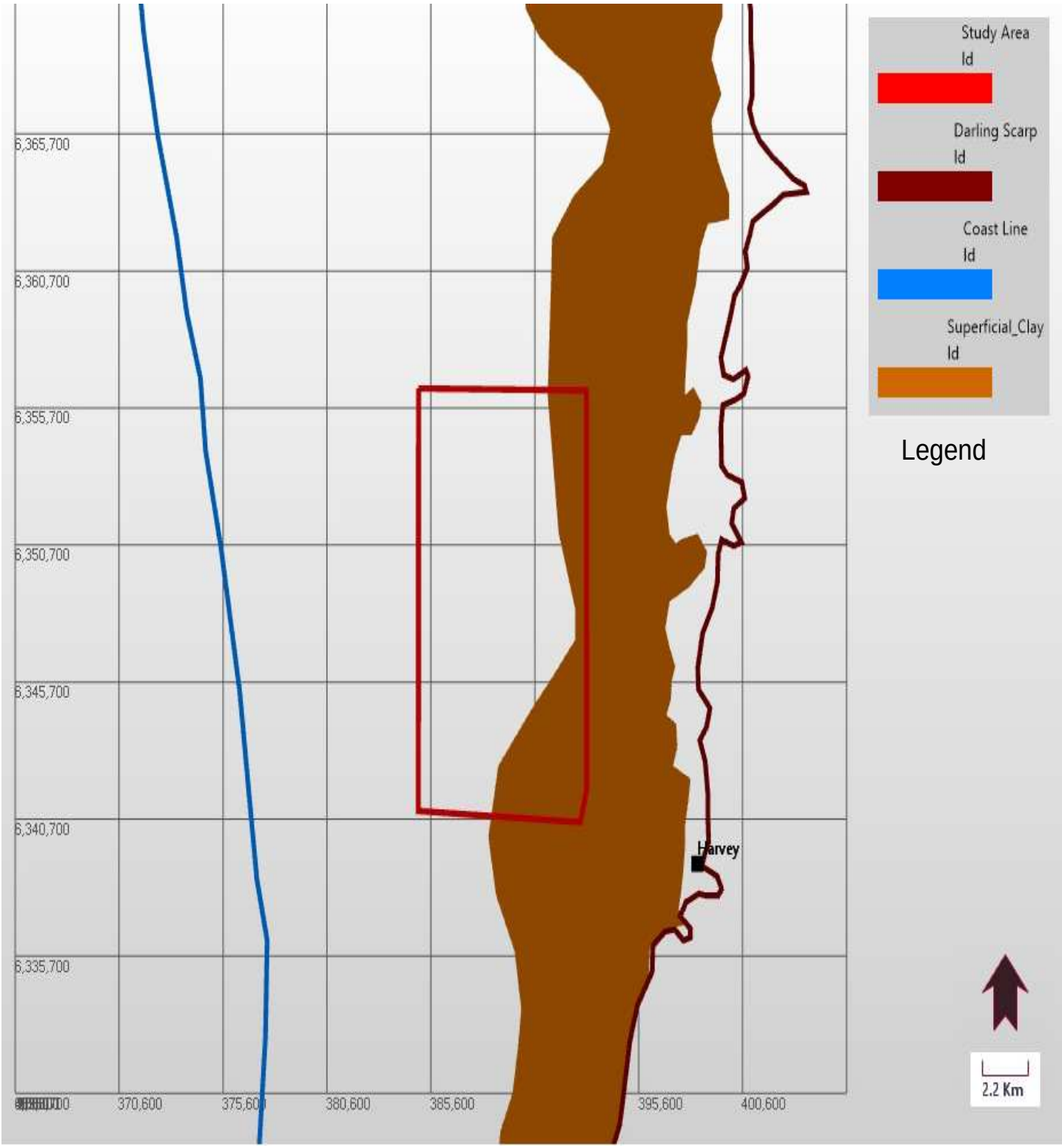
**Figure 4 Wetlands in Harvey Waroona Region-Landgate 2016**




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**Figure 5 Groundwater Contours in Superficial Aquifer showing Yanget and Mialla Mounds**

