Groundwater Assessment of the Fractured Rock Aquifers in the Northern Flinders Ranges, South Australia

By

Natchanok Ounping

Thesis
Submitted to Flinders University
for the degree of

Master of Science (Groundwater Hydrology)

College of Science and Engineering
18 July 2024

TABLE OF CONTENTS

ABSTRACT

Iga Warta, Leigh Creek Station, Kalkalpurannha, and Yappala are self-supplied remote communities located in the hard rock area of the Northern Flinders Ranges. These four communities are identified as being very vulnerable to water insecurity in the next decade by the Department for Environment and Water. Groundwater presents a potential solution to mitigate this issue, as rainwater is highly variable due to the influence of arid and semi-arid climatic conditions. Therefore, groundwater assessment is required to obtain crucial information on the water quantity and quality of fractured rock aquifers in order to assist government agencies in formulating appropriate water strategies for each remote community. This study is designed to synthesise existing data in the desktop study stage from two major sources, the WaterConnect website and the scanned microfiche images managed by the South Australian government. The primary aquifers at Iga Warta, Leigh Creek Station, Kakalpurannha, and Yappala are Wilkawillina Limestone, Angepena Formation, Wonoka Formation, and Bonney Sandstone, respectively. These fractured rock aquifers are formed of different types of lithologies, resulting in diverse capacities to yield groundwater, and giving unique characteristics in groundwater quality. The Wilkawillina Limestone aquifer has a higher groundwater yield than the other three aquifers, with an average discharge rate of 6.73 L/sec, although it has the potential to provide groundwater of over 10 L/sec. The Angepena Formation, primarily comprised of shale and siltstone, and Wonoka Formations, predominantly formed of shale and limestone, have similar groundwater production capabilities, with a mean rate of 1.3 L/sec. The maximum rate of yield from these two aquifers is around 10 L/sec. The Bonney Sandstone has an average well yield rate of less than 1 L/sec and lacks the capacity to supply groundwater at a rate of higher than 3 L/sec.

All four aquifer formations have unique characteristics in groundwater chemistry. The Wilkiwillina Limestone aquifer exhibits a signature of pronounced hardness, and high chloride and sodium in its groundwater. The Angepena Formation aquifer also has high chloride, hardness, and sodium content, while groundwater extracted from the Wonoka Formation aquifer presents outstanding sodium, hardness, and chloride. The lack of available water chemistry data prevents the identification of a groundwater quality signature from the Bonney Sandstone aquifer. Additionally, the groundwater from the four fractured rock aquifers is unsuitable for consumption due to its physical and chemical characteristics above the values specified in the Australian Drinking Water Guidelines, including chloride, hardness, sodium, sulphate, total dissolved solids, and nitrate, although this groundwater remains suitable for non-potable application. The development for future use is possible in terms of quantity since the fractured rock aquifers exhibit the potential to yield high volumes of groundwater. However, groundwater quality from all aquifers should be treated to ensure its safety for consumption and to enhance user satisfaction.

DECLARATION

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Signed...Natchanok Ounping.................

Date...18 July 2024..............................

ACKNOWLEDGEMENTS

First and foremost, I would like to acknowledge the Groundwater Development Fund and the Department of Groundwater Resources, Thailand, for awarding me a scholarship to enhance my knowledge of groundwater at Flinders University. I also appreciate their recognition of the importance of developing their staff proficiencies and skills.

I would like to express my gratitude to my principal supervisor, Dr Eddie Banks, and my co-supervisor, Dr Margaret Shanafield, for their great support and guidance throughout my major research journey. Their expertise, feedback, and comments have been instrumental in the completion of this study. I also extend my sincere thanks to the Department for Environment and Water, South Australian Government, for their generous support in providing the essential data for this research.

Finally, I would like to thank my colleagues, friends, and family for their love, unwavering support, and encouragement during challenging times. I am deeply grateful to all of you for standing by me. Most importantly, I express appreciation to myself for persistently moving forward until the completion of this research journey.

