Shamrock Station Irrigation Development Stage 1 Hydrogeological Assessment

A report prepared for Argyle Cattle Company

FINAL REPORT

10 June 2017

Cover photo: Existing production bore PB1 on Shamrock Station.

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by

Innovative Groundwater Solutions

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Acknowledgements

Thanks to Chris Ham (DAFWA) for providing regular expert advice on the expected crop water requirements of the proposed development and to Paul Raper (DAFWA) for providing critical datasets and helpful advice to assist the numerical modelling for this assessment.

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The information in this report is considered to be accurate with respect to information provided and conditions encountered at the site at the time of investigation. IGS has used the methodology and sources of information outlined within this report and has made no independent verification of this information beyond the agreed scope of works. IGS assumes no responsibility for any inaccuracies or omissions, however the were no indications during our investigations that the information provided to IGS was false.

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Executive Summary

Australian Standard Agriculture Pty Ltd. (ASA) is overseeing the management of Shamrock Station for the new owners trading under Argyle Cattle Company Pty Ltd. (ACC). Stage 1 development at Shamrock Station is targeting the shallow water tables and most suitable soils near the northern boundary of the property, immediately east of the Great Northern Highway, for irrigation of Rhodes Grass.

IGS was commissioned by ASA on behalf of ACC to produce a scientifically defensible H3 Hydrogeological Assessment report, as required by Department of Water to support an application for water licence of up to 22 GL per annum. This report is only for Stage 1 development, and accordingly proposes only a portion of the total water entitlement volume that has been applied for.

The approach for this assessment was to synthesise a wealth of recent hydrogeological data from the DAFWA Royalties for Regions project, and then use that data in groundwater models to establish how many centre-pivot irrigators could be confidently installed and operated without causing deleterious impacts to existing users and known sites of ecological/cultural importance. In other words, what would sustainable development look like? The existing dataset included AEM geophysics, drilling results, hydraulic properties obtained from aquifer pumping tests, groundwater chemistry, and recharge estimates.

A suite of new groundwater modelling tools has been developed to assess the sustainable level of groundwater abstraction for Stage 1. The models vary in complexity and the physical processes that they include, but all use consistent data sets to predict drawdown impacts on existing licensed and unlicensed groundwater users, the saltwater interface and Injudinah Swamp – a potential groundwater dependent wetland of high cultural and ecological significance located about 15 kilometres to the southwest of Stage 1.

In order to simulate hypothetical groundwater abstraction within the footprint of Stage 1, as defined by the flora/fauna survey extent, it was necessary to develop a pumping schedule based on local DAFWA expert knowledge of crop water requirements for Rhodes Grass. Monthly pumping volumes required to meet average crop water requirements, with 80% irrigation efficiency, were converted to equivalent continuous rates to reflect long-term average climate conditions. Average monthly crop water requirements range from 12.5 L/s in June to 38.0 L/s in November, with an average annual rate of 24.2 L/s. An analytical modelling approach was then used to compare the predicted drawdown impacts that result from applying either variable pumping across each month or an average continuous rate of 25 L/s. The results demonstrated that an average continuous pumping rate of 25 L/s per production bore is a valid simplification for long-term modeling purposes.

After running multiple scenarios through the various models, the optimum number of production bores operating at 25 L/s continuously for 365.25 days per year was determined to be twelve. This continuous abstraction equates to 9,467 ML/annum and was predicted to cause minimal cumulative groundwater level drawdown (i.e., including impacts of licensed use by nearby Shamrock Gardens) after 10 years of operation:

- Shamrock Gardens: 1.64 - 2.59 m cumulative drawdown with 0.77 - 0.78 m of this total drawdown being due to the proposed Stage 1 development;
- Injudinah Swamp: 0.46 - 0.65 m cumulative drawdown with 0.27 – 0.35 m of this total drawdown being due to the proposed Stage 1 development;
- Nearest Aboriginal Community (Nygah Nygah): 0.42 - 0.61 m cumulative drawdown with 0.29 - 0.41 m of this total drawdown being due to the proposed Stage 1 development; and
- Nearest simulated position of the saltwater interface: 0.42 - 0.64 m cumulative drawdown with 0.31 - 0.54 m of this total drawdown being due to the proposed Stage 1 development.

A highly conservative assessment based on the magnitude and rate of drawdown was used to estimate that the risk to Injudinah Swamp from the proposed Stage 1 development is low to moderate, with the most likely scenario being a low risk. Further investigation and monitoring of water levels in and around this important water-dependent ecosystem will be implemented as part of the Stage 1 licensing conditions. This will allow the impacts of the proposed development on the wetland to be better predicted, identified early and mitigated if necessary.

A combination of numerical and analytical modelling of the saltwater interface has identified that it may be located closer to the coast than previously suggested by the results of the DAFWA AEM survey, i.e. that the toe of the interface occurs approximately between 3.5 km and 4.2 km from the coast at its closest point to the proposed Stage 1 development. The modelling suggests that, after 30 years of pumping by Shamrock Gardens (full allocation) and the proposed Stage 1 bores, the toe of the interface may move inland by between 1.4 km and 3.1 km. This presents no risk to existing users or the environment, both of which are only reliant on the shallow water table.

The sustainable abstraction regime has been implemented in the various models as 12 production bores, each pumping continuously at 25 L/s to supply 40 Ha centre-pivot irrigators with a sprinkler option (43.2 Ha total area). This pumping rate equates to an annual water use of 18.3 ML/Ha/annum. In practice, water could be used to supply fewer or more than 12 pivots. For example, if the average annual water use was managed at 15 ML/Ha/annum, which is the middle of the range 12 – 18 ML/Ha/ annum advised by a local expert DAFWA agronomist, then more pivots could be installed. As long as the total actual water use within the Stage 1 footprint does not exceed the simulated 9,467 ML/annum, the predicted impacts on receptors will not change because they are located at large distance compared to the scale of the footprint.

A Stage 1 monitoring network has been proposed to meet DOW licensing requirements and to provide ACC with ongoing knowledge to support sustainable development. The monitoring approach includes manual measurements on production bores and both automated and manual measurements on numerous monitoring bores. The network comprises 12 production bores; six existing bores including both DAFWA monitoring bores and pastoral and MRD bores; three new dedicated monitoring bores; and one surface water monitoring station in Injudinah Swamp. The latter is to facilitate ongoing scientific investigations on the groundwater-dependence of this iconic ecosystem.

CONTENTS

1 Introduction

1.1 Background

Australian Standard Agriculture (ASA) is overseeing the management of the aggregation of pastoral stations previously known as SAWA for the new owners trading as Argyle Cattle Company (ACC). A key project for the aggregation is to develop Shamrock Station as a depot for increasing the value of cattle exported domestically and internationally from ACC properties and the broader Kimberley and Pilbara regions. This will be achieved using multiple clusters of centre-pivots irrigating fodder crops with groundwater from the shallow Broome Sandstone aquifer. These clusters of pivots will be “stand-and-graze” operations.

The project will be staged over a number of years with final pivot numbers being determined by the total volume of groundwater available for allocation and the specific crop water requirements. Initial discussions between ASA and the Department of Water (DOW) have identified an annual water requirement of 22 GL, even though it is recognised this figure exceeds the volume remaining available for allocation in the LaGrange north sub-area (Department of Water, 2010). Nevertheless, a volume of 22 GL equates to between approximately 1,200-1,800 Ha of irrigation assuming an annual crop water requirement of between 12-18 ML/Ha/yr provided by Chris Ham (Irrigation Development and Agribusiness Officer, DAFWA). This total area of irrigation equates to between 30-45 pivots at 40 Ha each.

Given the large scale of this proposed development, careful planning towards each individual stage is critical for ultimate success of the overall project. Notwithstanding the business and capital investment planning that is required, it will be critical to manage the staged licensing and approvals processes in a coordinated and strategic manner. To that end, the immediate requirement of ASA is to identify appropriate Stage 1 development while recognising the long-term goals to enable lodging of meaningful applications with the relevant authorities.

Application to DOW for an initial annual water entitlement (AWE) to enable Stage 1 development in 2017 requires a detailed hydrogeological assessment, the centerpiece of which is a numerical groundwater model developed to industry best practice and in accordance with the Australian Groundwater Modelling Guidelines (Barnett et al., 2012). The development of a robust modelling tool in the early stages of the Shamrock project will also facilitate future decision-making and licensing applications.

Innovative Groundwater Solutions Pty Ltd. (IGS) was engaged by ASA on behalf of ACC to provide hydrogeological services for both Stage 1 and the long-term irrigation development plan for Shamrock Station. IGS was selected by ASA as the preferred respondent to a targeted request for quote on the basis of unparalleled consulting experience in all of the following aspects: scientific research and assessment, liaising with and providing advice to Government, and water allocation planning in the west Kimberley region.

1.2 H3 Hydrogeological Assessment

Consolidated Australian Pastoral Holdings Pty Ltd. lodged the application for water licence of 22,000,000 kL per annum on 5 December 2016. In response to that application, the Department of Water wrote to ASA on 16 May 2017 advising that additional information was required to progress the application, one of which was for 'Submission of a H3 Hydrogeological Assessment Report'.

The Department of Water's (2009) *Operational policy no. 5.12 – Hydrogeological reporting associated with a groundwater well licence* outlines the expected content of an H3 Hydrogeological Assessment Report:

1. Introduction
2. Climate/rainfall
3. Hydrogeology
4. Existing groundwater use
5. Groundwater investigations
6. Drilling
7. Test pumping
8. Groundwater chemistry
9. Groundwater modelling
10. Assessment of potential impacts
11. Groundwater monitoring
12. Management approach/conclusions

1.3 Overview of Approach

In anticipation of the requirement for an H3 Hydrogeological Assessment report, ASA wrote to DOW Director of Regions on 28 February 2017 and requested that appropriate senior staff member from DOW's licensing and technical teams attend an upcoming meeting in Broome. The purpose of the meeting was to provide an overview of the project, discuss and agree on the exact technical scope of the H3 assessment, and then set actions to expedite the timely delivery of required data.

The meeting was held on Monday 13 March 2017 at the Mangrove Hotel, Broome where IGS presented the proposed approach and received endorsement from both DOW regional managers and the DOW senior hydrogeologist. Briefly, the approach relied upon synthesizing a wealth of existing hydrogeological data collected by DAFWA through the '*La Grange Agriculture Opportunities*' project, and using those datasets to build new fit-for-purpose groundwater modelling tools to quantitatively predict the impacts of the proposed Stage 1 development on existing licensed and unlicensed users, the saltwater interface, and known environmental assets. Table 1.1 below is a summary of the approach for Stage 1, and future stages, aligned to DOW's specific requirements of an H3 hydrogeological Assessment report (Section 1.2).

Table 1.1. Summary of agreed approach for this Stage 1 H3 Hydrogeological Assessment

<table>
<tr><th></th><th></th><th>Stage 1 (2017)</th><th>Stage 2 (2018)</th><th>Stage 3 (2019)</th></tr>
<tr><td>1</td><td>Introduction</td><td colspan="3">Overview</td></tr>
<tr><td>2</td><td>Climate/rainfall</td><td colspan="3">Synthesis of BOM data</td></tr>
<tr><td>3</td><td>Hydrogeology</td><td colspan="3">Synthesis of previous works</td></tr>
<tr><td>4</td><td>Existing groundwater use</td><td colspan="3">Refer to LaGrange Evaluation Statements</td></tr>
<tr><td>5</td><td>Groundwater investigations</td><td rowspan="2">DAFWA RfR Project</td><td rowspan="2">Install new Prod. & Mon. bores</td><td rowspan="2">Install new Prod. & Mon. bores</td></tr>
<tr><td>6</td><td>Drilling</td></tr>
<tr><td>7</td><td>Test pumping</td><td rowspan="2">Shamrock PB1</td><td>Test New</td><td>Test New</td></tr>
<tr><td>8</td><td>Groundwater chemistry</td><td>Sample New</td><td>Sample New</td></tr>
<tr><td>9</td><td>Groundwater modelling</td><td>New Model</td><td>Update Model</td><td>Update Model</td></tr>
<tr><td>10</td><td>Assessment of potential impacts</td><td colspan="3">Model Predictions at Agreed Receptors</td></tr>
<tr><td>11</td><td>Groundwater monitoring</td><td>Install New</td><td>Install New</td><td>Install New</td></tr>
<tr><td>12</td><td>Management approach/conclusions</td><td colspan="3">Staged development & knowledge generation</td></tr>
</table>

The proposed approach was again confirmed in the field on the following day, when all three key DOW staff members met with ASA and IGS on site at Shamrock Station.

Following the meetings in Broome and on site, ASA and IGS travelled to Perth to meet with DOW Director of Regions and the Kimberley Regional Manager on Thursday 16 March 2017 to brief them on the project and the proposed approach for Stage 1 hydrogeological assessment. They too endorsed the approach summarised above and adopted for the following report.

2 Geography and Climate

Shamrock Station is located in the West Kimberley region of Western Australia, approximately 60 km south of Broome, in the western portion of the La Grange Groundwater Sub-Area (Figure 2.1). The main land use in the western portion of the La Grange Groundwater Sub-Area is pastoral grazing of cattle, with several pastoral stations located along the Great Northern Highway, which stretches south of Broome. The landscape ranges from flat coastal plains in the west, to a gently undulating, aeolian sandplain that rises to over 200 m in the east. Other physiographic features of the region include scattered hills and mesas, laterite rises and claypans. Topographic elevations across Shamrock Station range from approximately 30 m AHD m to 150 m AHD.

There is no permanent surface water on or around Shamrock Station, although the landscape is criss-crossed with numerous ephemeral drainage systems. Several springs occur on the inland margin of the coastal plain, with Injudinah Swamp located north-east of Bidyadanga being of most significance to this study (see further discussion in Section 4.2).

The closest Bureau of Meteorology rainfall station to Shamrock Station is Bidyadanga (station number 003030; Easting 371378, Northing 7933654), with rainfall data available for the period from 1907 to 2016. Figure 2.2 shows data from this station for 1964 to 2016 only due to several periods of missing data prior to 1964. The mean annual rainfall for 1964 to 2016 was 573.7 mm, with a minimum of 196.6 mm (in 1992) and a maximum of 1,542.4 mm (in 2000; Figure 2.2). Across the La Grange area, there is a strong seasonality in rainfall patterns, with 75 to 85 percent of rainfall occurring during the wet season (December to March).

The residual mass curve (also known as cumulative deviation from the mean) for the Bidyadanga station shows periods of below-average rainfall between 1964 and 1974, 1984 and 1990 and 2004 and 2010 (Figure 2.2). Figure 2.2 shows that periods of above average rainfall occurred between 1980 and 1984, 1996 and 2001, and 2010 and 2013. Paul et al. (2013) noted an increase in the average annual rainfall by 27 percent during the period 1996 to 2010 for this rainfall station, with an increase of between 27 and 47 percent across the whole La Grange area. A similar pattern was observed by CSIRO (2009) in the nearby Fitzroy Catchment suggesting that this was a regional phenomenon. The data of Paul et al. (2013) extended to 2011 only. Figure 2.2 shows that Bidyadanga has subsequently experienced above average rainfall during 2012, 2013 and 2016.

The mean monthly maximum temperature at Bidyadanga is approximately 36°C in April and the mean monthly minimum temperature is approximately 14°C in July (Paul et al., 2013). Mean annual potential evaporation in the La Grange area is 3,200 mm at the coast and increases to 3,600 mm inland.