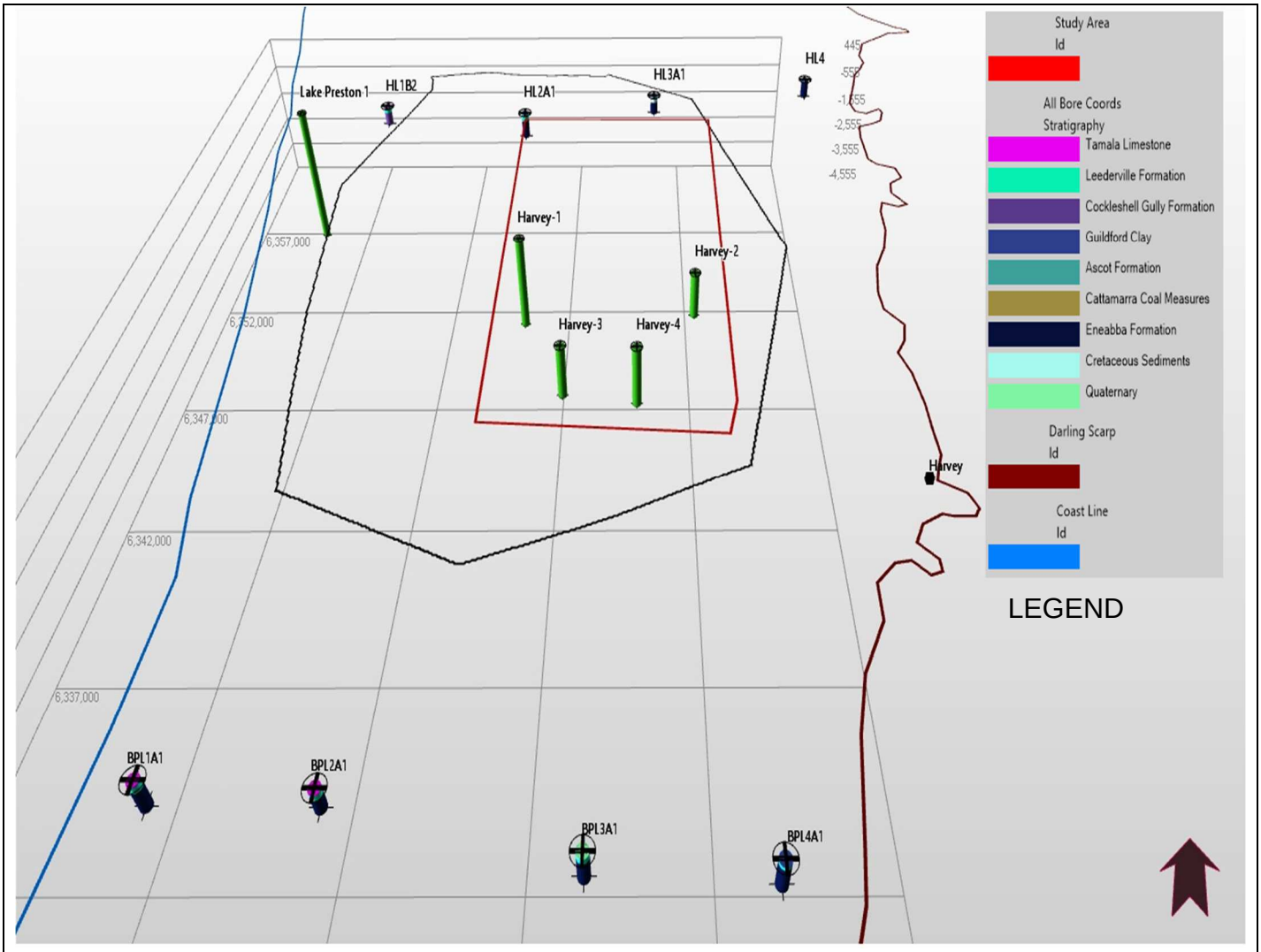



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**Southern Perth Basin**

**Figure 6 Extent of Guildford Clays overlap into Study Project Area preventing recharge into Leederville Aquifer**

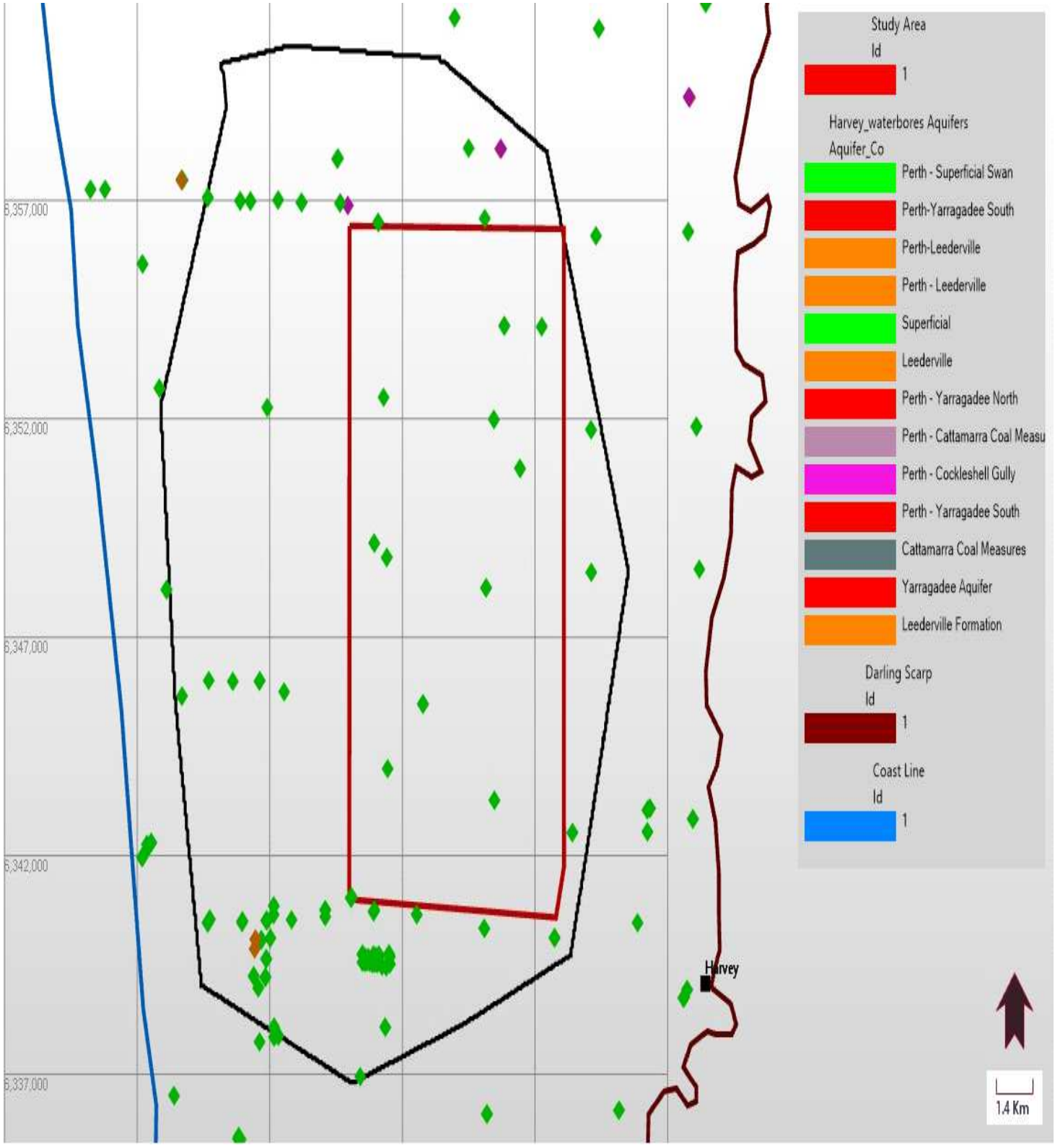



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**Figure 7A Deep Bores used for Conceptual Model**