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE INTRODUCTION

1.1 Background

Every human being on earth daily requires water for drinking, food preparation, and household activities (Martínez-Santos 2017). Access to water is a fundamental human right that should not be denied to anybody based on discrimination, as stated in the UN Assembly's 2010 Declaration on the Human Right to Water and Sanitation (Cetrulo et al. 2020). Nevertheless, a significant number of people have been struggling to obtain sufficient and clean water in recent years. More than 2 billion people reside in countries experiencing water scarcity, and it is predicted that the effects of climate change and population expansion will exacerbate the situation in certain regions; moreover, at least 1.7 billion people globally rely on contaminated and unsafe water sources for drinking (World Health Organization 2023).

Arid and semi-arid regions are defined as drylands with average annual precipitation ranging from 25 to 500 mm (Williams 1999). These areas cover a large part of the global land area and are home to hundreds of millions of people (Shen & Chen 2010). The availability of surface water is limited in drylands due to low levels of rainfall and high evapotranspiration rates (Etikala et al. 2021). Groundwater is the only dependable water resource in these regions and is commonly used for agricultural, domestic, and industrial purposes (Priyan 2021). However, excessive pumping has led to a reduction in water levels, leading to the presence of saline or highly mineralized groundwater (Etikala et al. 2021). Consequently, people living in arid and semi-arid zones encounter difficulty in accessing water due to drought, water shortage, and poor water quality (Priyan 2021).

Seventy percent of Australia's land surface is occupied by arid and semi-arid drylands, and this region is classified as remote and very remote areas based on accessibility to services set in the Accessibility or Remoteness Index of Australia (Davies & Holcombe 2009). Generally, a group of people who live temporarily or permanently in remote and very remote regions are referred to as remote communities (Water Services Association of Australia 2022). According to Dockery and Lovell (2016), there are 1,112 remote communities across Australia, with an estimated population of 607,600 people, comprising both Aboriginal and Torres Strait Islanders, as well as non-Indigenous Australians. However, water and sanitation services are unevenly distributed among remote communities; in addition, low water quality is becoming a significant issue (Balasooriya et al. 2023). The findings of the study conducted by Wyrwoll et al. (2022) showed that drinking water quality in numerous remote communities fails to meet Australian Drinking Water Guidelines, causing health risks to residents. Nitrate levels surpassed the maximum limit in 19 communities, while E. coli was detected in 13 communities. Uranium, fluoride, and manganese were also found to exceed permissible concentrations in eight, six, and three communities, respectively. Similarly, excessive levels of antimony and barium were observed in one community. Moreover, intensified drought due to climate change results in changes to water quality and quantity since drinking water becomes contaminated with saltwater and pollutants, while aquifers receive low recharge, leading to salinity in reliable groundwater resources (Balasooriya et al. 2023).

South Australia has around 64 remote communities with populations ranging from less than 50 to 4,000 people per community or approximately 10,000 people in total (Croma & Willis 2022). Most of these communities acquire water supply from service providers such as local government, SA Water, and the Regional Anangu Services Aboriginal Corporation. Some remote communities primarily depend on self-managed water supply (Water Services Association of Australia 2022). People in self-supplied communities commonly operate their own water systems with groundwater and rainwater (Department for Environment and Water 2023). In terms of both quantity and quality, groundwater access is limited to only one or two bores in these communities, and it contains a high concentration of minerals, salt, and an unpleasant smell and colour. At the same time, rainwater is insufficient and highly dependent on the weather as well as there is a concern about its quality as it runs through the roof before collecting in tanks (Grey-Gardner 2008; Pearce et al. 2008; Willis et al. 2015). The result of the stocktake and water security assessment from the Department for Environment and Water (2024) revealed that 7 out of 19 self-supplied remote communities in South Australia had been recognised as facing a significant risk of water supply insecurity in the next decade. Therefore, it is necessary to enhance water availability and security for self-supplied communities to mitigate water issues by increasing the reliability of groundwater or searching for new groundwater resources that yield more water and have acceptable quality. However, groundwater is an invisible natural resource as it is stored in pores or fractures beneath the ground surface, and it is challenging to locate aquifers, particularly in hard rock areas where four of the seven high-risk communities in South Australia are located, namely Iga Warta, Leigh Creek Station, Kakalpurannha, and Yappala.