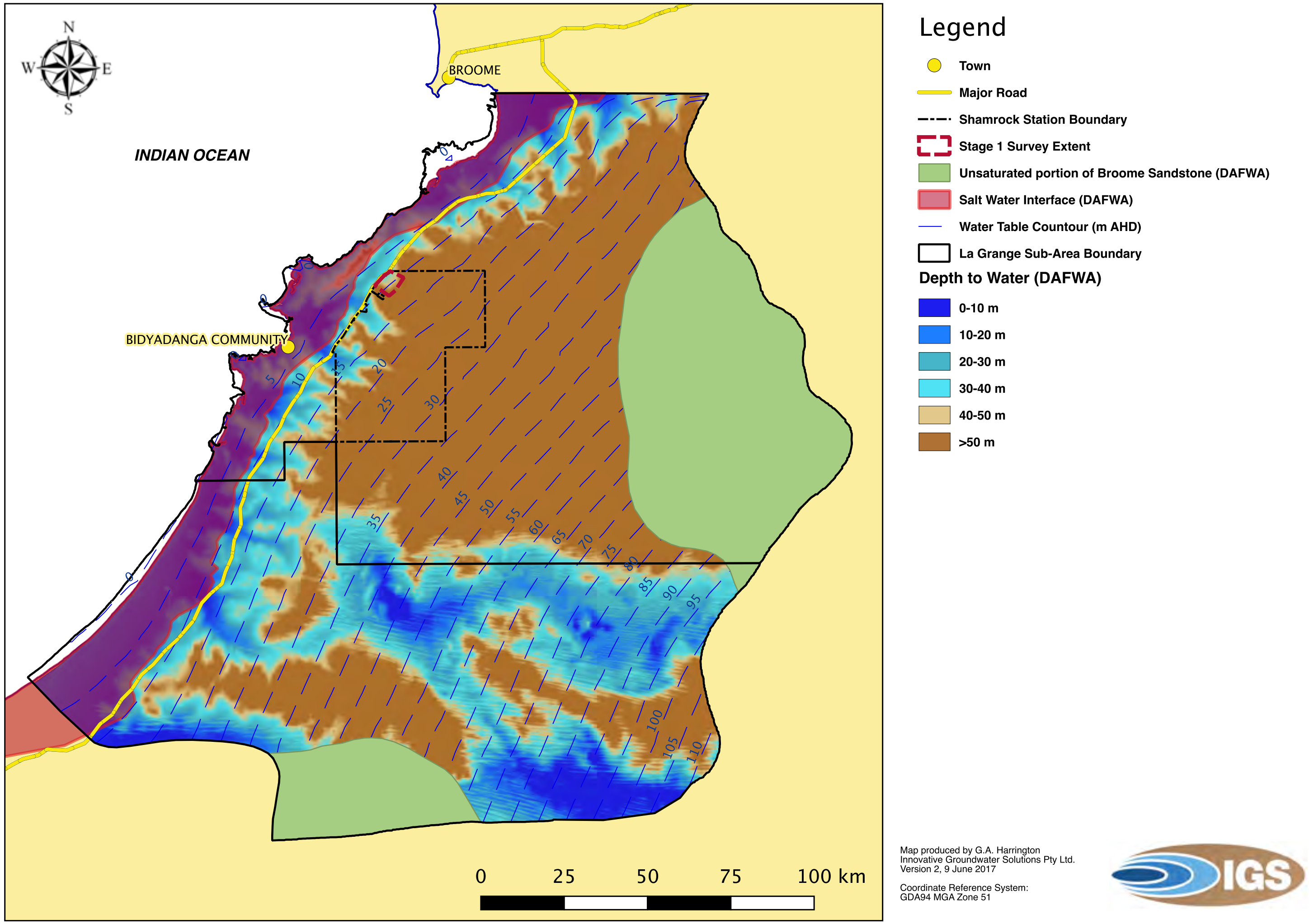


Figure 2.1. Hydrogeological map of the La Grange Sub-Area showing the location of Shamrock Station, the Stage 1 survey extent, water table contours, depth to water table and the location of the AEM-mapped salt water interface.

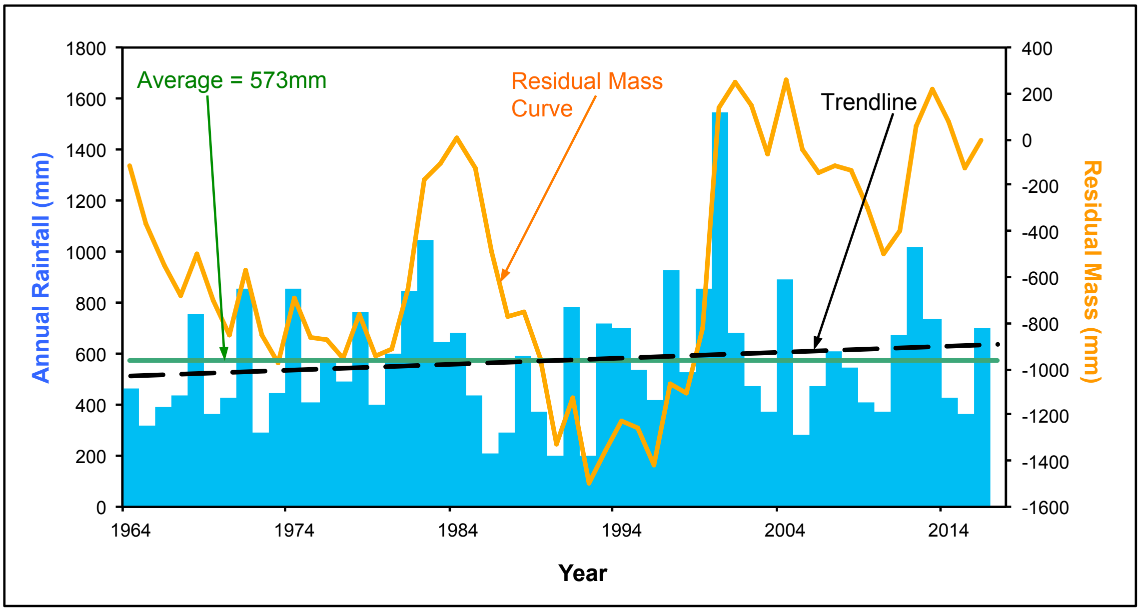


Figure 2.2. Annual rainfall data for Bidyadanga between 1964 and 2016 The 'Residual Mass' curve is also known as 'cumulative deviation from the mean'.

3 Hydrogeology

Shamrock Station is located in the La Grange Groundwater Sub-Area, which is part of the Canning Basin, the largest sedimentary basin in Western Australia (Paul et al., 2013). Much of the available data and information on the geology and hydrogeology of the La Grange area, particularly the Broome Sandstone, has been summarized by Paul et al. (2013). The aquifer of interest for the proposed Shamrock Station development is the unconfined Broome Sandstone aquifer, which is the uppermost major aquifer in the La Grange area. The Broome Sandstone provides the main water source for irrigation, stock and domestic purposes. It covers more than 30,000 km^2 of the Canning Basin and has an average saturated thickness of approximately 150 m (Paul et al., 2013). It was deposited during the Lower Cretaceous period and is separated from the underlying Middle Jurassic confined Wallal aquifer by the low-permeability Jarlemai Siltstone and Alexander Formations.

The Broome Sandstone comprises friable fine- to coarse-grained sandstone, which is mainly unconsolidated. It contains minor beds of grey siltstone, claystone and pebble conglomerate, as well as some thin coal seams (Paul et al., 2013). Available data suggest that it is relatively continuous across the La Grange area. In the east of the area, the Jarlemai Siltstone is exposed with Broome Sandstone being ‘draped’ across this unit and increasing in thickness from east to west. At the coast, the Broome Sandstone is approximately 200 m thick. The contact between the Broome Sandstone and the Jarlemai Siltstone is relatively flat, dipping at approximately 0.3 percent towards the west.

The Broome Sandstone aquifer is generally unconfined. However, evidence from some pumping tests suggests that it may become confined beneath fine-grained sediments in the coastal flats areas (GCS, 2016). Laws (1991) describes the Broome Sandstone as a layered aquifer, with the coarser layers producing better yields and water quality. Bores screened in the coarser layers can produce yields of 2,800 m^3/day. Shallower bores with slotted PVC casing have been reported to have lower yields and the bores in the Broome town water supply borefield have yields of 1,200 m^3/day to 1,500 m^3/day (Paul et al., 2013). Associated hydraulic conductivities are estimated to be between 2 m/day and 42 m/day, but are generally around 15 m/day (Paul et al., 2013). The La Grange Water Allocation Plan provides an estimate of the volume of water available for extraction based upon a hydraulic conductivity value of 20 m/day (Department of Water (2020) in Paul et al. (2013)).

Several studies have estimated the hydraulic properties of the Broome Sandstone outside of the La Grange area. Leech (1979) estimated values between 3 m/day to 15 m/day for the area to the south of the La Grange area. Specific yield values were not calculated, although they were estimated at 0.1 to 0.3. Vogwill (2003) also carried out a detailed study of the Broome Sandstone in the Broome / Roebuck Plains / Roebuck Bay area, concluding that the Broome Sandstone in that area can be divided into an upper deltaic or transitional facies and a lower fluvial facies. He went on to use a variety of methods at different scales to estimate hydraulic conductivities of between 0.7 m/day to 161 m/day for the upper facies and 2 m/day to 168 m/day for the lower facies.

Groundwater flow in the Broome Sandstone aquifer is from east to west, towards the coast (consistent with the potentiometric surface plotted in Figure 2.1). Depths to groundwater in the study area range from less than 1 m to approximately 158 m, with the shallowest depths to groundwater occurring in the coastal areas (Figure 2.1). There is no long-term record of groundwater levels for the La Grange area. Paul et al. (2013) describe fortnightly monitoring of 12 bores by Western Agricultural Industries in 1999 and results from loggers installed in three bores during 2011-12 by DAFWA. Groundwater level measurements in the same bores by these programs indicated an overall groundwater level rise of between 1.0 m and 2.1 m across the La Grange area, consistent with higher than average rainfall during that period.

Routine monitoring of groundwater levels in the La Grange area has occurred since 2013 and temporal groundwater level data are now available from a series of monitoring bores scattered across Shamrock Station and in the adjacent coastal areas (Figures 3.1 to 3.3). Manual measurements of groundwater level have been obtained approximately every three to six months since 2013 for bores on Shamrock Station, Shamrock Gardens and Frazier Downs, as well as two Main Roads Dept. bores (MRD010 and MRD012) (Figure 3.2(a) and (b)). The Shamrock Station, Shamrock Gardens and Main Roads bores display stable water levels between June 2013 and March 2015. Between March 2015 and May 2016, a very gentle decline in groundwater levels was observed in all of these bores (Figure 3.2(a)). For the Frazier Downs bores, this gentle decline in groundwater level occurs from April 2014 (Figure 3.2(b)).

A series of new observation bores installed recently by DAFWA in 2015 (and one in 2016) have also had groundwater levels measured manually on two to three occasions since installation. The records for these bores are insufficient to determine any trends in groundwater level with any confidence.

Groundwater level loggers installed on three observation bores (15LAG06S, 15LAG11S and 15LAG11I) provide groundwater level data at a fine temporal scale for the 2015/16 wet season (November 2015 to April 2016; Figure 3.3). The data for bore 15LAG06S, which is a shallow observation bore located near the north-western boundary of Shamrock Station, shows a gentle decline in groundwater levels by approximately 0.1 m over this time (Figure 3.3(a)). In contrast, an intermediate depth bore, 15LAG11I, located near Injudinah Swamp, displays an increase in groundwater level by 0.9 m between December 2015 and February 2016 (Figure 3.3(c)). This is followed by a period where water levels are stable until March 2016 and then decline, albeit with two events of increasing water levels, until the end of the record in April 2016. A shallow observation bore located adjacent bore 15LAG11I (15LAG11S) displays a similar pattern in groundwater levels, although the water level fluctuations are slightly delayed and damped compared with 15LAG11I (Figure 3.3(b)). These 15LAG11 bores clearly demonstrate the effects of filling of the ephemeral Injudinah Swamp by wet-season rains on water levels in the aquifer.

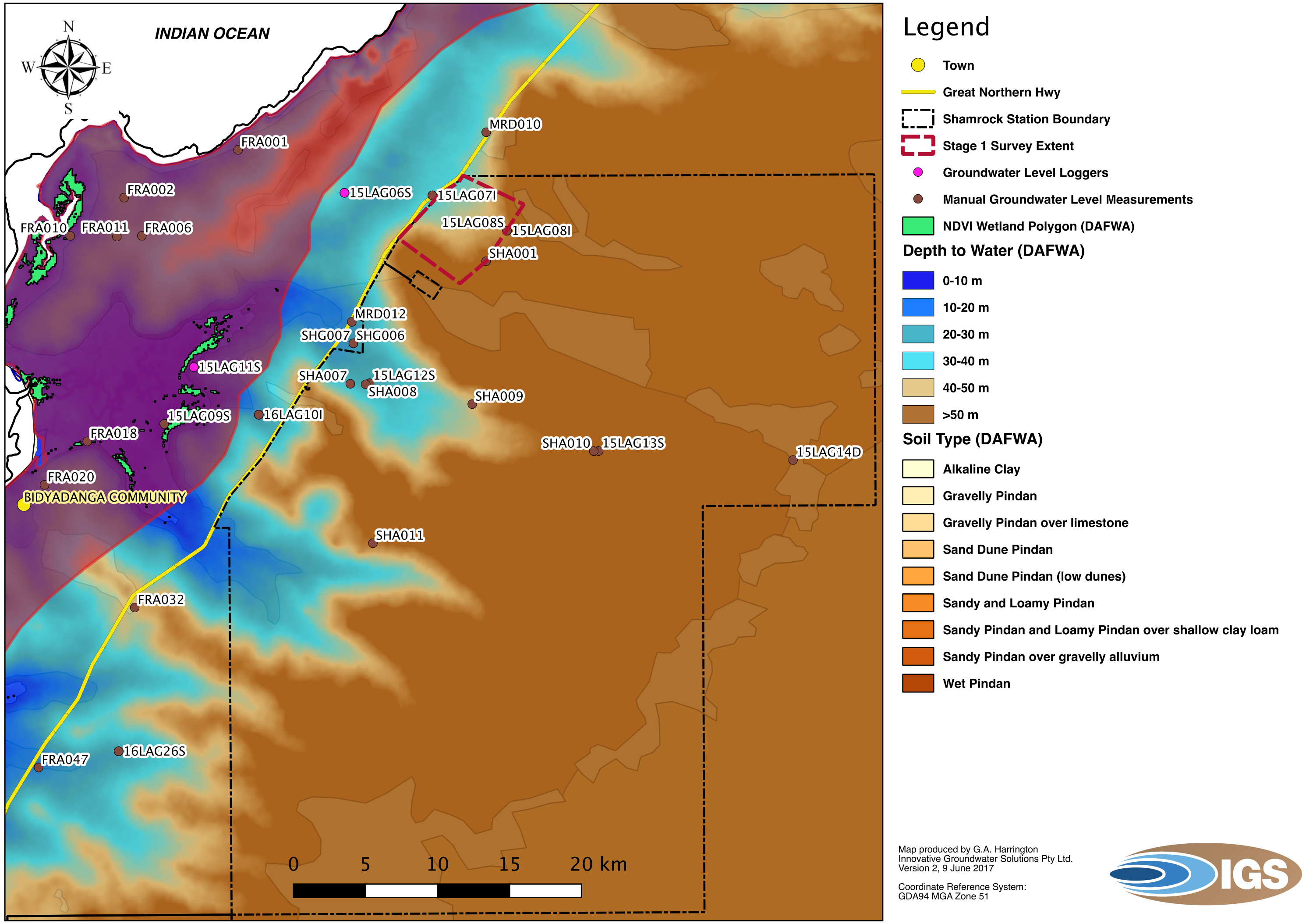
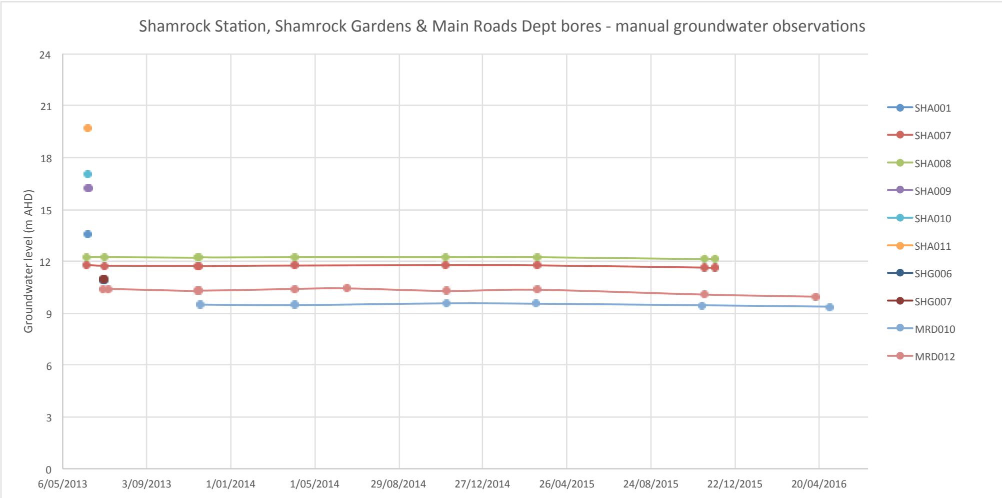
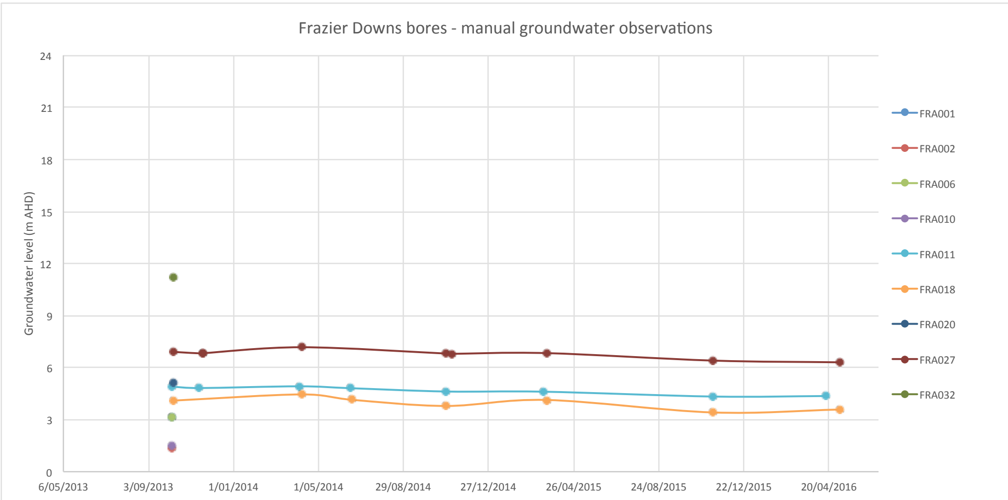


Figure 3.1. Map showing the locations of groundwater monitoring bores on and around Shamrock Station.