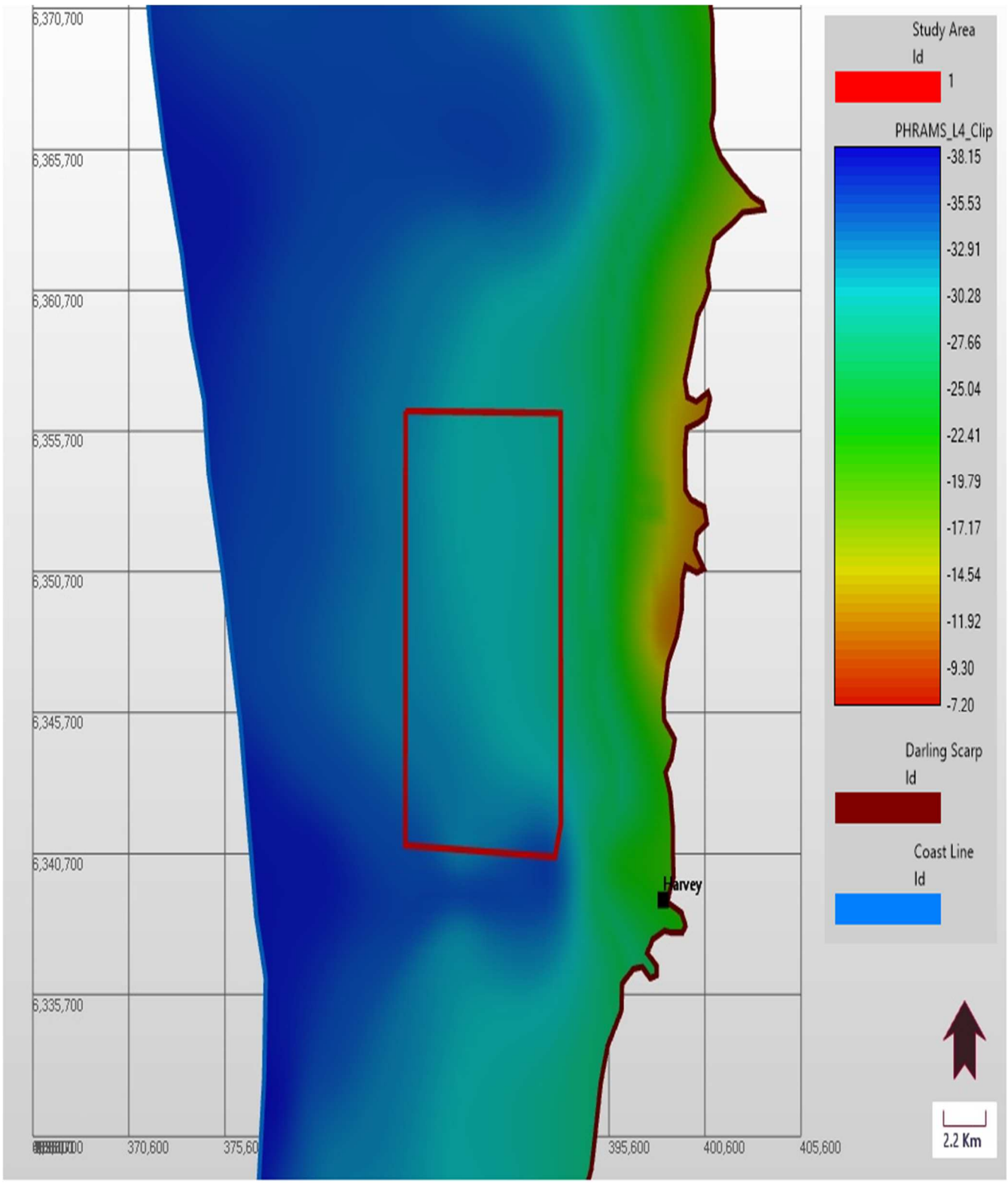



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**Figure 7B Bore data in Harvey- Waroona Region with Relevant Aquifers**

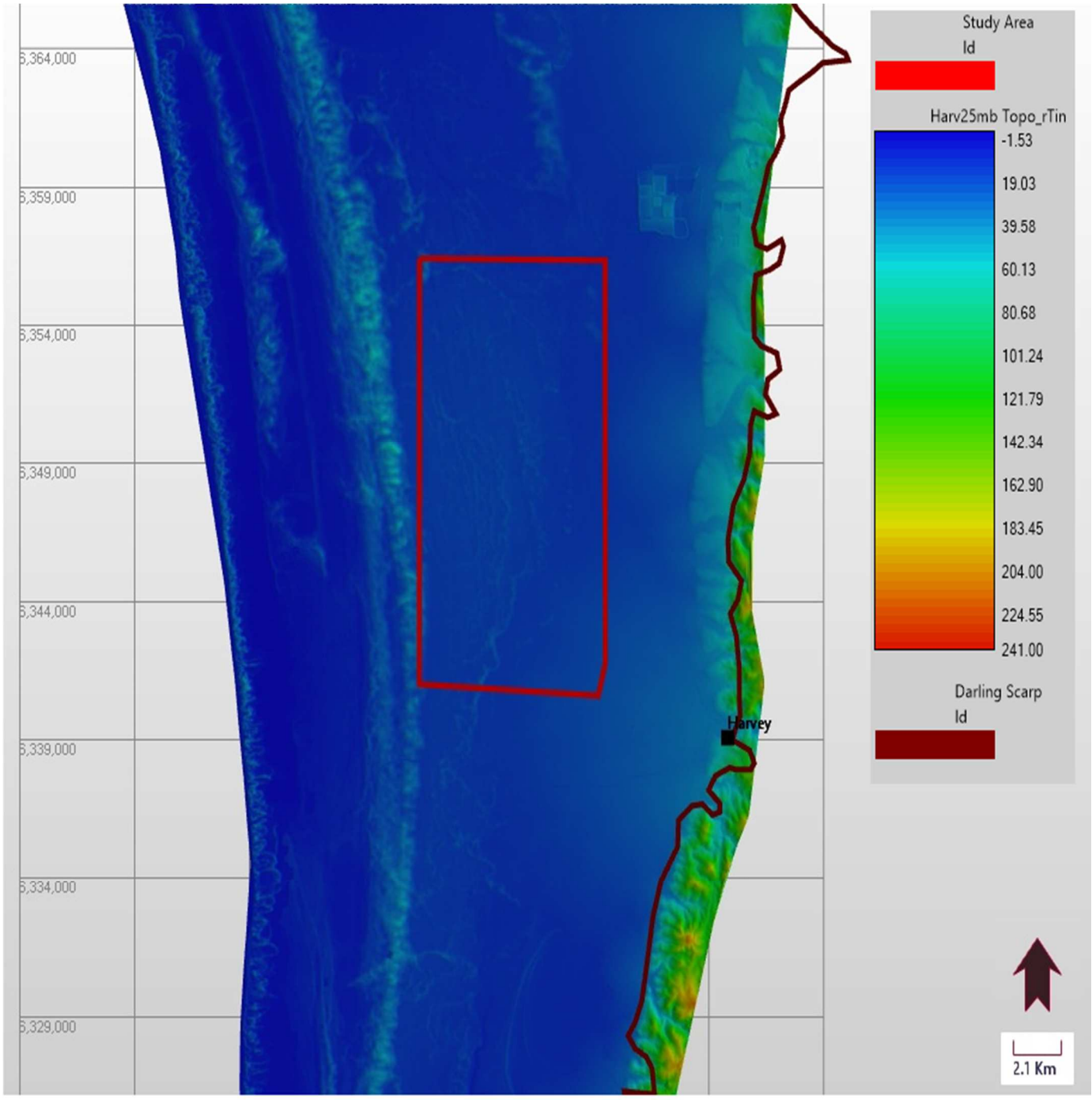



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**Figure 8 Example of PHRAMS data for top of Leederville Aquifer**