Hard or fractured rock aquifers vary widely in hydraulic conductivity and flow rates (Cook 2003). They may release a high volume of water in certain regions and store very low water quantity in other areas as the distribution of fractures in nearly all rock types is complex (Shapiro 2002). In addition, fracture connectivity significantly influences the transmission of water through fractured rocks (Odling & Roden 1997). Poorly connected fractures generally provide low-flow systems, and groundwater bores installed in these systems typically release small yields, whereas groundwater flow systems with densely connected networks of fracture can function as high-yield aquifers (Parashar & Reeves 2017). Hence, groundwater assessment in hard rock areas of self-supplied communities is required in order to obtain crucial information on water quantity and quality of aquifers. This groundwater information will assist policymakers or government agencies responsible for water resources in determining water security solutions for each self-managed community to ensure that everyone can access a safe, clean, and sufficient water supply.

1.2 Aims and objectives

1.2.1 Main aim

The aim of this study is to assess groundwater in fractured rock aquifers of remote communities in South Australia. This included four self-supplied communities in the Northern Flinders Ranges: Iga Warta, Leigh Creek Station, Kakalpurannha, and Yappala. This study synthesises existing data, which is available in digital formats and online sources managed by the South Australian government and the Australian government to assist water managers in deciding water supply options in these four communities.

1.2.2 Specific objectives

Three specific objectives are determined to achieve this study's main objective.

1) Characterise the major fractured rock aquifer units and their lithology of the four communities.

2) Examine the quantity and physical and chemical quality of groundwater from fractured rock aquifers in each community.

3) Compare the available groundwater quantity and quality in these four communities and how it compares to other aquifer systems and the Australian Drinking Water Guidelines.

CHAPTER TWO LITERATURE REVIEW

Hard or fractured rocks is the term that refers to igneous, metamorphic, and consolidated sedimentary rocks (Krásný & Sharp 2007). Globally, these types of rocks cover more than 20% of the Earth's land surface and are distributed in both broad stable regions and the central parts of major mountain ranges (Gustafson & Krásný 1994). Moreover, they also serve as a basement rock beneath large basins and facilitate the movement of groundwater not only locally but also over larger geographic scales (Krásný & Sharp 2007). In the past decades, groundwater in hard rocks has played an essential role in providing water to people in arid and semi-arid regions as surface water is typically unavailable. During the late 20th century and early 21st century, fractured rock aquifers have become increasingly interested in both tropical and temperate climate zones due to advancements in hydrogeological knowledge and the recognition of the significance of hard rock aquifers (Krásný et al. 2014).

2.1 Fractured rock aquifers as water resources globally

Rising demands in water supply have caused an increased reliance on groundwater resources, particularly on those within fractured rock aquifers (Shapiro 2002). In recent years, the extraction of groundwater resources has been directed toward fractured rock aquifers located at greater depths beneath more accessible and frequently more productive porous media aquifers (Parashar & Reeves 2017). Many regions across the globe exploit fractured-rock aquifers to fulfil the diverse water requirements of the population.

Sub-Saharan African region mainly relies on groundwater in fractured-rock aquifers to cover its population's demand, particularly in rural communities (MacDonald & Davies 2000). Almost 80% of the present land area of sub-Saharan Africa is underlain by hard rock aquifers, including crystalline basements, volcanic rocks, and consolidated sedimentary rocks (Masiyandima & Giordano 2007). These three major rock aquifers sustain a population of over 350 million people through dug and collector wells in shallow groundwater zones, as well as boreholes for deep levels of groundwater (MacDonald et al. 2002). Even though these hard rock aquifers typically yield a low volume of water, they serve as vital sources in meeting the water requirements of rural populations (Adelana 2009).