(a)



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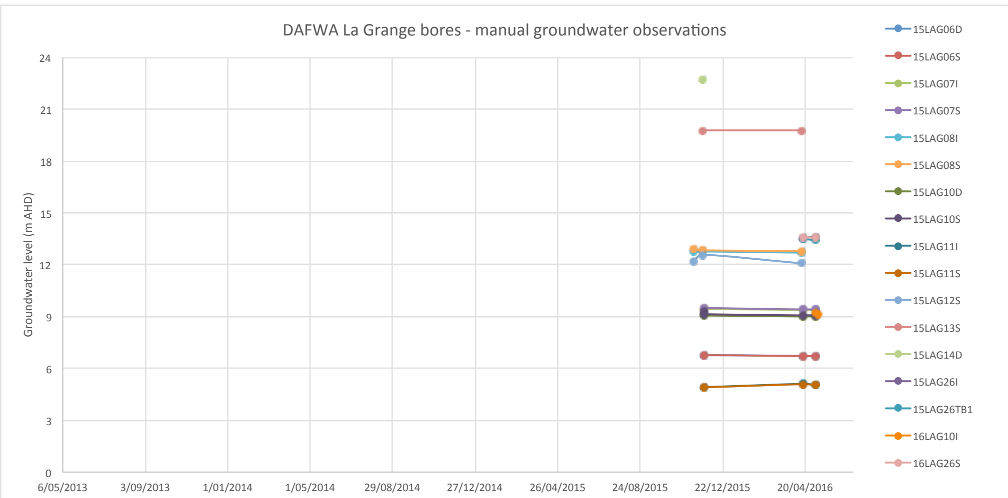
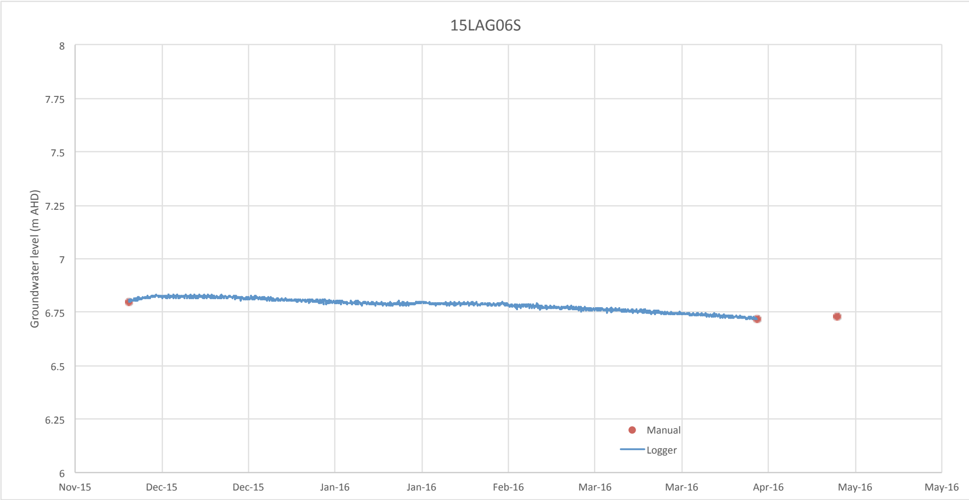
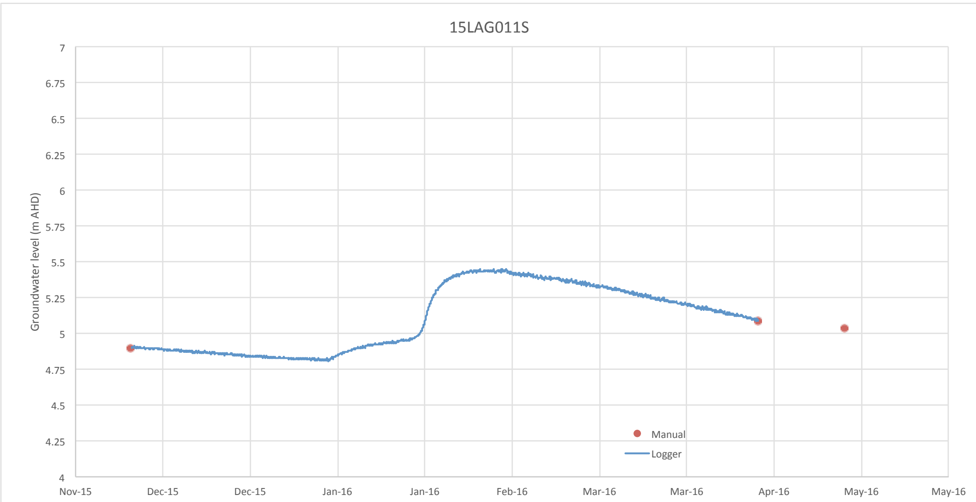


(c)

Figure 3.2. Hydrographs from manual readings for (a) Shamrock Station, Shamrock Gardens and Main Roads Dept. bores, (b) Frazier Downs bores and (c) DAFWA La Grange monitoring bores.



(a)



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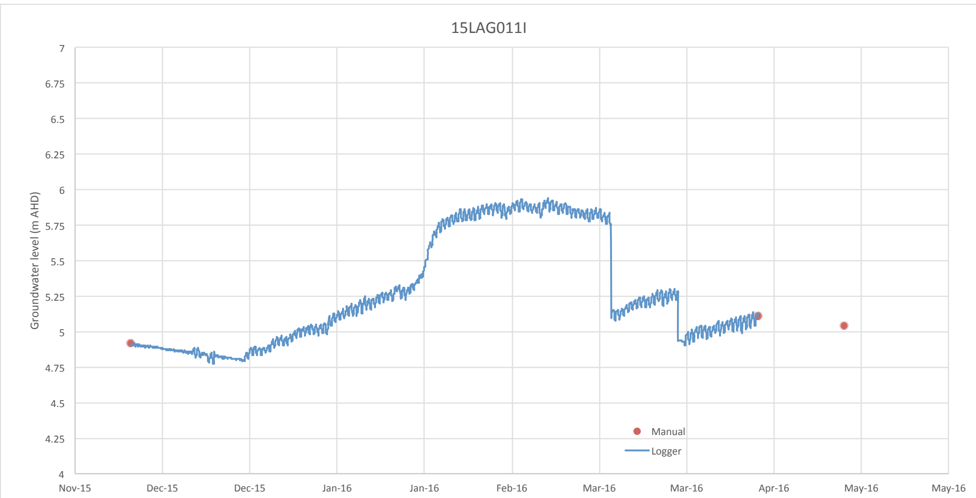


(c)

Figure 3.3. Hydrographs from logger data for (a) Observation bore 15LAG06S, (b) 15LAG11S and (c) 15LAG11I.

4 Existing Groundwater Users

Due to a number of factors, including but not limited to the occurrence of shallow water tables and suitable soils, Stage 1 irrigation development will be focused on the northern boundary of Shamrock Station, immediately east of the Great Northern Highway (Figure 4.1). Accordingly, it is important to identify the locations and annual demand profiles of existing groundwater users, including licensed and unlicensed extraction, plus potential groundwater dependent ecosystems (GDEs) that may be reliant to some extent on the permanence and water quality characteristics of shallow groundwater.

4.1 Licensed and Unlicensed Groundwater Extraction

Locations of existing groundwater users including Aboriginal Communities and licensed users are shown in Figure 4.1, while details for licensed users presented in Table 4.1. DOW provided the following information about the Aboriginal Communities shown on Figure 4.1 (pers. comm. Karis Tingey, 17 March 2017): Nygah Nygah is a permanent site with two houses and a population of four; Yardoogarra (also known as Garimba) is a seasonal site with one house but possibly no permanent residents; Pelling Pelling is not necessarily an established site; Wanamulnyndong (also known as Mijilmil – Mia) is a permanent site with five houses and a population of 20; and Kalyadayan is a seasonal site but may not have any houses present.

4.2 Groundwater Dependent Ecosystems

A number of potential Groundwater Dependent Ecosystems (GDEs) have been identified in the La Grange area (Wright et al., 2016). The nearest of these to the proposed Stage 1 development is Injudinah Swamp (Figure 4.1) and this is the only significant GDE identified within the zone of potential impacts from the Shamrock Station Stage 1 development. This swamp is listed in Environment Australia's Directory of important wetlands in Australia as a wetland of State significance (Environment Australia 2001). The northern edge of the wetland (i.e. the location closest to the proposed Stage 1 development ~15 km away) is indicated on Figure 4.1 and this point is used as an assessment point for impacts predicted through the groundwater modelling described in Section 9.

Table 4.1. Details of existing groundwater users identified around Shamrock Station (data provided by DOW; 17 March 2017).

	Licensed Volume	Bore Name	Easting	Northing	Average Annual Water Use (ML/yr)
Shamrock Gardens	2.5GL	AB	394549	7946344	~10-30
		CD	394271	7946074	~100-130
		EF	394074	7945410	~100-130
		GH	394059	7944832	~400
		JK	393780	7944537	~10-30
Ryall Pty Ltd. (Port Smith CP)	19ML		378154	7952308	
Janice Bell (Barn Hill)	40ML	Tank bore	398722	7968771	
		Shed bore	398635	7968815	
Frank Hamlett	10ML		374093	7952142	

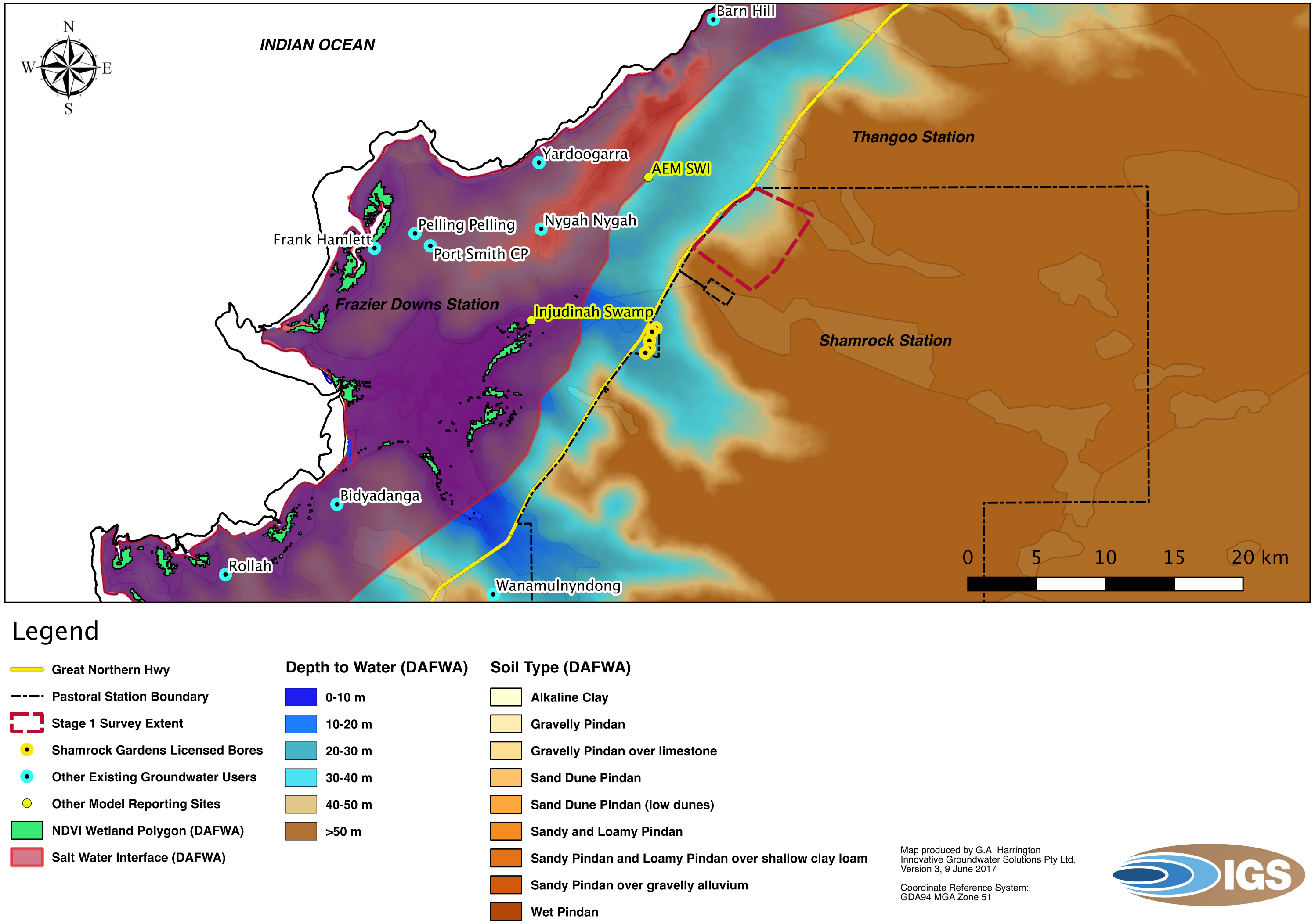


Figure 4.1. Locations of existing groundwater users in the study area. The closest point of the AEM-inferred SWI toe and Injudinah Swamp are also shown.

5 Groundwater Investigations

A wealth of hydrogeological data and knowledge has recently been acquired for the Broome Sandstone aquifer in the LaGrange area – including Shamrock Station and surrounding properties – by the recent Department of Agriculture and Food (DAFWA) '*La Grange Agriculture Opportunities*' project.

Key elements of the DAFWA project included the following:

- Bore reconnaissance and baseline water quality survey (Paul et al., 2013);
- Airborne Electro-Magnetic (AEM) survey to map the location of the saltwater interface (SWI) and the distribution of aquifer thickness (Annetts et al., 2014);
- drilling and geophysical logging of numerous production and monitoring bores (see Section 6 herein);
- groundwater level monitoring to map depth to water table (DTW) (Wright et al., 2016.);
- hydrochemical/isotope analysis for recharge/flow analysis (Harrington and Harrington, 2016); and
- aquifer pumping tests (see Section 7 herein).

Two important datasets from the AEM survey and DTW mapping are shown in Figure 2.1. When these features are overlain with soil suitability maps, which were also produced as part of the project (Smolinski et al., 2016), the most prospective areas for future irrigation development in La Grange (i.e., suitable soils, shallow DTW and inland from the toe of the AEM-inferred SWI) become readily apparent.

The location of the SWI is a focus of the present assessment because it is important that any new groundwater development does not cause unacceptable adverse impacts to the groundwater system and existing users through ingress of the saltwater interface. Whilst the AEM survey has provided a map (Figure 2.1 and Figure 4.1) of the inferred toe of the saltwater interface, this has not been widely ground-truthed. Questions remain around the accuracy of the map due to the presence of finer-grained (this higher conductivity) layers towards the base of the aquifer system that may have influenced the result (P. Raper, DAFWA, pers. comm. 28 February 2017). In addition, recent modelling of the saltwater interface by DAFWA has been unable to simulate the formation of a saltwater / freshwater interface as far into the aquifer as that mapped by the AEM. This is an important consideration when predicting the impacts of the proposed development on the location of the saltwater / freshwater interface and is discussed further in Sections 9.7 and 10.4.

IGS was contracted to DAFWA during the '*La Grange Agriculture Opportunities*' project (2014-2016) to assist with the design of monitoring bore construction and groundwater sampling programs, as well as to analyse and interpret the hydrochemical/isotope data to estimate groundwater recharge rates, residence times and flow paths. A key output of that work was the map shown in Figure 5.1, which provides recharge rates from three different methods (i.e., chloride mass balance, 1-D CFC modelling and 2-D radiocarbon modelling) and at different spatial and temporal scales over the majority of the La Grange area. For each method the mean recharge rates (Table 5.1) are biased towards one or two very high values, which are not consistent between bores. Therefore, the median values of recharge rates are considered most appropriate for regional groundwater modelling.

Table 5.1. Summary statistics for annual recharge rates to the Broome Sandstone aquifer (from Harrington and Harrington, 2016).