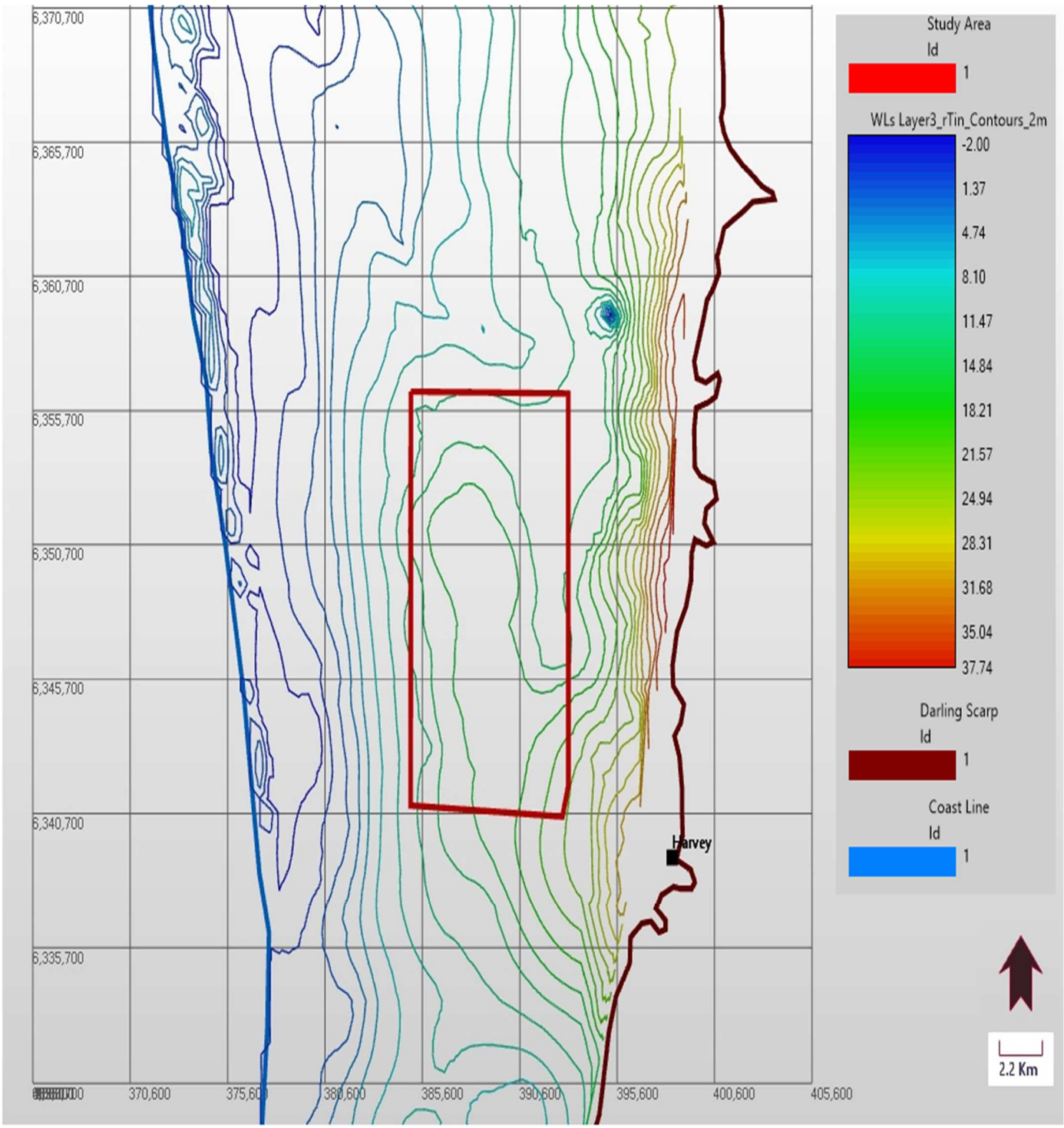



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**Figure 9 Topographic Data Imported into Conceptual Model**

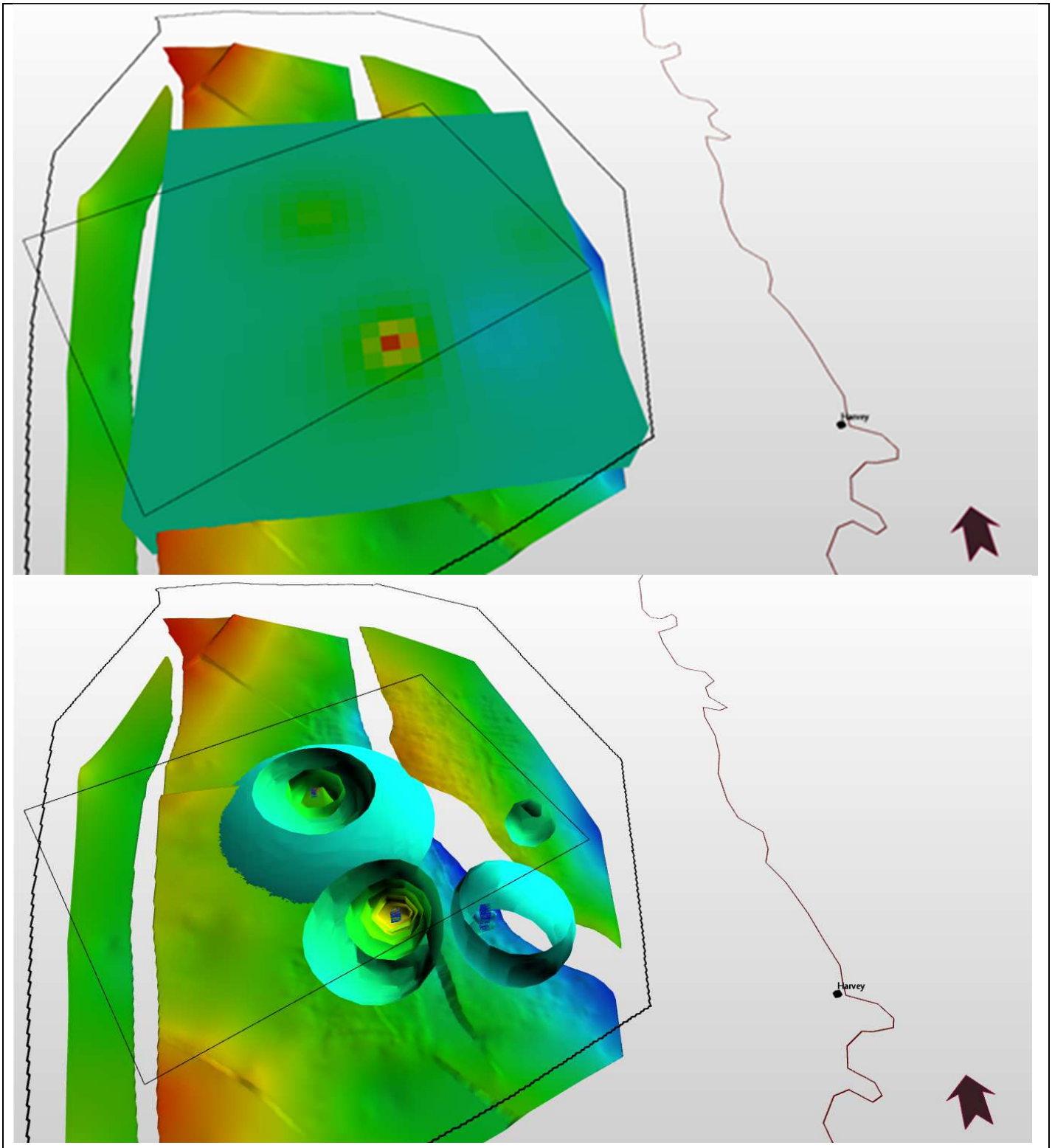



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**Figure 10 Water Levels generated for the top of the Superficial Aquifer**

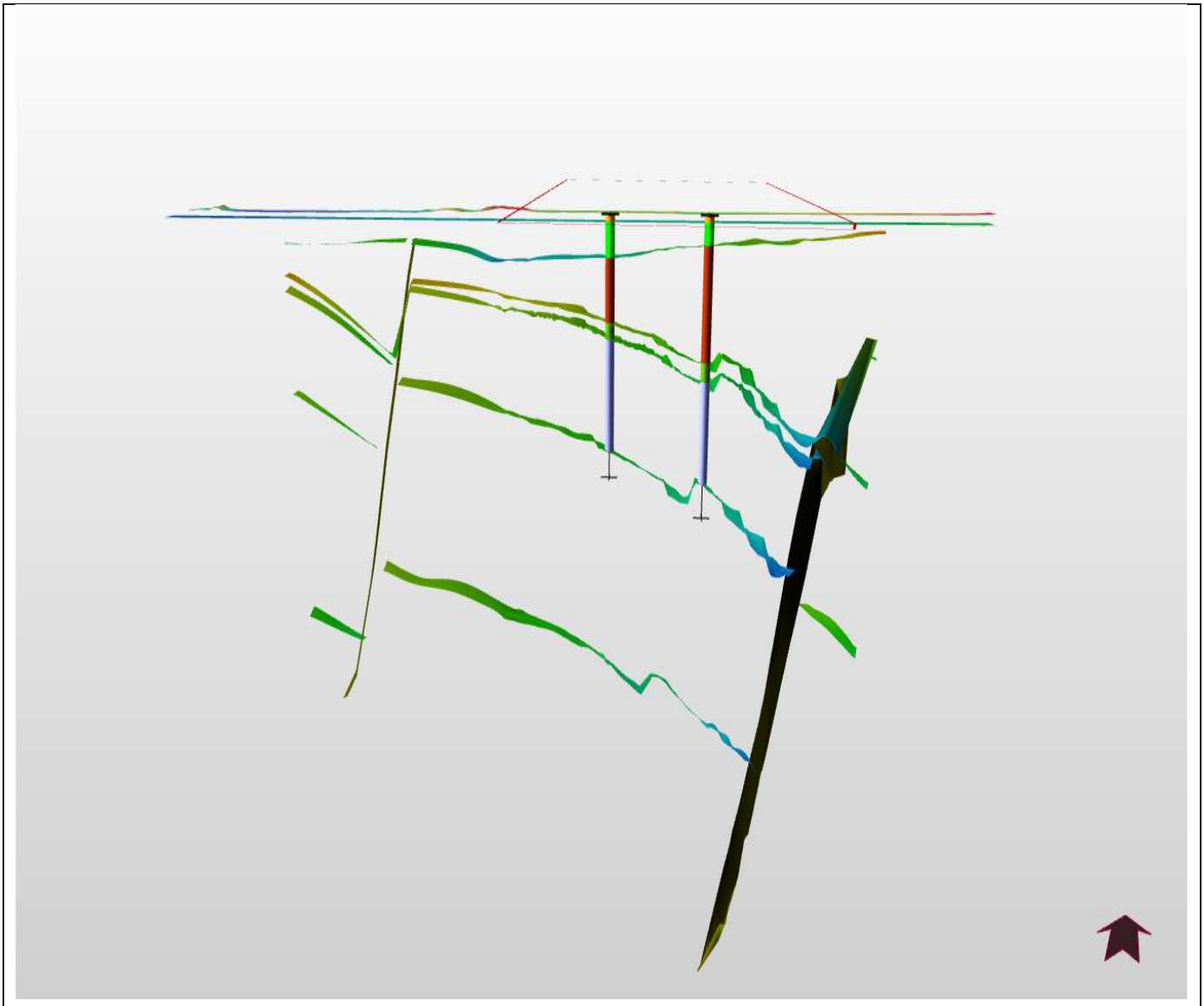



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**Figure 11 Correlation attempt "perm_facies_energy: mD" variable of the four Harvey-1 to Harvey-4 bores**