Method	Scale of Estimate	Number of Samples	Mean Recharge Rate (mm/yr.)	Median Recharge Rate (mm/yr.)
Chloride Mass Balance	point	192	16.9	13.6
CFC-12 Models	small spatial ave.	15	< 22.9	< 16.5
Radiocarbon Models	large spatial ave.	23	16.3	11.6

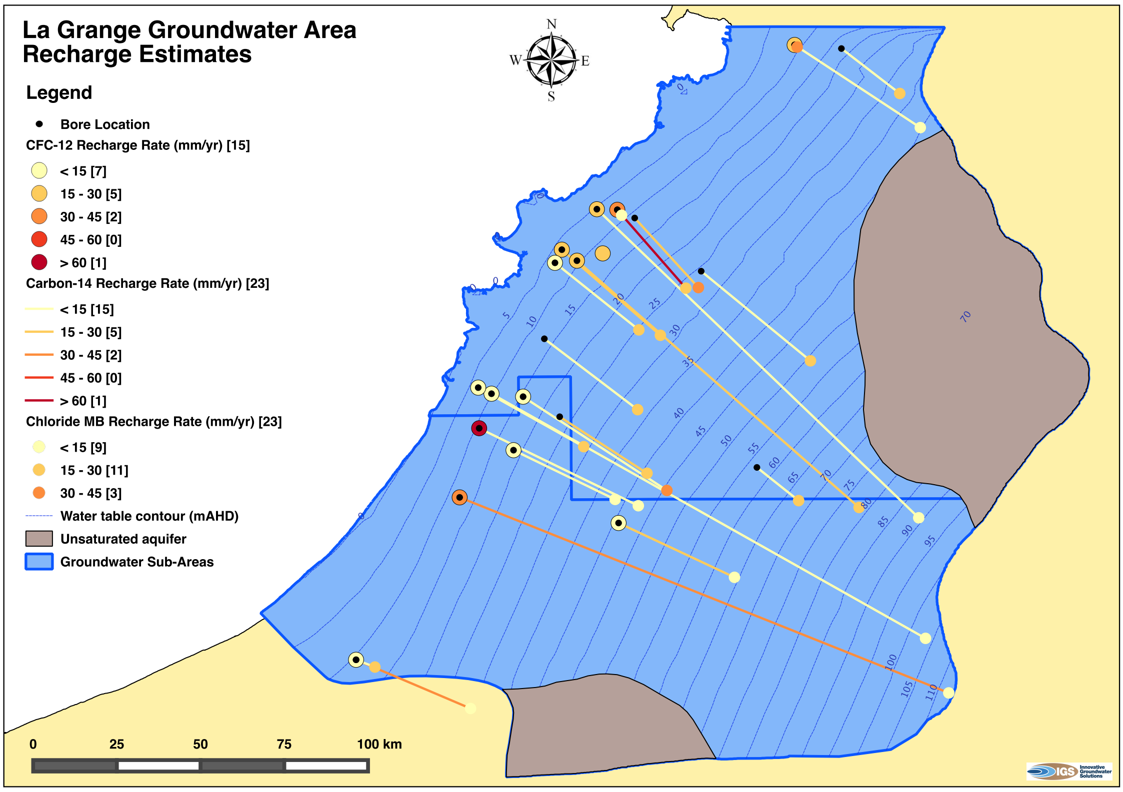


Figure 5.1. Recharge rates over different spatial extents (from Harrington and Harrington, 2016)

Figures 2.1 and 5.1 provide a high level of confidence that the shallow groundwater resource is both available and actively replenished by annual recharge. They also provide important datasets for input to and evaluation of the groundwater modelling presented in Section 9.5.

6 Drilling

There are several old production bores located on Shamrock Station (Figure 6.1). However, a number of bores have also been drilled on the station in the last two decades as part of targeted investigations. Drilling records and sampling and testing of these bores provide insight into the characteristics of the local Broome Sandstone aquifer.

6.1 Shamrock 1 and 2

A preliminary investigation into the Broome Sandstone was carried out for Western Agricultural Industries (WAI) in 1997 by Rockwater Pty Ltd. The investigation included drilling of two investigation bores on Shamrock Station, Shamrock Bores No. 1 and 2. The details of these bores provided below have been taken from a summary by Paul et al. (2013). Shamrock 1 and 2 were included in sampling for groundwater chemistry and isotopes by IGS (2014) and their locations are shown on Figure 6.1.

Shamrock Bore No. 1 was drilled to a total depth of 168 m and completed with 50 mm class 18 uPVC casing, which was hand-slotted between 24.7 m and 168.7 m (Table 6.1). The top of the Jarlemai Siltstone at this location was reported to be at a depth of 164 m. Downhole geophysics (gamma and resistivity) identified layers of silty sandstone and higher porosity moderately to weakly cemented sands at this location. An airlift groundwater sample had a Total Dissolved Solids concentration (TDS) of 270 mg/L.

Shamrock Bore No. 2 was drilled approximately 1.5 km to the east of Shamrock Bore No. 1 to a total depth of 54 m (Table 6.1). Downhole geophysics suggested that the Broome Sandstone has a low porosity at all depths at this location, except for the top 9 m which comprises aeolian sands. A siltstone band was also identified between 46 m and 54 m depth. An airlift groundwater sample had a TDS of 360 mg/L.

6.2 Production Bore PB1

Production bore PB1 was drilled in August / September 2015 to a depth of 155 m. This bore is located within the proposed Stage 1 development area (shown in later maps, but refer to Figure 3.1 as PB1 is immediately adjacent bores 15LAG08I/S). The bore was completed with 250 mm ID PVC casing to 95 m depth below which a slotted PVC casing (aperture 0.5 mm) was installed between 95 m and 153 m depth (GCS, 2016). The gravel pack extends from 75 m to 153 m depth. Above this, the annulus of the bore has been sealed with cement grout. The drillers' log for PB1 describes predominantly sandstone, which is coarse between 50 m and 68 m, fine-medium between 68 m and 100 m, medium-coarse from 100 m to 122 m and coarse from 122 m to the bottom of the hole at 155 m. The hydraulic properties of the bore and the aquifer at this location are described in the following section.

6.3 La Grange Observation Bores

Observation bores 15LAG08S and 15LAG08I (Table 6.1; Figure 6.1) were drilled on Shamrock Station in November 2015 to provide observation points for a pumping test carried out on PB1 in 2016 (see Section 7.3 below). Other observation bores, 15LAG07, 15LAG12 and 15LAG14, were also installed on Shamrock Station around this time as part of the new La Grange monitoring network.

Table 6.1. Details of bores drilled on Shamrock Station or Shamrock Gardens during previous investigations.

Bore	Easting	Northing	Elevation (m AHD)	Screen Interval (m BGL)	
Shamrock 1	393889	7942107	34.86	24.7-168.7	
Shamrock 2	394957	7942071	31.79	8-54	
15LAG08S	404773	7952718	55.82	46-49	Drilled 4/11/15
15LAG08I	404773	7952718	55.906	96-102	Drilled 4/11/15

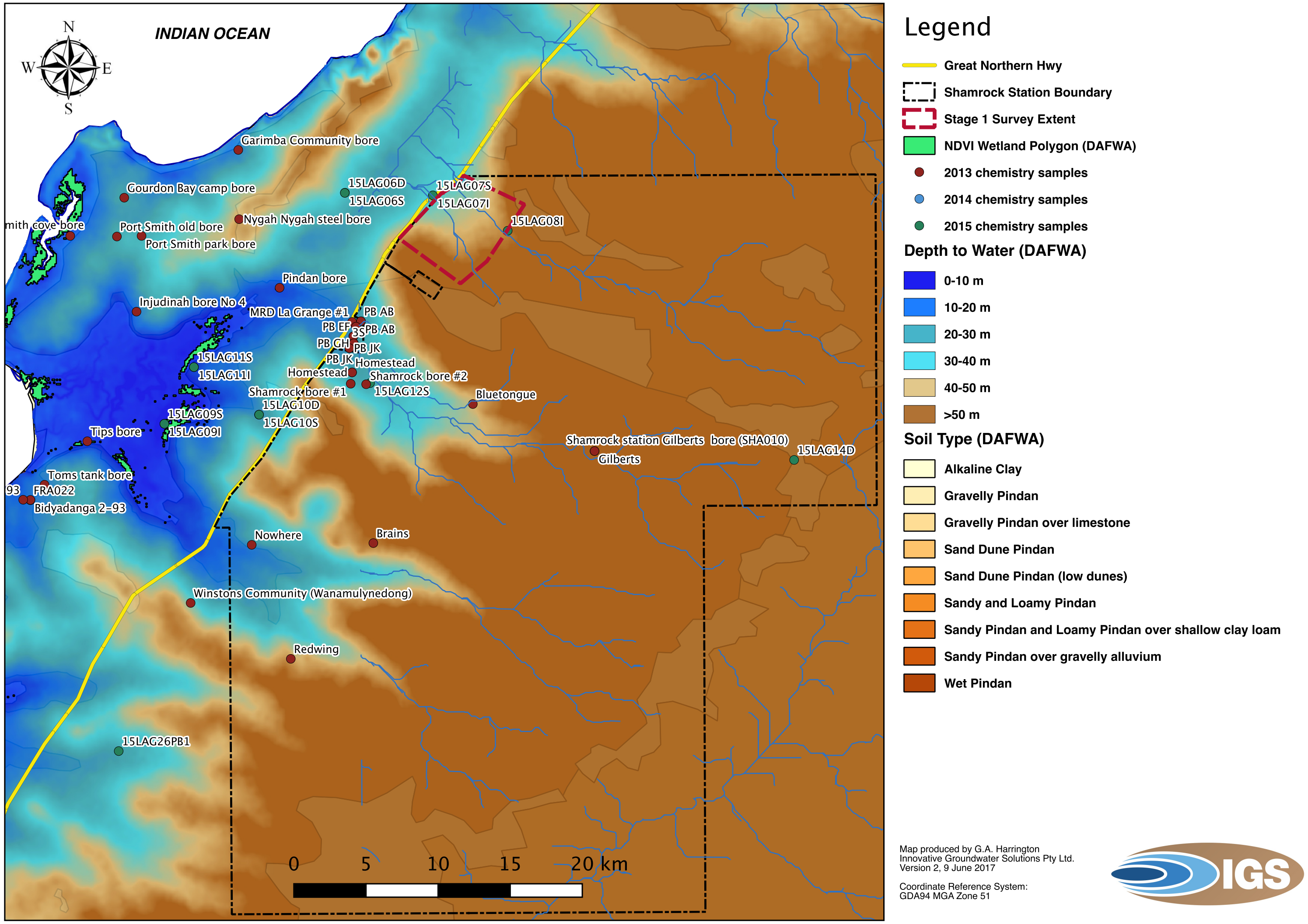


Figure 6.1. Bores sampled for groundwater chemistry during 2013, 2014 and 2015.

7 Aquifer Pumping Tests

7.1 Shamrock Gardens H Bore

Paul et al. (2013) describe the results of a pumping test carried out on H bore at Shamrock Gardens in 1999 by Water Management Consultants (WMC). The production bore had two sets of nested observation bores (each with a shallow (18-30 m screen) and deep (80 to 92 m screen) observation bore) associated with it. These two nests were located at 1.2 m and 10 m from the production bore. During the test, H bore was pumped at an average rate of 44.5 L/s for 46 hours with 7 m of drawdown observed in the production bore. The interpretation of the results by WMC was that the aquifer is horizontally stratified, with leaky responses being observed between layers. Hydraulic conductivity values ranging between 111 m/day and 177 m/day were determined using the Jacob method. However, these are considered to be erroneous by Paul et al. (2013) due to use of the screen length of the production bore rather than the saturated thickness of the aquifer. Paul et al. (2013) suggest that hydraulic conductivity values between 25 m/day and 45 m/day are more realistic for this test and Groundwater Consulting Services Pty Ltd (GCS, 2016) further suggest that a hydraulic conductivity of 16 m/day is reasonable based on an aquifer thickness of 190 m and the derived transmissivity of 3,000 m^2/day.

7.2 Shamrock Station Various Bores (2010)

GCS (2010) carried out 48-hour pumping tests on various bores on Shamrock Station, with discharge rates of 3,890 kL/day, estimating a transmissivity value of 9,600 m^2/day (K = 55 m/day) and a storativity value of 1.5 x 10^{-3}.

7.3 Shamrock Station Bore PB1

GCS (2016) carried out a pumping test on production bore PB1 on Shamrock Station as part of the '*La Grange Agriculture Opportunities*' project. The bore completion details are described in Section 6.2. It has a screen interval that extends through both the upper (lower permeability) and lower (higher permeability) sections of the Broome Sandstone (Table 7.1). The pump was installed at a depth of 75 m.

Table 7.1. PB1 pumping test bore details and observed drawdowns.

	PB1 (pumping bore)	15LAG08S	15LAG08I
Distance from pumping bore (m)	0	352	355
Screen Interval (m)	95-153	46-49	96-102
Aquifer unit	Upper (low K) and lower (high K)	Lower – high K	Lower – high K
Corrected drawdown – End of step test (m)	-	0.03	0.18
Corrected drawdown – End of const. discharge test (m)	-	0.18	0.27

Two monitoring bores were especially designed and installed by DAFWA to assess the horizontal and vertical propagation of drawdown from the pump test. The bores (15LAG08S and 15LAG08I) are located approximately 350 m from the production bore

(Table 7.1). 15LAG08S (S=shallow) is screened in the upper (lower K) section of the Broome Sandstone, whilst 15LAG08I (I = intermediate) is screened in the lower (higher K) section (Table 7.1). Manual water level measurements were made throughout the constant discharge test at 15LAG08S, 15LAG08I). Dataloggers were installed in 15LAG08I and 15LAG08S, La Grange #1 (located adjacent Shamrock Gardens, 12.3 km from production bore) and Thangoo #1 (located on the Great Northern Highway, approximately 6.4 km to the north-west of PB1).

The pumping test comprised a step test (four one-hour step tests) and a 48-hour constant discharge test at 78 L/s (Table 7.2). The peak flow achieved at bore PB1 was 86.7 L/s, with a drawdown of 7.02 m (Table 7.2). The specific capacity of the bore was estimated to be 11.2 L/s/m and this was only constrained by the capacity of the pump and the casing diameter. This high specific capacity was assumed to be due to the long screen interval of the bore and the fact that it was screened throughout the deeper, more permeable unit of the Broome Sandstone. Despite the long screen interval, the bore was deemed to have an efficiency of only 50%. The bore produced dirty water on pump startup and it was thought that it may not have been developed properly.

Table 7.2. Summary of pumping bore data for pump test on bore PB1 (GCS, 2016).

	Step 1	Step 2	Step 3	Step 4	Recovery	Constant Discharge	Recovery
Duration (mins)	60	60	60	60	600	2880	1440
Flow Rate (L/s)	54.2	68.8	80.5	86.7	0	78.3	0
Uncorrected Stage Drawdown (m)	4.405	5.755	7.005	7.655	-	7.02	0.046
Specific Capacity (L/s/m)	12.3	12.0	11.5	11.3	-	11.2	-

No responses to the pump test were observed at La Grange #1 or Thangoo #1. Measurements of drawdown in the two closer observation bores (15LAG08S and 15LAG08I) located at different depths in the Broome Sandstone showed differential drawdowns in the two aquifer sub-units screened by the two bores (Table 7.1).

The pumping test data were analysed using the Neuman solution for unconfined aquifers. The solution does not account for multi-layer aquifers and therefore the matches with the shallow bore drawdown response was poor. Baseline groundwater conditions for the two observation bores, to account for natural fluctuations in water level due to changes in barometric pressure and seasonal trends, were obtained from a bore on Frazier Downs and using trends in barometric pressure.

The assumed aquifer thickness for the pump test analysis was 176 m. An average transmissivity value of 2,000 m^2/day was derived. In reality, the transmissivity of the upper portion of the aquifer would be slightly lower and that of the lower portion would be slightly higher than this average. The resulting estimated hydraulic conductivity value was 11 m/day. The estimated specific yield was 0.05 with a storativity of 0.0018.

7.4 Summary

Table 7.3 provides a summary of the results of aquifer pumping tests carried out on Shamrock Station and Shamrock Gardens.

Table 7.3. Summary of aquifer hydraulic properties obtained from pumping tests on Shamrock Station and Shamrock Gardens.

Study	Location / Bore	K (m/day)	Storage	Comments
WMC (1999)	Shamrock Gardens H Bore	111 - 177		Interpretation by WMC – considered incorrect by others
		25 - 45		Re-interpretation by Paul et al. (2013)
		16		Re-interpretation by GCS (2016)
GCS (2010)	Shamrock Station – various bores	55	$S = 1.5 \times 10^{-3}$	
GCS (2016)	Shamrock Station PB1	11	Sy = 0.05 S = 0.0018	

8 Groundwater chemistry

Due to a number of factors, including but not limited to the locations of shallow water tables and suitable soils, Stage 1 irrigation development will be focused on the northern boundary of Shamrock Station, immediately east of the Great Northern Highway. Accordingly, it is important to understand the chemistry of the underlying unconfined Broome Sandstone aquifer in the Stage 1 development area in relation to its suitability for irrigation supply.