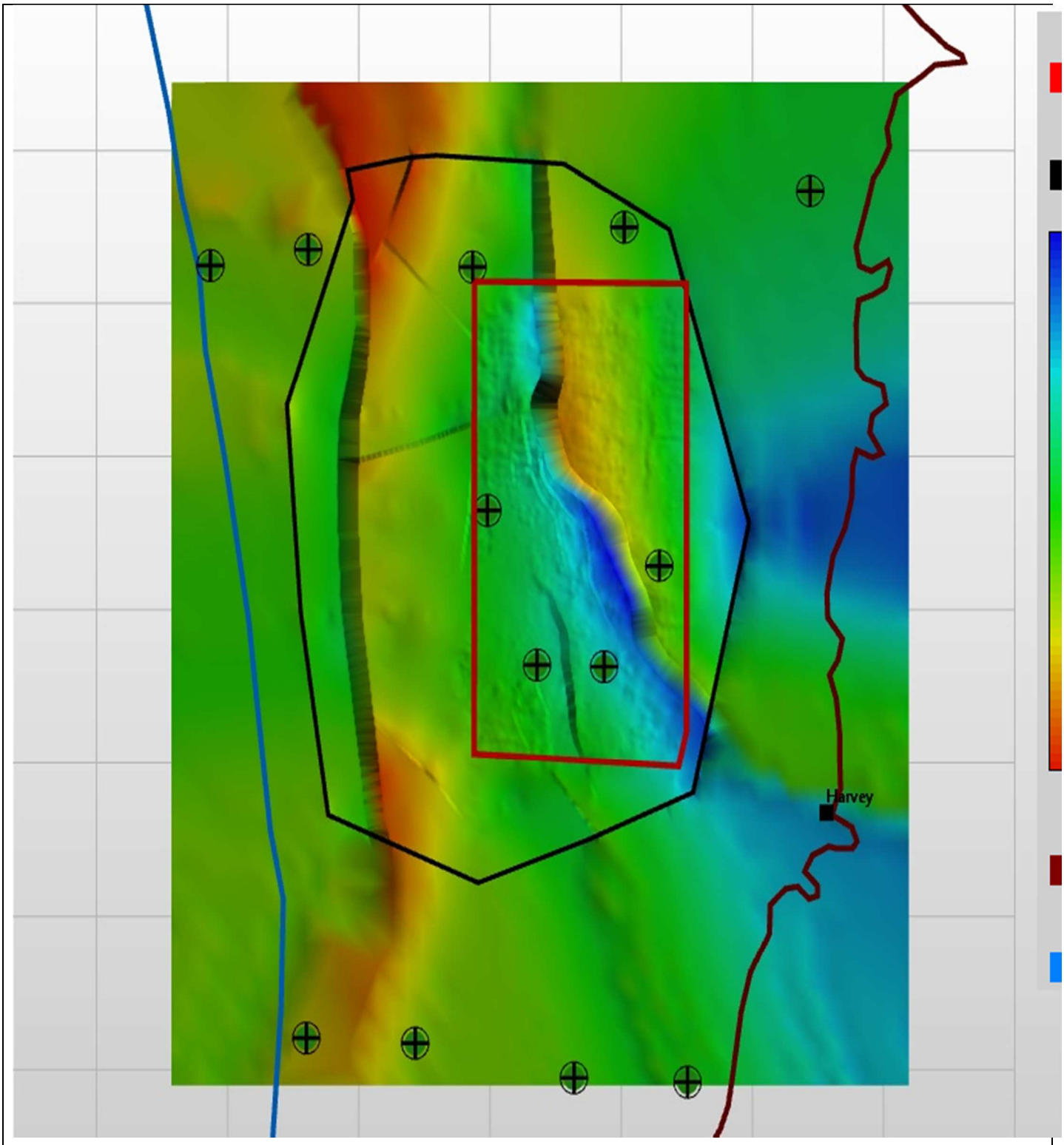


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**Figure 12 Cross Section of Hydrogeological units and Faults taken to assist with drafting of Conceptual Hydrogeology Diagram**

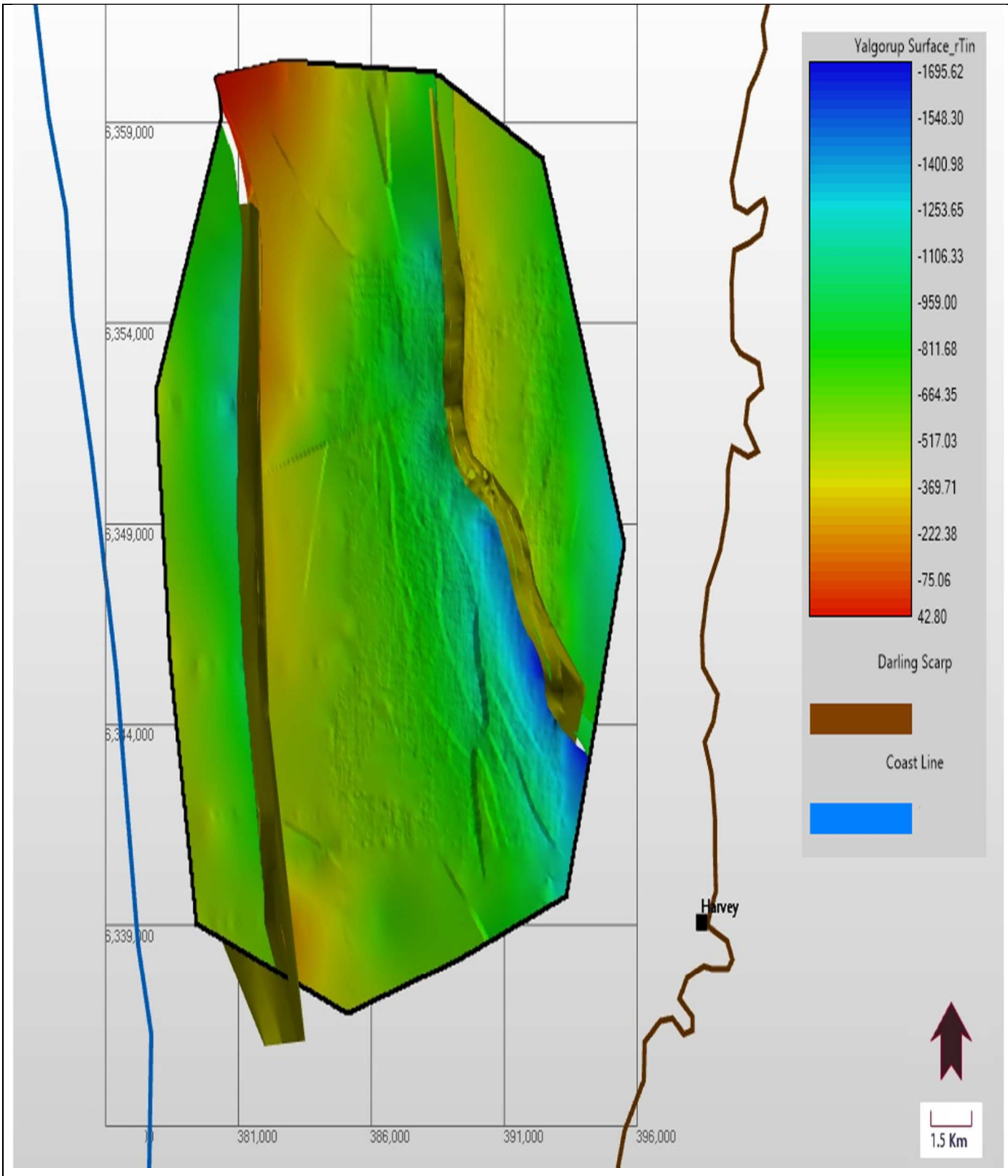



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**Figure 13A Example of Extended Sabina Surface outside Study project Area using Algorithm**

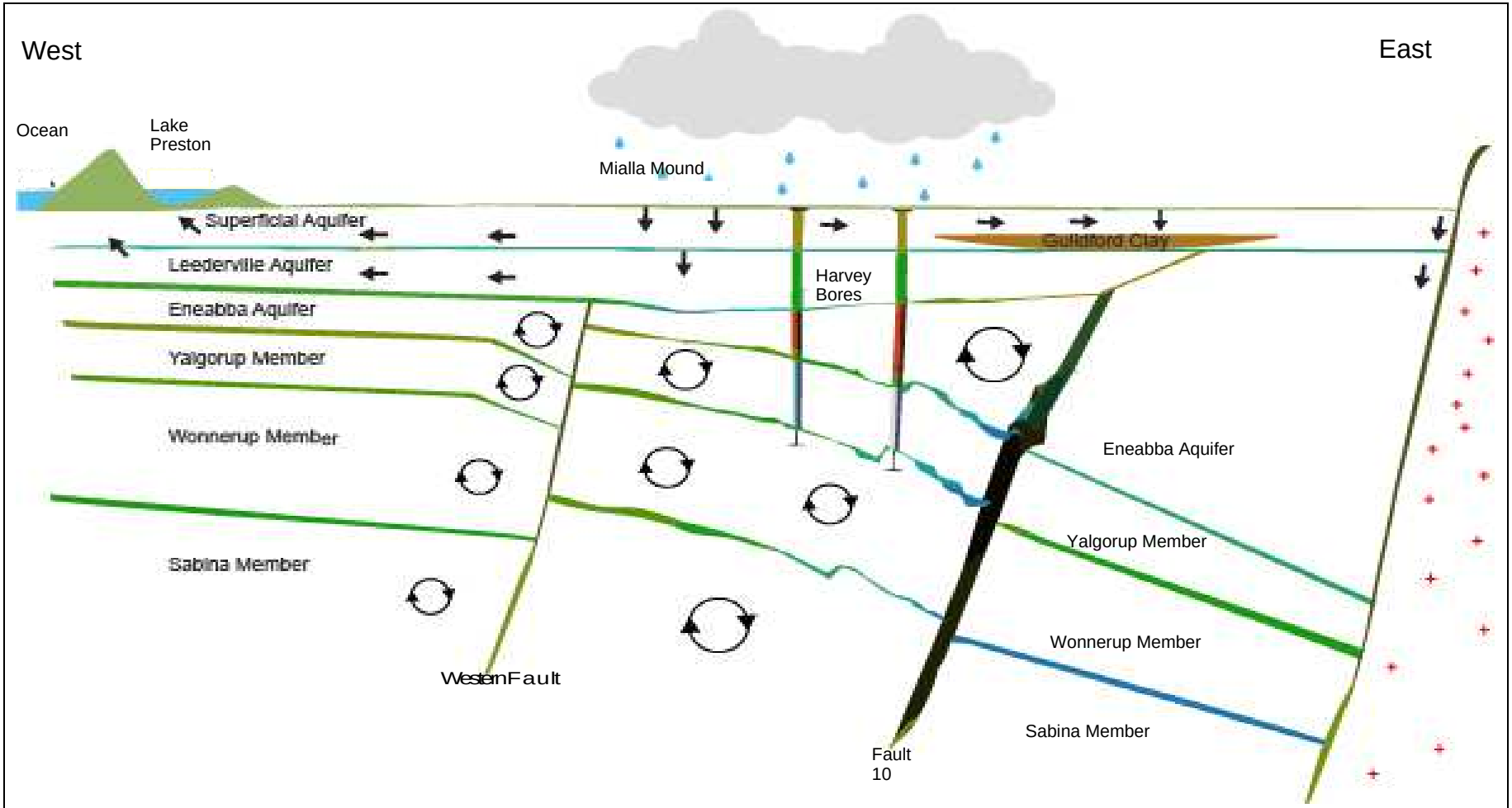



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**Figure 13B Yalgorup Surface showing Western Fault and Fault 10**




Legend

Groundwater Flow Paths →

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**Figure 14 Conceptual Hydrogeology of Study Project area Hydrogeology east to west.**

Sample | Ca | Mg | Na | K | Cl | NO3 | SO4 | HCO3 | pH | EC | TDS

Sample: | Calcium | Magnes | Sodium | Potassiu | Chloride | Nitrates | Sulphat | Bicarbo | pH | EC | TDS | Import Da