A bore reconnaissance and baseline water quality survey (Paul et al., 2013) sampled 142 Broome Sandstone bores across the La Grange area. Using the hydrochemical analyses from that sampling, IGS (2014) found that using groundwater from the Broome Sandstone aquifer presented very few concerns for irrigation development in terms of the following parameters:

- Salinity, through yield loss and enhanced corrosion of pumps/pipes;
- Sodium, through changing soil structure (sodium adsorption ratio, SAR);
- Boron, through plant toxicity; and
- Iron, through precipitation in pumps and pipes.

Eight of the bores sampled in 2013 were on Shamrock Station. Since then, new groundwater chemistry data from the Broome Sandstone aquifer has been collected as part of the '*La Grange Agriculture Opportunities*' drilling program (see Section 5) and from Shamrock Station production bore PB1 during the 2016 pumping test (Section 7). All local groundwater chemistry data most relevant to the Stage 1 development area (Figure 6.1), has been summarised in Table 8.1.

Groundwater from the Broome Sandstone aquifer generally has a Na-Cl dominated composition (Figure 8.1). Groundwater salinity underlying the Stage 1 development area is below the desirable irrigation limit of 1,000 mg/L, ranging from 90 – 940 mg/L TDS (or 16 – 171 mS/m) (Table 8.1). Furthermore, the upper salinity range of the aquifer is below the zero-yield loss threshold for Rhodes grass (270-635 mS/m, (DAFWA, 2016); 7 dS/m (ANZECC/AMCANZ, 2000)).

In general, it is unlikely that the use of the Broome Sandstone aquifer for irrigation will cause soil structure degradation given a SAR ranging from 2.4 – 8.5 (Table 8.1; Figure 8.2). However, very low salinity groundwater and low SAR in the Shamrock Gardens area (PB-JK: ECi = 0.13 dS/m, SAR = 2.4 & PB-EF: ECi = 0.18 dS/m, SAR 3 in July 2013) indicate soil structure degradation may occur and corrective action could be required, e.g. application of lime or gypsum. However, subsequent sampling of these two bores in October 2013 yielded salinity and SAR values marginally into the stable soil category (Figure 8.3). Under non-saline conditions, Rhodes grass itself has a high tolerance to the effect of sodium on crop yield (SAR = 46-102 (ANZECC/AMCANZ, 2000)).

One bore in the Stage 1 development area recorded a boron concentration elevated above the 0.5 mg/L long-term trigger level, albeit only 0.52 mg/L. Five bores recorded elevated iron concentrations exceeding the long-term trigger of 0.2 mg/L, although only one of those exceeded the short-term trigger of 10 mg/L (15LAG14D = 44 mg/L; ANZECC/AMCANZ, 2000).

The Broome Sandstone aquifer showed no change in groundwater chemistry during the period 2013 to 2017, highlighted by little difference between the results of the 2013 and 2015 sampling of Gilberts bore (Table 8.1).

Interpreting major ion concentrations relative to chloride concentration can be used to examine groundwater chemistry trends as it removes any evaporative effects. As reported by Harrington and Harrington (2016) all samples from the Broome Sandstone aquifer within the Stage 1 development area are slightly enriched in Na relative to marine aerosols (Figure 8.3). Similarly, all samples are enriched in both Ca and HCO_3 relative to marine aerosols, which indicates calcite weathering as a possible source of these ions. Many groundwater samples exhibit a Ca/HCO_3 ratio less than 0.5, consistent with weathering of a Mg-calcite rather than pure calcite. The Ca/SO_4 ratios suggest some samples may have acquired Ca and SO_4 through gypsum dissolution (Ca/SO_4 ~ 1), however the majority of samples have significant excesses of Ca over SO_4 providing further evidence for the importance of calcite weathering.

The Cl/Br ratio suggests no halite salt dissolution process occurring in the Broome Sandstone aquifer (Sonney et al., 2010).

Table 8.1. Summary of all recent groundwater chemistry data for Shamrock Station and Shamrock Gardens.

Bore ID	Sampled	EC (mS/m)	pH	TDS	Alkalinity	HCO3	Na	K	Ca	Mg	Cl	SO4	S	Br	Fe	N_NOx	N	Si	Sr	B	Est. ECi (dS/m)	SAR
				mg/L																		
Bluetongue	12/06/2013	55.6	6.5	310	53	64.7	72.1	4.8	15.8	8.2	115	7.5	2.5	0.52	0.01	7.0	7.5	35.0	0.26	0.32	0.47	4.0
Gilberts	12/06/2013	48.3	6.4	270	49	59.8	64.9	6.2	13.1	7.6	94	4.5	1.5	0.47	0.01	7.6	8.0	33.0	0.20	0.27	0.41	3.9
Nowhere	12/06/2013	52.7	6.9	290	57	69.5	73.6	2.0	14.1	7.3	105	7.5	2.5	0.49	0.04	6.5	7.0	36.0	0.24	0.34	0.44	4.4
Homestead	12/06/2013	63.2	6.8	350	64	78.1	80.3	3.9	18.0	10.3	124	9.9	3.3	0.58	0.03	7.0	7.8	36.0	0.31	0.37	0.53	4.1
Homestead A	12/06/2013	64.9	7.2	360	64	78.1	82.4	4.0	18.0	10.4	128	10.2	3.4	0.57	0.03	7.1	7.7	37.0	0.31	0.40	0.54	4.2
PB EF	3/07/2013	21.5	7	120	26	31.7	31.8	1.2	5.5	3.0	39	2.7	0.9	0.16	0.05	2.8	2.9	4.8	0.10	0.11	0.18	3.0
PB JK	3/07/2013	16.2	6.8	89	21	25.6	22.2	1.7	4.1	2.4	29	2.1	0.7	0.13	0.01	2.2	2.2	3.1	0.06	0.08	0.13	2.4
PB AB	3/07/2013	39.1	6.9	220	40	48.8	55.9	2.5	9.5	6.0	73	5.4	1.8	0.34	0.01	5.6	6.0	7.0	0.17	0.18	0.33	3.9
3S	4/07/2013	171	6.4	940	11	13.4	145.0	94.3	49.6	24.6	227	90.0	30.0	0.70	0.26	94.0	110.0	21.0	0.75	0.43	1.41	4.6
3D	4/07/2013	53.2	6.9	290	58	70.8	68.7	4.5	14.6	8.5	102	6.3	2.1	0.45	0.01	6.9	7.5	30.0	0.23	0.23	0.44	3.9
Shamrock bore #1	5/07/2013	42.1	6.9	230	55	67.1	61.7	4.9	9.0	5.6	75	5.4	1.8	0.33	0.02	5.7	6.1	31.0	0.15	0.22	0.35	4.4
Shamrock bore #2	5/07/2013	56.8	6.8	310	53	64.7	72.5	2.5	17.7	9.9	123	8.7	2.9	0.46	0.10	7.1	7.3	32.0	0.29	0.28	0.47	3.8
MRD La Grange #1	10/07/2013	62.5	6.7	340	48	58.6	83.4	1.0	15.8	11.6	135	9.0	3.0	0.52	0.03	4.7	8.1	37.0	0.32	0.25	0.51	4.4
PB EF	16/10/2013	50.9	6.9	280	58	70.8	69.2	2.8	13.6	7.5	88	6.3	2.1	0.37	0.01	6.0	6.8	35.0	0.21	0.26	0.42	4.1
PB AB	16/10/2013	56.2	6.9	310	55	67.1	75.5	3.5	14.2	9.0	101	7.5	2.5	0.42	0.07	7.1	7.8	35.0	0.23	0.28	0.47	4.3
PB GH	16/10/2013	54.7	6.9	300	56	68.3	71.5	5.3	15.9	8.9	111	7.8	2.6	0.40	0.01	6.2	6.8	32.0	0.23	0.25	0.45	3.9
PB JK	16/10/2013	47.8	6.9	260	56	68.3	66.5	5.2	12.6	7.0	82	6.3	2.1	0.35	0.01	5.6	6.3	32.0	0.19	0.24	0.39	4.1
PB CD	16/10/2013	53.8	6.6	300	51	62.2	72.7	3.0	14.8	9.4	96	7.2	2.4	0.37	0.02	8.0	8.9	37.0	0.26	0.26	0.45	4.0
15LAG07I	6/11/2015	56.2	7.1	310	56	68.3	67.7	2.2	20.3	12.5	110	7.0	2.3	0.43	0.02	6.4	6.6	33.0	0.31	0.24	0.47	3.2
15LAG07S	7/11/2015	96.5	7.3	530	51	62.2	144.0	1.5	21.8	13.9	215	6.0	2.3	0.85	0.30	19.0	22.0	62.0	0.39	0.31	0.80	6.6
15LAG06D	7/11/2015	101	7.8	560	107	130.5	155.0	15.0	25.0	14.6	186	58.0	19.0	0.66	1.50	0.3	0.6	9.2	0.34	0.33	0.84	6.7
15LAG06S	7/11/2015	102	7.3	560	73	89.1	168.0	3.4	19.9	9.3	215	21.0	6.3	0.85	1.30	12.0	12.0	51.0	0.29	0.40	0.84	8.5
15LAG14D	9/11/2015	85.5	8	470	101	123.2	169.0	10.9	23.8	12.4	113	110.0	36.0	0.43	44.00	11.0	15.0	45.0	0.43	0.42	0.71	7.7
15LAG12S	9/11/2015	101	7.1	550	87	106.1	147.0	3.3	32.1	16.6	205	21.0	8.1	0.89	3.30	8.4	8.5	38.0	0.45	0.52	0.83	5.8
15LAG08I	9/11/2015	44.5	7	240	58	70.8	60.4	4.9	13.0	8.5	75	5.0	1.9	0.34	0.15	5.9	7.0	30.0	0.19	0.24	0.36	3.6
Gilberts	23/11/2015	48.6	7	270	47	57.3	64.4	6.3	13.4	8.1	94	5.0	1.5	0.42	0.01	7.2	7.3	32.0	0.20	0.23	0.41	3.8
Shamrock PB1	18/04/2016	45.6	7.4	250	54	65.9	62.0	5.1	12.2	7.7	96	7.0	-	-	0.30	5.9	6.3	-	-	-	0.38	3.8

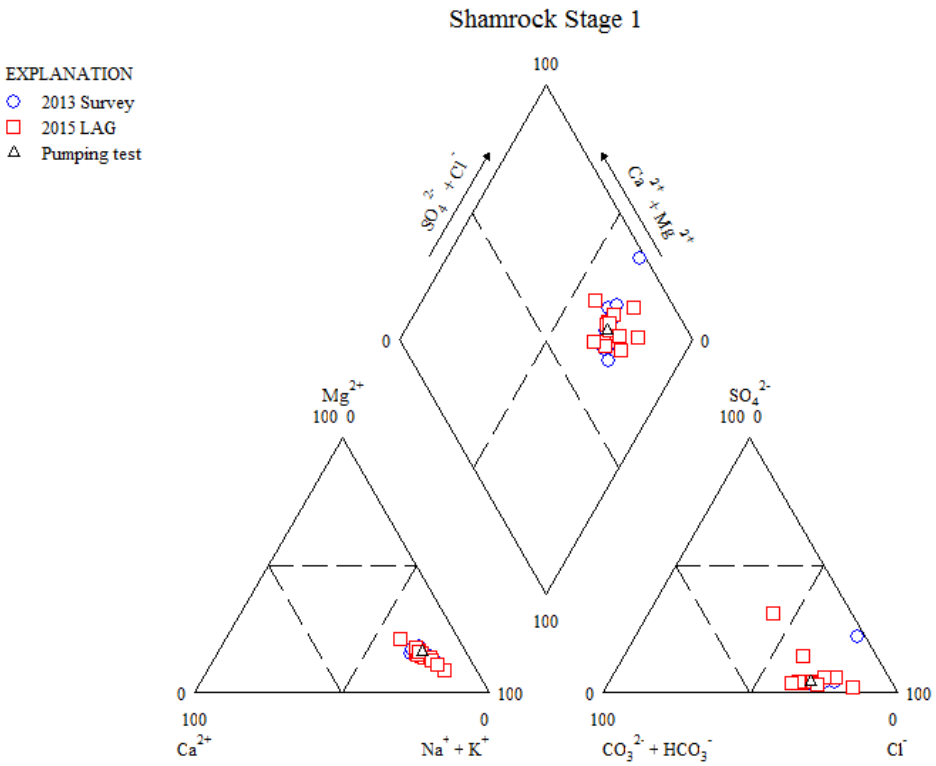


Figure 8.1. Piper diagram showing groundwater chemistry data collected on Shamrock Station.

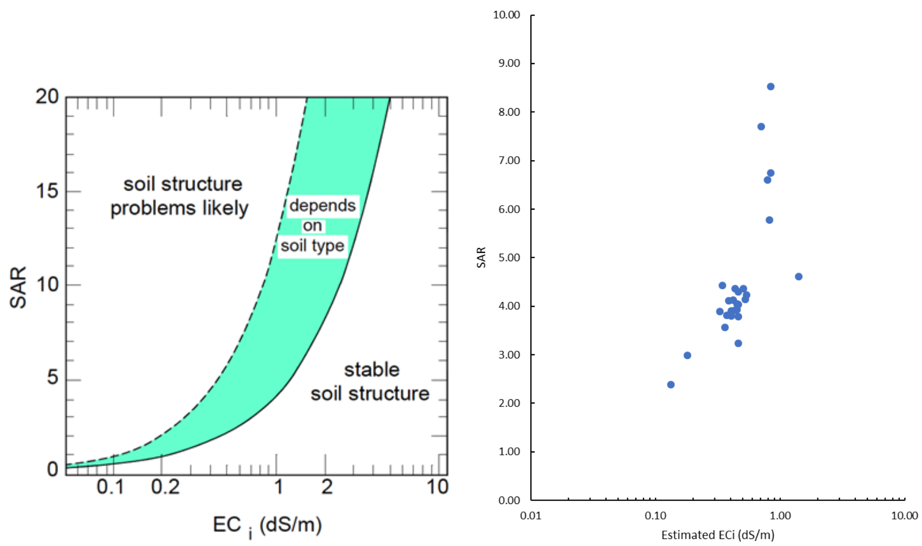
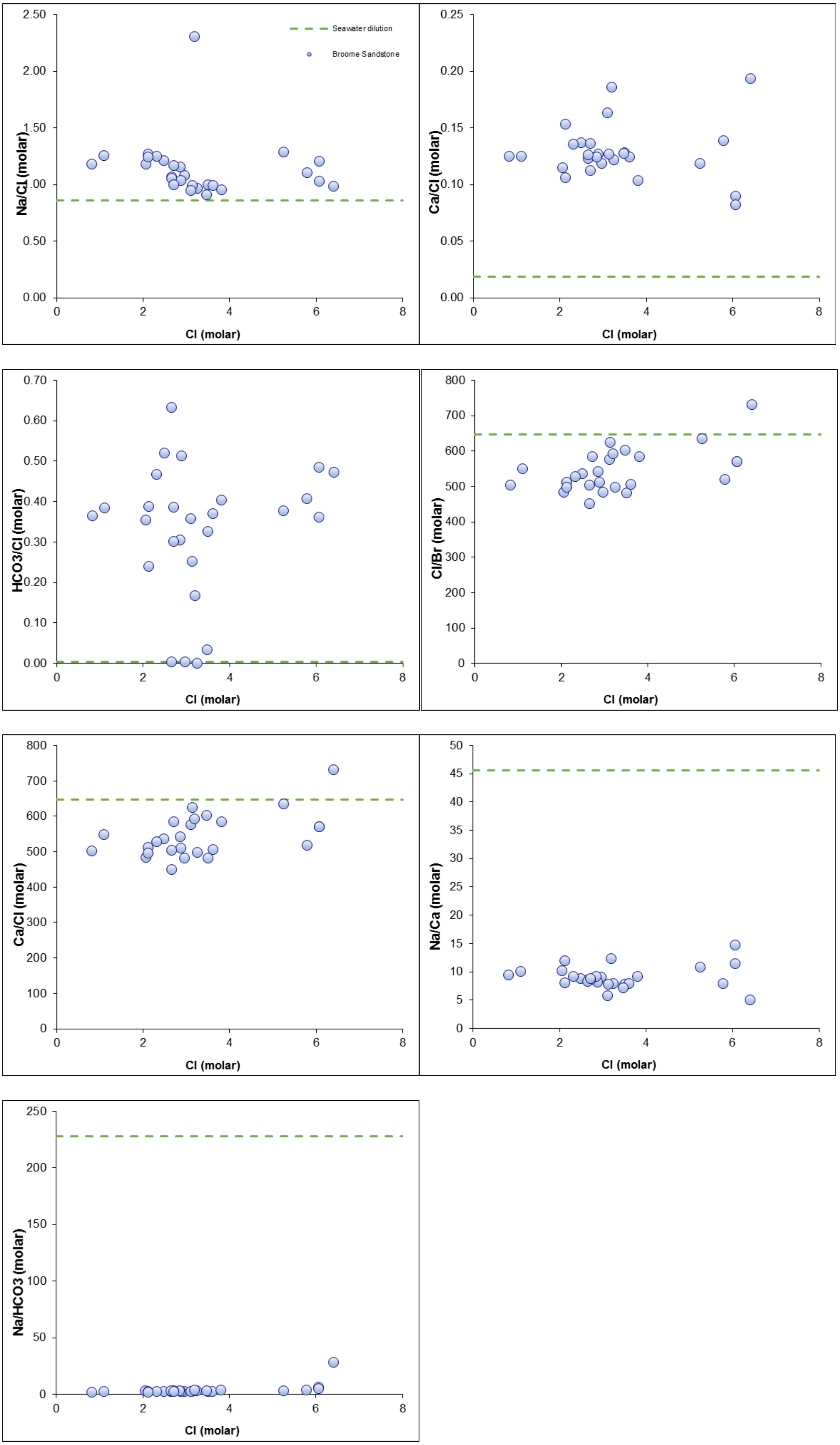


Figure 8.2. Soil structure as a function of the sodium adsorption ratio (SAR) and electrical conductivity (ECi) of irrigation water (after ANZECC/AMCANZ, 2000). (b) Broome Sandstone groundwater samples, with EC estimated using the following approximation, ECi (dS/m) ~ 0.0015 x TDS (mg/L).


Seawater dilution
Broome Sandstone
Na/Cl (molar)
Cl (molar)
Ca/Cl (molar)
Cl (molar)
HCO3/Cl (molar)
Cl (molar)
Cl/Br (molar)
Cl (molar)
Ca/Cl (molar)
Cl (molar)
Na/Ca (molar)
Cl (molar)
Na/HCO3 (molar)
Cl (molar)

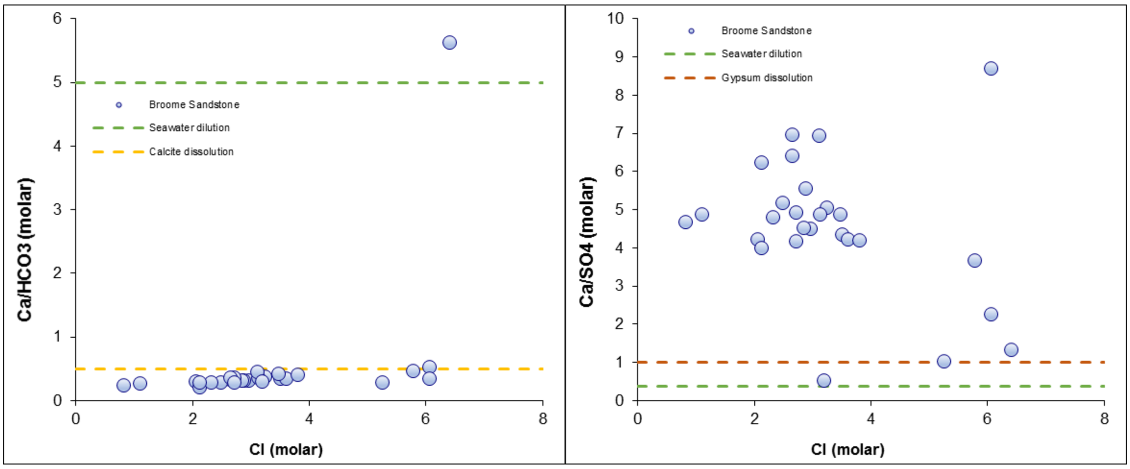


Figure 8.3. Major ion ratios versus chloride concentration for local groundwater.

9 Groundwater Modelling

- **Development of a suite of complimentary models provides a range of tools to address the range of model objectives and added confidence in model outcomes.**
- **Two calibrated steady state numerical models cover the range of plausible K / R scenarios (Scenario 1 and Scenario 2) for the study site, capturing the uncertainty in these key parameters and the impacts of associated model 'non-uniqueness'.**
- **Groundwater fluxes in Scenario 2 are almost double those in Scenario 1, whilst steady-state calibration is achieved by both, highlighting the importance to model outcomes of employing this multi-scenario approach.**
- **Numerical and analytical modelling of the saltwater interface suggests that, down-gradient of the proposed Stage 1 development, the interface may occur closer to the coast than has been inferred from the results of the AEM survey.**

9.1 Objectives

Groundwater modelling is a critical component of a H3 Hydrogeological Assessment, as well as for the planning of any large-scale groundwater development. As emphasized in the Australian Groundwater Modelling Guidelines (Barnett et al., 2012), the groundwater modelling approach adopted must be carefully designed to suit the needs of the project and hence the objectives of the modelling exercise. The objectives of the groundwater modelling carried out for this project were to:

1. Inform the preliminary design of the Stage 1 irrigation development (i.e. the number, locations and pumping rates of Stage 1 bores) to optimize the amount of water that can be extracted whilst minimizing pumping costs and the impacts on existing users and environmental constraints.
2. Predict drawdowns associated with the proposed Stage 1 development at:
   a) the Stage 1 production bores;
   b) the locations of all existing groundwater users described in Section 4, which includes licensed and un-licensed users; and
   c) the closest groundwater dependent ecosystem, Injudinah Swamp.
3. Predict the impact of the proposed Stage 1 development on the location of the toe of the saltwater interface.
4. Provide tools that can be used in the future to:
   a) address queries or issues raised by stakeholders; and
   b) inform the design and assess the impacts of any future development proposals.

9.2 Overall Modelling Approach

In order to address the range of objectives described above, a range of models has been developed. This includes:

1. Analytical models of drawdown around multiple pumping bores. This simple tool does not include the effects of rainfall recharge and regional groundwater inflows on predicted drawdowns and hence provides a worst-case approximation of drawdowns around pumping bores. However, its simplicity allows first-pass assessments of the drawdown impacts of pumping scenarios for rapid decision-making. This tool was used in the early stages of the project to determine the number of production bores that may be commissioned whilst maintaining acceptable impacts to existing users and environmental constraints.
2. A regional-scale numerical groundwater flow model that was calibrated in steady-state mode to regional groundwater head data. The steady state version of this model was used to test the Conceptual Model of the groundwater system and to select the appropriate ranges of recharge and hydraulic conductivity values to be applied in subsequent transient simulations. Transient simulations with the calibrated model using these ranges of parameters were then used to determine the range of potential impacts of the proposed Stage 1 development, with bore numbers, locations and pumping rates provided from Step 1 above. The outcomes from this methodology then account for the uncertainty in rainfall recharge and hydraulic conductivity.
3. A regional-scale three-dimensional density-dependent solute transport (SEAWAT) model based on the groundwater flow model developed in (2) above. This complex model was used to test the conceptual model of the position of the saltwater interface adjacent Shamrock Station, providing confidence in the outcomes from 4 below. However, this modelling tool was not used in the prediction of impacts from the Stage 1 development as it is overly complex for the model objectives and compared with the level of understanding of the saltwater interface in the study area. Extremely large model run-times and data requirements mean that the approach cannot be used efficiently in the assessment of multiple pumping and conceptual model scenarios.
4. Analytical models of the position of the saltwater interface that were informed by (2) and (3) above. These allow efficient assessments to be made of the impacts of various pumping scenarios on the position of the toe of the saltwater interface that are consistent in complexity with the level of data and knowledge available on the saltwater interface in the study area.

This suite of modelling tools allows the best tool to be used to address individual objectives outlined above within the required timeframes. All models are based upon the same conceptual model and the outcomes of each model has been used to inform the development and application of the others, adding confidence to the assessments made using each approach.

9.3 Conceptual Model

The various models described in this Section are based on the same Conceptual Model of the groundwater system in the Broome Sandstone aquifer around Shamrock Station. Various aspects of this Conceptual Model have been described in detail in Sections 2 to 8 and are summarized in Figure 9.1 and the sections below.

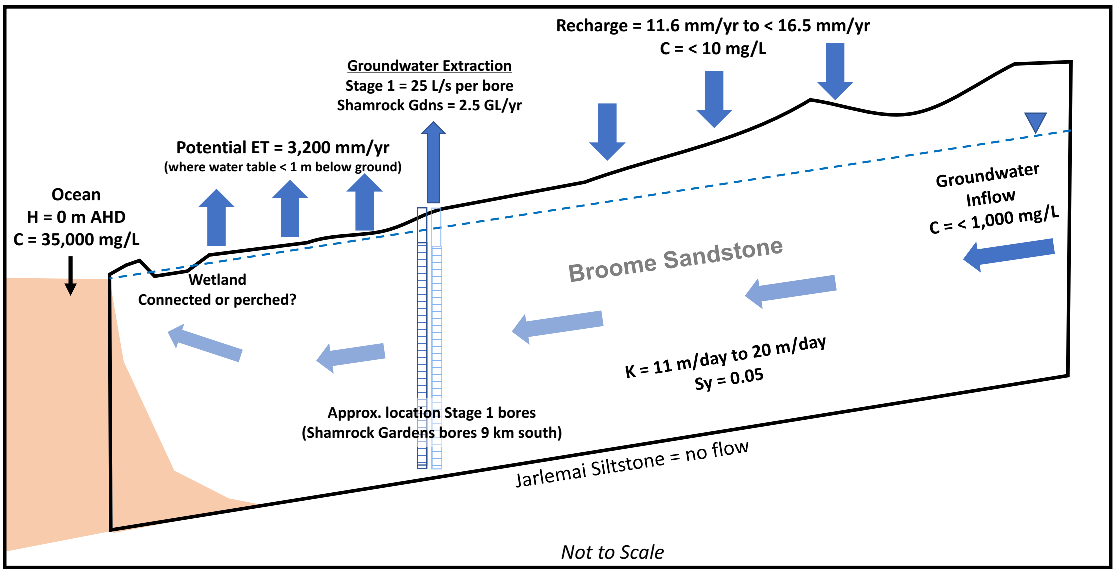


Figure 9.1. Summary of the conceptual model for the Broome Sandstone aquifer in the La Grange Groundwater area.

9.3.1 Aquifer Geometry and Boundary Conditions (Regional Groundwater Inflows and Outflows)

The Broome Sandstone aquifer is conceptualized for this project as a single-layer unconfined aquifer, which is continuous with the surface deposits that lie above it. Whilst previous studies have divided the aquifer into an upper low permeability and a lower high permeability layer, there is little data available to define the boundary between these layers. Additionally, all aquifer pumping tests carried out on the Broome Sandstone aquifer around Shamrock Station have been carried out on production bores screened across both units where present. Hence there is no data available about the relative permeabilities of these layers. The top of the aquifer is therefore considered to be defined by the topographic surface. The base of the aquifer occurs at the top of the Jarlemai Siltstone, which is thought to be an effective aquitard and hence forms a no-flow boundary. Depth to water varies from 0 m to more than 50 m (Figure 2.1).

Regional groundwater inflow occurs to the east of Shamrock Station. Groundwater outflow at the coast is controlled by the constant head imposed by the presence of the ocean at this boundary. Groundwater flow in the Broome Sandstone aquifer is expected to be predominantly horizontal as rainfall recharge is relatively constant along the groundwater flow path (Section 5) and the only significant groundwater discharge occurs in the coastal areas.

9.3.2 Aquifer Properties

The recent pump test on Shamrock Station bore PB1 has provided a local hydraulic conductivity value of 11 m/day (Section 7.3). Bore PB1 is screened across both the low permeability and the high permeability units of the Broome Sandstone and this pump test treats the aquifer as a single layer. The discussion in Sections 3 and 7 suggest that, at a regional scale, hydraulic conductivity values up to 15 or 20 m/day may be reasonable when considering the Broome Sandstone as a single layer.

9.3.3 Rainfall Recharge and Evapotranspiration

Based on the discussion presented in Section 5, annual rainfall recharge is estimated to range between 11.6 and (up to) 16.5 mm/yr in the La Grange area. Annual potential evapotranspiration is 3,200 mm/yr based on measurements at the Bidyadanga rainfall station. Evapotranspiration is expected to be significant in the coastal areas where depths to water table are less than 1m and groundwater dependent wetlands are present.

9.3.4 Surface Water

There are no major surface watercourses in the study area (Section 2). Figure 4.1 shows the locations of groundwater-dependent wetlands in the coastal portion of the study area. These wetlands are thought to be either surface expressions of the water table in the Broome Sandstone aquifer or perched groundwater systems sitting above low-permeability coastal sediments.

9.3.5 Groundwater Salinity

Groundwater in the Broome Sandstone aquifer has a very low salinity (< 1,000 mg/L). Groundwater entering the study area via groundwater inflow and rainfall recharge also has a very low salinity (< 1,000 mg/L and < 10 mg/L respectively). In contrast, groundwater present in the aquifer at the coast is expected to have a salinity equivalent to that of seawater (35,000 mg/L), with a wedge of saltwater extending into the aquifer via density-driven flow to a distance that is controlled by the dynamics of the groundwater flow system. Information on the position of the toe of this saltwater interface has been provided through the AEM survey described in Section 5. This suggests that the saltwater interface at the point closest to the Stage 1 development may occur approximately 6 km from the coast, which is also approximately 6 km from the proposed development.

9.3.6 Stage 1 Water Use Assumptions

All groundwater modelling undertaken for this H3 Hydrogeological Assessment has been based upon theoretical crop water requirements for Rhodes Grass grown under conditions of historical climate at Bidyadanga Bureau of Meteorology station. Detailed modeling results for the maximum and minimum monthly crop water requirements, assuming 80% irrigation efficiency, were provided via discussions and spreadsheets from Mr. Christopher Ham (DAFWA Irrigation Development and Agribusiness Officer, Broome, 13 March 2017).

In order to reflect long-term average climate conditions, the average monthly crop water requirements have been adopted for this assessment, and are shown in Table 9.1. These requirements were then multiplied by the area of a 40 Ha pivot with optional end sprinkler (total 43.2 Ha) and converted to average continuous pumping rates, the latter of which range from 12.5 L/s in June to 38.0 L/s in November. The average pumping rate for all 12 months of the year is 24.2 L/s (Table 9.1). The analytical modelling approach described in Section 9.4.1 was then used to compare the predicted drawdown impacts that result from applying either variable pumping across each month (as per Table 9.1) or an average continuous rate of 25 L/s. The results of this test are shown in Section 9.4.2 and demonstrate that an average continuous rate of 25 L/s per pivot is a valid simplification for long-term modeling purposes.

Table 9.1. Average monthly crop water requirements (CWR) and equivalent continuous pumping rates per pivot for irrigation of Rhodes Grass (derived through modeling and informed discussion by C. Ham, DAFWA, March-May 2017).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Average CWR (ML/Ha)	1.7	1.3	1.5	1.3	1.0	0.8	0.9	1.2	1.6	2.1	2.3	2.2	17.6
Total ML for 43.2 Ha pivot	72.1	54.5	64.7	56.9	41.5	32.5	38.2	50.0	68.1	91.2	98.5	93.4	761.4
Effective pumping rate (L/s)	26.9	22.5	24.3	22.0	15.5	12.5	14.2	18.7	26.3	34.0	38.0	34.9	24.2

Figure 9.2 shows the locations of up to 17 potential production bores for Stage 1 within the flora/fauna survey extent. Coordinates are provided in Table 9.2. In addition to existing production bore PB1, there are 11 potential ‘Priority 1’ pivots (labeled S1PB01 – S1PB11) that have been sited to occupy the area of shallowest water tables and to avoid drainage lines inferred from the DEM. There are also five potential ‘Priority 2’ pivots (labeled S1PB12 – S1PB16) that could be developed if either or both of the following occur:

(a) modeling demonstrates acceptable water level drawdown impacts caused by extraction for the 11 ‘Priority 1’ pivots and some (or all) of the five ‘Priority 2’ pivots; or

(b) the outcomes of the flora/fauna survey require some of the ‘Priority 1’ sites to be set aside for conservation purposes.

The use of continuous pumping rates across all production bores (i.e., 25 L/s) and the proposed locations of the 17 potential production bores are both considered appropriate assumptions for this H3 hydrogeological assessment because the distance of Stage 1 from receptors, including existing groundwater users and environmental assets, is large (i.e., >10 km) compared with the size of the footprint of Stage 1. In other words, running models with alternating pumping schedules across different clusters of pivots, or moving individual production bores by several hundred metres, would have immeasurable impact on the predictions made in this assessment.