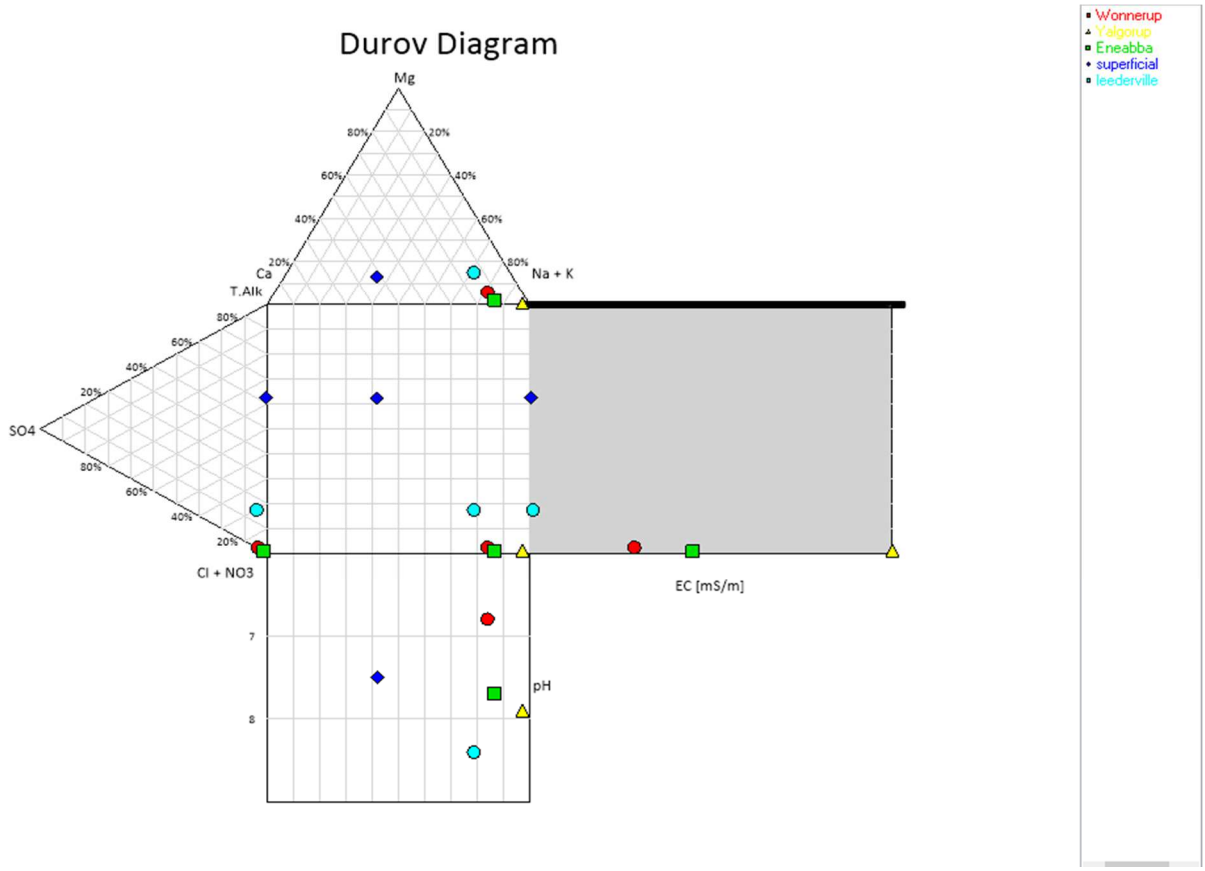
| Sample | Ca | Cl | HCO3 | K | Mg | Na | SO4 | NO3_N | pH | EC | TDS | Color | Sharp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wonnerup | 2020 | 24840 | 160 | 4680 | 535 | 11440 | 1500 | 0 | 6.8 | 27138 | 45230 | | Circle |
| Yalgorup | 1100 | 74700 | 150 | 74270 | 105 | 4420 | 2110 | 0 | 7.9 | 94176 | 156960 | | Triangle |
| Eneabba | 2700 | 37060 | 91 | 20250 | 260 | 9280 | 775 | 0 | 7.7 | 42300 | 70500 | | Square |
| superficial | 90 | 117 | 336 | 4 | 14 | 68 | 2 | 0 | 7.5 | 287.4 | 479 | | Diamond |
| leederville | 68 | 679 | 220 | 16 | 45 | 394 | 55 | 0 | 8.4 | 834 | 1390 | | Circle |

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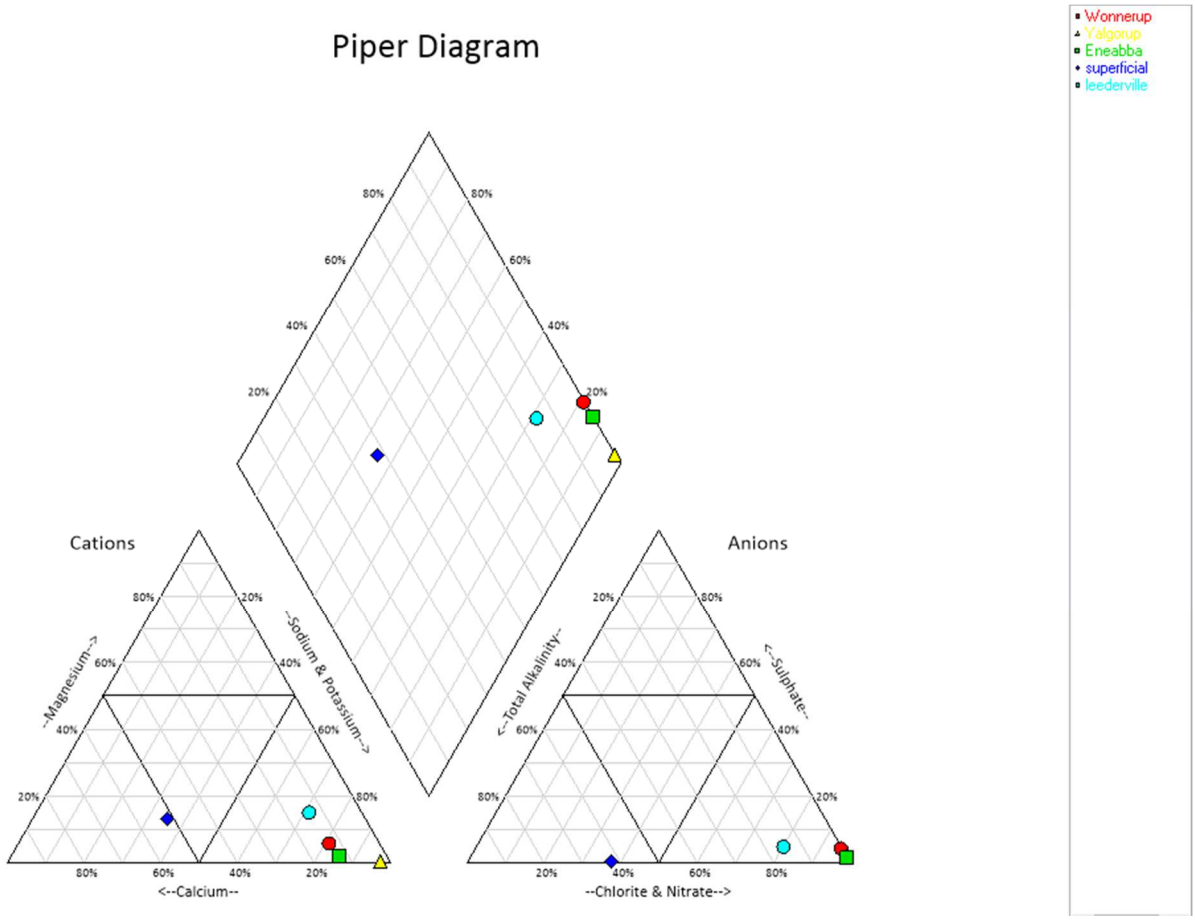
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**Figure 15a Water Quality Used for Groundwater Chemistry Plots**




| | |
|---|---|
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| | **Figure 15b Expanded Durov Used for Groundwater Chemistry Plots** |




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**Figure 15c Piper Diagram Used for Groundwater Chemistry Plots**