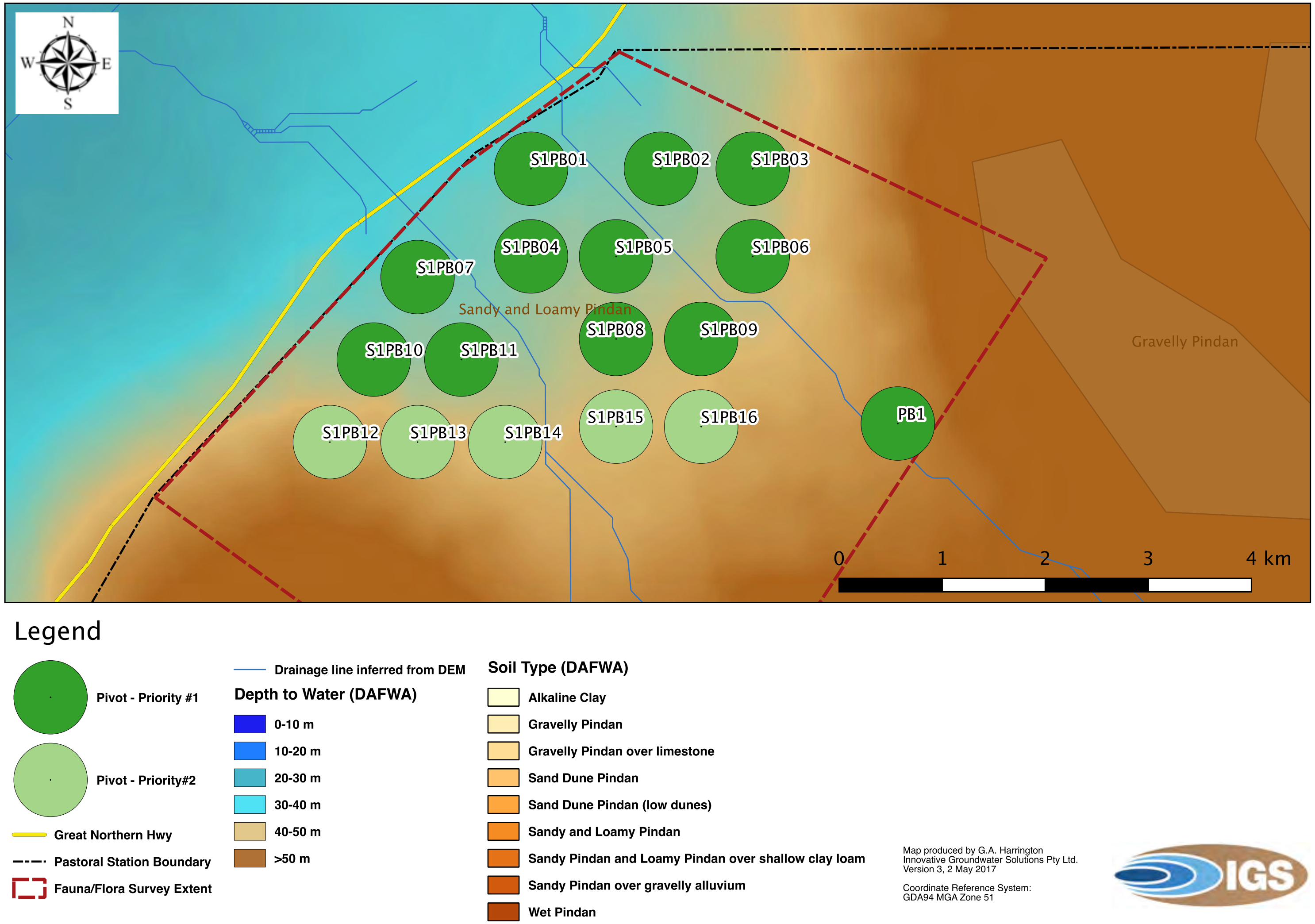


Figure 9.2. Potential locations of Stage 1 production bores and pivots in relation to soil type and depth to water table.

Table 9.2. Coordinates for potential Stage 1 production bores.

	Bore ID	Easting GDA94 MGA Zone 51	Northing GDA94 MGA Zone 51
Existing	PB1	404457	7952880
Priority 1	S1PB01	400900	7955350
	S1PB02	402160	7955350
	S1PB03	403050	7955350
	S1PB04	400900	7954500
	S1PB05	401725	7954500
	S1PB06	403050	7954500
	S1PB07	399800	7954300
	S1PB08	401725	7953700
	S1PB09	402550	7953700
	S1PB10	399375	7953500
	S1PB11	400225	7953500
Priority 2	S1PB12	398950	7952700
	S1PB13	399800	7952700
	S1PB14	400650	7952700
	S1PB15	401725	7952850
	S1PB16	402550	7952850

9.3.7 Other Groundwater Extraction

Shamrock Gardens is the only existing licensed user extracting significant volumes of groundwater within 20 km of Shamrock Station (Section 4). Although the licenced allocation for this user is 2.5 GL/yr, historical annual use has always been less than 720 ML/yr (Table 4.1). However, for the purpose of the modelling carried out in this study, use of the full allocation of 2.5 GL/yr is assumed for Shamrock Gardens.

Other existing licences form a total licenced extraction of 69 ML/yr (Table 4.1) which, when spread across a year, is insignificant compared with the proposed Stage 1 development and the licensed volume for Shamrock Gardens. Extraction by these users have therefore not been included in the conceptual model for the modelling component of this project.

9.4 Analytical Models

9.4.1 Method

Analytical modeling was performed using the Forward Simulation functionality of AQTESOLVE (Duffield, 2007) and the Neuman (1974) analytical solution for an unconfined aquifer – this is the same solution as used by GCS (2016) for interpretation of the long-term constant discharge test (CDT) on production bore PB1 (Section 7.3). Likewise, the hydraulic properties used in the analytical modeling are identical to those derived from the CDT (i.e., T = 2,000 m^2/day, b=176 m, S=0.0018, S_y=0.05). Because the analytical solutions do not incorporate seasonal groundwater recharge, which would enable water levels to recover each wet season, the magnitude of drawdowns predicted from this modeling will be an over-estimate of actual drawdown and should therefore be considered as highly conservative.

9.4.2 Sensitivity to monthly pumping regime

As described in Section 9.3.6, the analytical modelling approach was first used to compare the predicted drawdown impacts that result from applying either variable pumping across each month (as per Table 9.1) or an average continuous pumping rate of 25 L/s. Impacts of a single production bore pumping for 3650 days (10 years) were assessed at the two most critical environmental receptors[1]. Whilst not strictly a receptor, the toe of the saltwater interface can be expected to migrate further inland as the water table over the interface declines. This process can only be accurately simulated using numerical models or analytical solutions that take into account density-dependent processes (see Sections 9.7 and 10.4); however, an estimate of drawdown at this location provided by the analytical model provides preliminary confidence that saltwater ingress will be minimal. For the purposes of the preliminary analytical model, the closest position of the toe of the saltwater interface was assumed to be that derived from the AEM survey, as shown on Figure 4.1. The validity of this assumption is explored further in Sections 9.7 and 10.4.

The other environmental receptor at which drawdown was predicted is Injudinah Swamp, which is a potential groundwater dependent ecosystem. The locations of the toe of the AEM-inferred saltwater interface and Injudinah Swamp are shown in Figure 4.1.

Due to the large distance of potential receptors from the proposed Stage 1 borefield, there should be little difference in drawdown at these receptors between a scenario employing a monthly varying pumping schedule and one implementing pumping at an equivalent constant rate. Model results shown in Table 9.1 support this hypothesis by demonstrating there is immeasurable difference between the two pumping scenarios in simulated impacts at (a) the location of the AEM-inferred toe of the saltwater interface (SWI) and (b) the closest point of Injudinah Swamp to the Stage 1 development. Additionally, the simulated drawdown at the location of the production bore under the constant pumping rate scenario is equivalent to the average annual drawdown simulated under the variable monthly pumping scenario. This provides confidence that the simplified approach of implementing pumping as a constant rate is valid and has no impact on model outcomes.

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[1] Potential drawdown impacts have been predicted at numerous additional sites, including existing licensed and unlicensed groundwater users, with the more complex numerical groundwater model (Section 10).

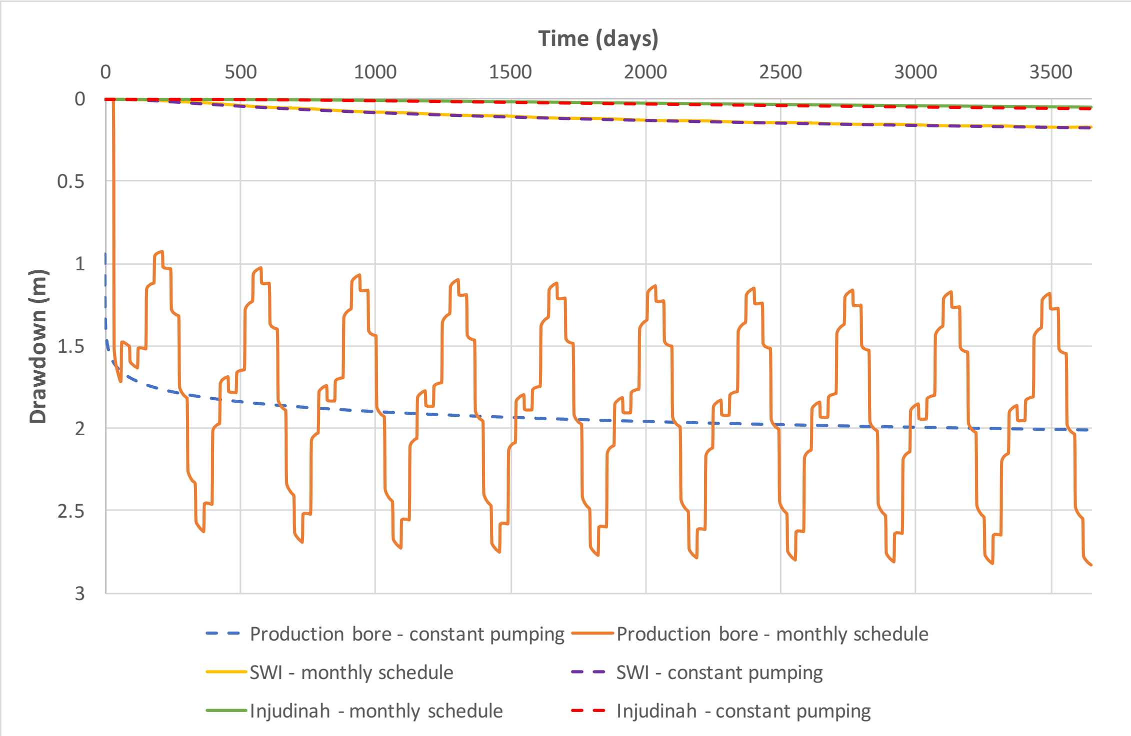

Figure 9.3. Graph showing simulated drawdown at the Stage 1 production bores, the toe of the saltwater interface (SWI) and Injudinah Swamp under both the monthly pumping schedule scenario and the constant pumping scenario (all bores pumping constantly at 25 L/s). This graph shows that the constant pumping scenario produces a drawdown at the production bores equivalent to the average drawdown under the monthly pumping schedule and that there is no measurable difference in simulated drawdown at the SWI toe or Injudinah Swamp between the two pumping scenarios.

9.4.3 Determining the optimum number of production bores and pivots

As described in Section 9.2, the analytical modelling approach was also used to explore the ideal number of production bores, each pumping continuously at 25 L/s, that could be operated whilst achieving acceptable drawdown impacts at the two most critical environmental receptors.

Multiple scenarios have been tested using the analytical models, however only two extreme cases are shown in this report. Both scenarios assume continuous pumping at 25 L/s, with the first scenario having just the 12 ‘Priority 1’ production bores (PB1 plus S1PB01-11) and the second scenario having all 17 production bores (PB1 plus S1PB01-16). Drawdown versus time curves are presented for the 12 production bore scenario over a 3,650-day (10 year) and 10,000-day (27.4 year) timeframe in Figure 9.4(a) and Figure 9.5(a), respectively. Curves are presented for each of the production bores as well as the closest point of the AEM-inferred saltwater interface to Stage 1, and the closest point of Injudinah Swamp (see Figure 4.1). For ease of comparison, the drawdown versus time curves for the 17 production bore scenario are plotted alongside in Figure 9.4(b) and Figure 9.5(b), respectively. All results are summarized in Table 9.3.

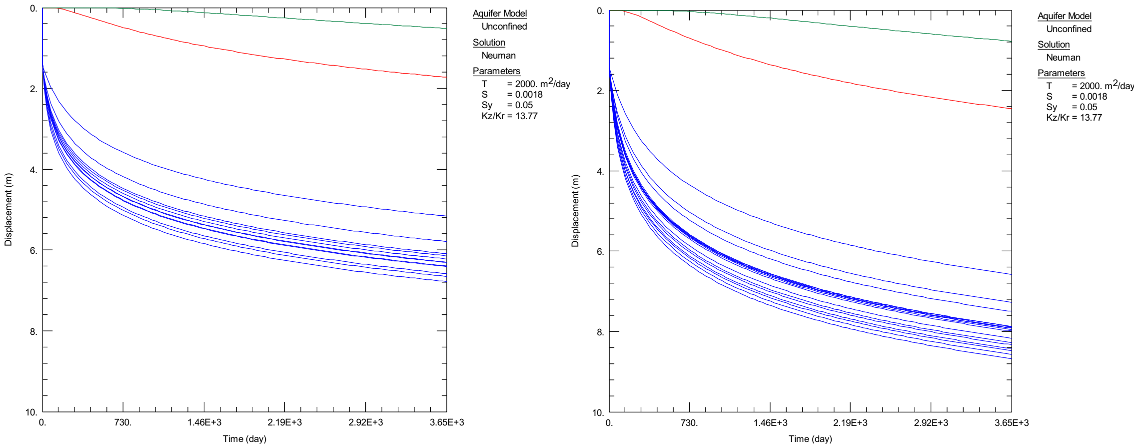

Figure 9.4. Analytical model results of predicted drawdown versus time (linear scale) up to 3,650 days (10 yrs) for (a) 12 production bores, and (b) 17 production bores operating continuously at 25 L/s. Blue curves represent production bores, red curve the closest position of the AEM-inferred saltwater interface, and green curve the closest point of Injudinah Swamp.

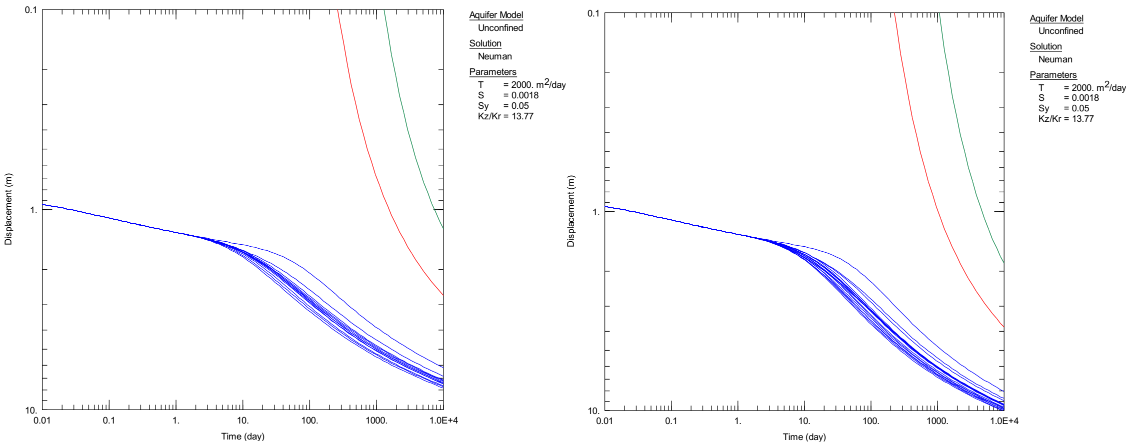

Figure 9.5. Analytical model results of predicted drawdown versus time (log scale) up to 10,000 days (27.4 yrs) for (a) 12 production bores, and (b) 17 production bores operating continuously at 25 L/s. Blue curves represent production bores, red curve closest position of the AEM-inferred saltwater interface, and green curve closest point of Injudinah Swamp.

Table 9.3. Analytical model results for predicted drawdown at key reporting sites.

	Easting GDA94 MGA Zone 51	Northing GDA94 MGA Zone 51	After 3,650 days (10 years) (Figure 9.2)		After 10,000 days (27.4 years) (Figure 9.3)	
			12 PB @ 25 L/s	17 PB @ 25 L/s	12 PB @ 25 L/s	17 PB @ 25 L/s
Maximum drawdown in production bores	See Table 9.2 above		6.8 m	8.7 m	7.8 m	10.1 m
Drawdown at closest toe of AEM-inferred saltwater interface	394000	7957300	1.7 m	2.5 m	2.7 m	3.8 m
Drawdown at closest point of Injudinah Swamp	385500	7946900	0.5 m	0.8 m	1.2 m	1.8 m

After 10 years of continuous operation with 12 production bores, the maximum predicted drawdown is 0.5 m at Injudinah Swamp, 1.7 m at the closest AEM-inferred toe of the saltwater interface, and 6.8 m in the production bores. In practice, drawdown will obviously be much less than these predictions due to a number of factors, including but not limited to (i) less frequent irrigation in cooler times of the growing season, (ii) breakdown and routine maintenance of pivots and pumps, and (iii) seasonal recharge. Nevertheless, these results provide useful insight to the worst-case impacts after 10 years, which considered acceptable for the 12 production bore scenario. The results after 27.4 years are also informative, however they are somewhat irrelevant because many changes will be experienced over this timeframe, including both climate and irrigation/cropping systems.

Under the 17 production bore scenario, the maximum predicted drawdown after 10 years is approximately 60% greater at Injudinah Swamp compared to the 12 production bore scenario, 50% greater at the closest AEM-inferred toe of the saltwater interface, and 30% greater in the production bores. Whilst these results are highly conservative, the magnitudes of drawdown at Injudinah Swamp and the toe of the saltwater interface are approaching values that may lead to adverse impacts. Therefore, based on the simplified analytical modeling alone, the 12 production bore scenario is considered to be more sustainable for Stage 1 development and forms the basis for the numerical modeling investigation.

9.5 Steady State Numerical Groundwater Flow Model

9.5.1 Introduction

As described in Section 9.2, the analytical modelling (Section 9.4) is informative as a preliminary assessment of potential drawdowns from the proposed Stage 1 development. However, it does not incorporate the influences of processes such as regional groundwater inflow, rainfall recharge and evapotranspiration on drawdown. As such, the analytical modelling provides a worst-case assessment of potential drawdowns. A numerical groundwater flow model is required to capture the effects of these additional processes on predicted drawdowns.

DAFWA are currently building a numerical groundwater flow model for the whole La Grange area. However, recent discussions with their modeller and other technical staff suggest that the model is not appropriate for rapid, local-scale assessments of groundwater extraction scenarios to support the application for a water licence. This is mainly due to the regional scale and saltwater interface functionality of the model, which makes computer run times for individual scenarios prohibitively long. In particular, the DAFWA model grid dimensions are too coarse to represent local-scale processes such as drawdown around Shamrock Station's production bores and key environmental assets.

Therefore, a suite of new 'fit-for-purpose' numerical groundwater flow models has been designed, constructed and calibrated for the Broome Sandstone aquifer around Shamrock Station. The new models, which differ in terms of the number of layers and complexity, have a consistent stratigraphic framework and input dataset to DAFWA's model and include additional local information such as recharge rates derived from local groundwater chemistry (Harrington and Harrington, 2016) and aquifer properties derived from local pumping tests (GCS, 2016). The model domain extends inland from the coast so that the model outcomes can be used to estimate the current position and potential future movement of the freshwater-saltwater interface. The models also include observation wells at the locations of existing users, Injudinah Swamp and the AEM-mapped toe of the saltwater interface, as these are potential constraints to long-term groundwater extraction. The numerical models include all available data for the study area and enable reliable predictive simulation of the potential drawdown impacts caused by Stage 1 and future groundwater development scenarios. In future, the models can be updated with new monitoring data and will enable testing of different pumping operation and groundwater management strategies.

The model development and calibration follows a methodology consistent with the Australian Groundwater Modelling Guidelines (Barnett et al., 2012), including the building of a stratigraphic model, assigning aquifer properties, recharge and boundary conditions, before undertaking a steady-state calibration to measured heads and the mapped position of the current saltwater interface.

9.5.2 Modelling Platform and Model Grid

The numerical groundwater flow model was developed using the industry-leading MODFLOW 2000 groundwater modelling code (Harbaugh et al., 2000) in the Groundwater Vistas graphical user interface (Environmental Simulations Inc., 2011), which also includes the SEAWAT module to facilitate simulating saltwater interface problems (Guo and Langevin, 2002; Langevin et al., 2007). As well as the impacts of groundwater extraction, the model was designed to incorporate the influences of the regional groundwater flow system and rainfall recharge on groundwater levels in the unconfined Broome Sandstone aquifer. The active model domain (Figure 9.6) is therefore approximately 95 km x 78.5 km. This domain is large enough to minimise any artificial effects from model boundary conditions on the area of interest for the model. The area of interest for the model is the area around the proposed Shamrock Station Stage 1 development (and future development stages), any existing licenced and unlicensed groundwater users or natural assets likely to be affected by the development (local aboriginal communities and wetlands) and the seawater interface.

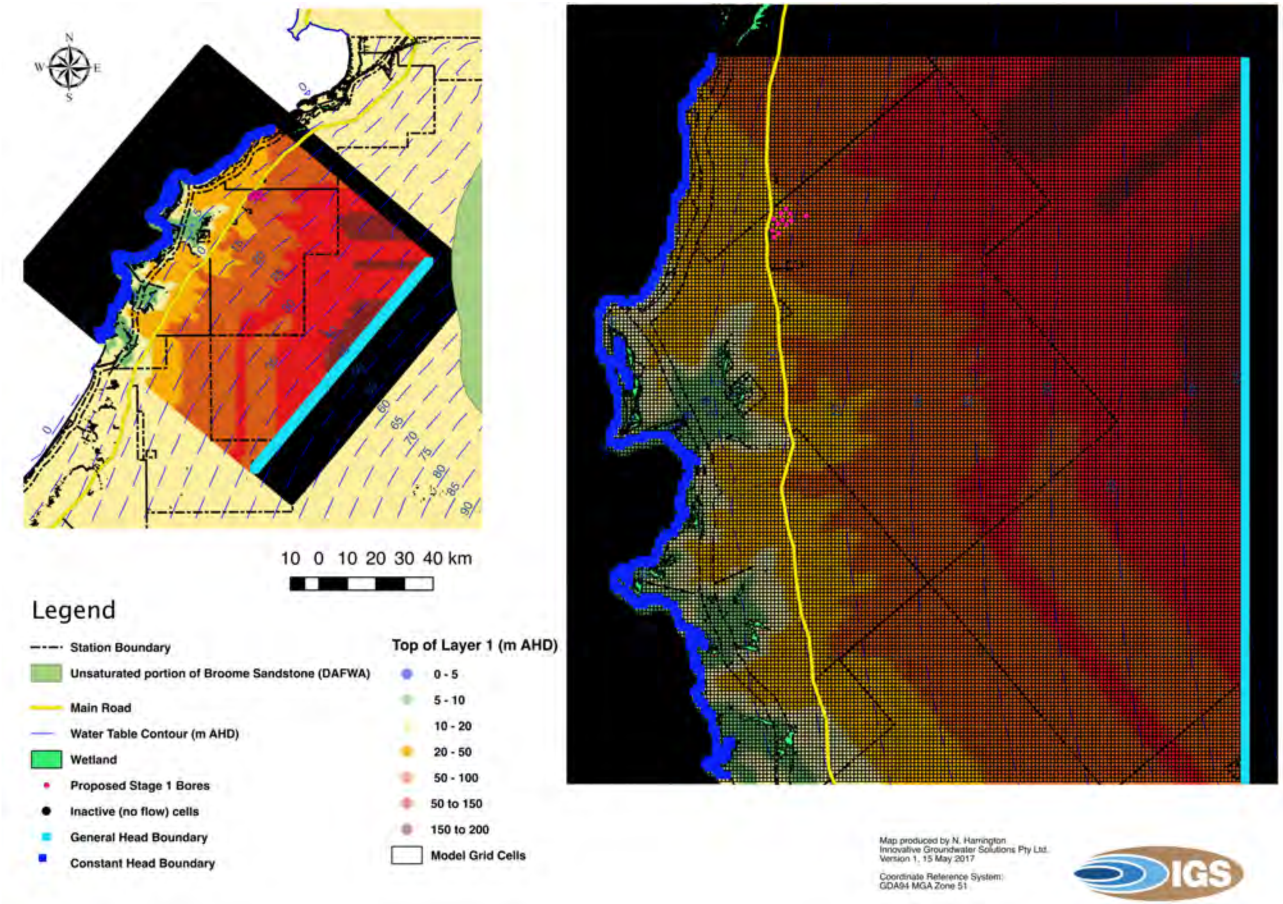

Figure 9.6. Map showing the location of the MODFLOW model domain (left), with the model grid shown in the right-hand map. The colour flood represents the elevations of the top of Layer 1. A general head boundary is set at the right hand side of the model domain, based on the location of the 50 m AHD potentiometric contour, to simulate regional groundwater flow into the model domain. A constant head boundary of 2.4 m AHD is set along the coastline to simulate groundwater outflow to the ocean. Cells coloured in black are set as no-flow (inactive).

The model domain has been rotated 40° to the east relative to the map to allow accurate simulation of groundwater flow using a finite difference grid (simulations are more accurate and boundary conditions can be simplified if groundwater flow is approximately parallel to rows or columns rather than diagonal to these) (Figure 9.6). The rotated model domain has been divided into a grid of 205 rows and 250 columns to simulate groundwater flow using the finite difference method. A large portion of the grid has been set as a "no-flow boundary", which is effectively inactive (coloured black in Figure 9.6). Some of these no flow cells are in the offshore portion of the grid (left hand side in Figure 9.6). These inactive cells can be activated in future should a review of model results or a change in model objectives require this. The active model domain therefore comprises 190 rows and approximately 157 columns (Figure 9.6).

The unconfined Broome Sandstone aquifer is represented in the groundwater flow model as a single layer, which ranges in thickness from approximately 165 m (in the north-east of the model domain) to 233 m (in the south west of the model domain). (Figure 9.7). The elevations of the top of this layer were derived from the digital elevation model (DEM) of the region (P. Raper, DAFWA, pers. comm., 8 March 2017) (Figure 9.6). The bottom elevations of the unconfined aquifer were derived from a shapefile provided by DAFWA, which is based on all available drillhole data (P. Raper, DAFWA, pers. comm., 8 March 2017).

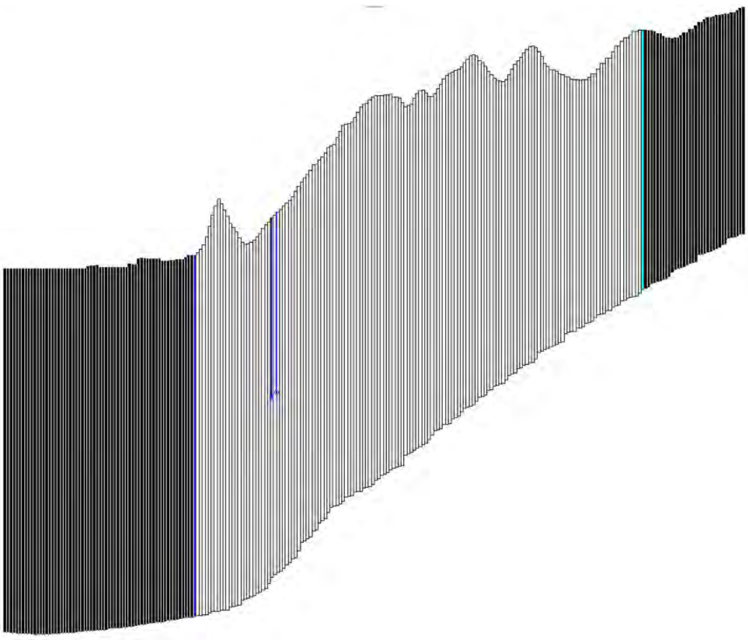

Figure 9.7. Cross section through model row 60 showing some Stage 1 extraction bores (blue vertical lines within model domain). Constant head and general head boundary cells are indicated by a dark blue cell at the left and an aqua coloured cell at the right of the active model domain respectively.

9.5.3 Boundary Conditions

Model boundary conditions simulate the regional groundwater flow regime. A density-corrected constant head boundary along the coast simulates groundwater outflow to the ocean. The density correction applied to the head at this boundary accounts for the density of seawater that imposes the coastal hydraulic head condition. The density corrected specified head was calculated using the formula (Environmental Simulations, Inc., 2010):

$$\Delta h = \Delta\rho \frac{C_i}{C_{max}} (h_i - z_i) \qquad \text{Equation 9.1}$$

Here Δh is the head correction added to the boundary head, $\Delta\rho$ is the fractional increase in density of 0.025, h_i is the boundary head at cell i (i.e., 0 m AHD), C_i is the concentration at cell i (i.e., 35 g/L), C_{max} is the maximum saltwater concentration (i.e., 35 g/L). z_i is the elevation of the midpoint of cell i.

The elevations of the midpoints of the cells located along the coastal boundary of the model domain range from –109.6 m AHD to –66.2 m AHD, which results in Δh values that range from 1.66 m to 2.74 m with a mean and median value of 2.4 m. The constant head value selected for use along the whole coastal boundary was 2.4 m.

A general head boundary located along the up-gradient (right hand) edge of the model domain simulates regional groundwater inflow to the model domain (Figure 9.6). The general head boundary is positioned so that it simulates regional groundwater inflow as accurately as possible but does not artificially influence heads in the area of interest. The head for the boundary is set at 50 m, at a distance of 6 km, which is consistent with the location of the 50 m head contour (Figure 9.6). The general head boundary could not be set with a head at a greater distance up-gradient of the active model domain due to the presence to the north-east of this of an area where the Broome Sandstone is dry. Implementation of a general head boundary that represents saturated conditions in this area would cause erroneous results. It was recognised during the implementation of the general head boundary that the contours of observed head at this boundary are based upon very sparse data may be limited in their accuracy. This has been taken into consideration during the assessment of the steady state calibration results (see Section 9.5.6).

9.5.4 Evapotranspiration

Evapotranspiration was implemented in the numerical model using the potential evapotranspiration rate of 3,200 mm/yr (Section 2) and an extinction depth of 1 m. This extinction depth was selected due to the fact that evapotranspiration is expected to have the greatest influence on water levels in the lower-lying coastal areas, where depths to groundwater are less than 1 m.

9.5.5 Sensitivity Analysis: Rainfall Recharge and Aquifer Hydraulic Conductivity

Rainfall recharge (R) and aquifer hydraulic properties (hydraulic conductivity (K) and storage) are usually the input parameters associated with the most uncertainty in groundwater flow models. Unless an area has been intensively investigated, there is usually little data available on R and K (and storage), all of which can vary significantly spatially. For this reason, R and K in particular are often varied within plausible ranges during steady-state calibration of models against observed hydraulic head data. However, more than one combination of R and K can achieve calibration (this is known as 'non-uniqueness'), as described in the Australian Groundwater Modelling Guidelines (Barnett et al., 2012). It is therefore good practice to present model results for a range of plausible recharge / hydraulic conductivity combinations, which recognises the uncertainty in these parameters and effectively quantifies a model's sensitivity to them.

The hydraulic conductivity value of 11 m/day obtained from the most recent pumping test carried out on Shamrock Station production bore PB1 (Groundwater Consulting Services Pty Ltd, 2016) is considered to be valuable site-specific information and was used as a starting point for calibration of the numerical model in steady state to observed head data provided by DAFWA. A spatially uniform recharge rate (R) was varied until a best match was obtained between simulated and observed head data, with an R value of 8 mm/yr finally being adopted (Scenario 1 described below).

A recharge rate of 8 mm/yr is at the low end of the plausible range of recharge for the study area; see Section 9.3.3 above). Hence, Scenario 2 tested the maximum R value that could be set whilst maintaining calibration with observed head data and K values within a plausible range. It was found that an R value of 14 mm/yr required a K value of 20 m/day to maintain reasonable calibration with observed data. This recharge rate is consistent with current estimates of median recharge for the study area (Table 5.1). A higher recharge rate would require a higher hydraulic conductivity, and 20 m/day is considered to be at the upper end of plausible values for the study area (see Section 9.3.2 above).

Results are therefore presented below for the following recharge / hydraulic conductivity Scenarios:

Scenario 1 (Low R, Low K): R = 8 mm/yr; K = 11 m/day

Scenario 2 (High R, High K): R = 14 mm/yr; K = 20 m/day

Because the recharge rate of 14 mm/yr is most consistent with estimates based on environmental tracers (Table 5.1; Section 9.3.3), Scenario 2 (high R, high K) is considered to be the most plausible scenario. However, it was considered appropriate to also provide results for Scenario 1 (low R, low K), which is consistent with the results of the pump test on production bore PB1. This provides a range of model outcomes that accounts for the uncertainly in hydraulic conductivity and rainfall recharge values for the study area.

9.5.6 Steady State Calibration Results

Figures 9.8 to 9.10 show the results of the steady state model calibration using observed hydraulic heads and head contours obtained from DAFWA. The latter are based upon the available data from observation wells shown spatially in Figures 9.8 and 9.9 as red-labelled points and plotted in Figure 9.10. Figures 9.8 and 9.9 show that a good match to the observed water table contours was achieved by Scenarios 1 and 2 in the areas where there is sufficient observation data available to develop head contours with some confidence. Whilst the match to the head contours is poor in the right-hand portion of the model domain, the contours in this area are based upon very sparse data and are hence not reliable targets for model calibration.