Asia is the world's largest continent both in terms of size and population. It occupies 43.5 million sq km and hosts a population of roughly 3.5 billion (Lee et al. 2018). The massive population and rapid pace of economic development since the 1970s have led to a dramatically increasing demand for groundwater resources, particularly in China, India, the Republic of Korea, and other South Asian countries (Jayakumar et al. 2009). Groundwater is predominantly sourced from carbonate rock aquifers in Southeast Asia, southern China, and the Indochina peninsula (Lee et al. 2018). Volcanic rock is another vital fractured-rock aquifer widely distributed across the circum-Pacific islands, yielding spring water distinguished by high-quality characteristics (Han et al. 2013). Moreover, fractured-rock aquifers situated in mountainous areas play a crucial role as transboundary aquifers, facilitating water exchange across the boundaries of two or more countries (Jayakumar et al. 2009).

Fractured rock aquifers have been discovered in several regions of Australia, including the Great Dividing Range in eastern Australia, Tasmania, the Mt Lofty and Flinders Ranges in South Australia, and the ancient hills and ranges of Western Australia and the Northern Territory (Harrington & Cook 2014). Approximately 33% of bores in Australia are installed within fractured rock aquifers, but this percentage of wells accounts for just around 10% of overall extraction as groundwater quantity is highly variable and relies on major fracture distribution (Geoscience Australia 2023). The primary focus of groundwater extraction in fractured-rock aquifers lies in consolidated sandstones and limestones in large sedimentary basins, and areas with high rainfall typically have better quality groundwater because it can effectively replenish the aquifers (Barnett et al. 2021). The extraction of this resource is crucial for supporting urban populations, irrigation, livestock, and domestic consumption (Geoscience Australia 2023).

2.2 The capacity of fractured rock aquifer

The amount of groundwater in fractured rock aquifers is estimated to be less than 2% of the rock volume, and this percentage reduces as the depth increases due to the narrowing and increasing distance between fractures (California Department of Water Resources 2004). Boreholes in fractured rock aquifers frequently yield a small volume of groundwater (Gustafson & Krásný 1994). However, the wells can produce high discharge rates under favourable conditions, including large size and interconnection of fractures, a good source of recharge, as well as proper implementation of well installation (California Department of Water Resources 2004). Although, the hard rock aquifers have low groundwater storage, they serve as important water resources locally (Ofterdinger et al. 2024).

Crystalline rocks, which include igneous and metamorphic rocks, form significant Precambrian shield areas found in various locations worldwide (Gustafson & Krásný 1994). Typically, these rock-type aquifers have a relatively low well production of less than 5 L/sec; although, certain places in southern Norway and central Sweden have reported a high yield of 23 L/sec (Singhal & Gupta 2010). Volcanic rocks cover a minor area of the continental crust compared to other types of rock, and they make up only 6.8-8% of all rock types on Earth’s continent (Fenta et al. 2020). Young volcanic rocks can provide high rates of groundwater due to their high permeability, as indicated by well yields ranging from 100 to 500 L/sec in the Hawaiian Islands, while low-yield wells are linked with older volcanic rocks, which are low to very low permeable (Custodio 2003). Carbonate rocks are present in a proportion of 20% of the land surface (Dar et al. 2014). Europe has the largest expanse of this type of rock, with Asia in second, whereas Australia, Oceania, and South America have the smallest area in comparison (Goldscheider et al. 2020). Groundwater wells from carbonate aquifers with good secondary porosity and permeability can have exceptionally high yields. For instance, the Ocala limestone in the USA has the potential to yield up to 475 L/sec, and fissured chalk aquifers in England have been reported to produce water at rates 50-100 L/sec. Similarly, the Pakhal and Cuddaph limestones in central India can yield groundwater ranging from 10-20 L/sec (Singhal & Gupta 2010). Sedimentary rocks are present at vast distances and develop extensive regional groundwater flow systems in central North America, central Australia, and northern Africa (Fitts 2013). The volume of groundwater from sedimentary rock aquifers exhibits variability similar to that of other hard rock aquifers. The wells in the sandstone of the Great Artesian Basin in Australia have a potential yield of 50-100 L/sec; in contrast, the Charmuria and Athgarh sandstones can discharge groundwater at rates of 1.5 L/sec and 1-10 L/sec, respectively (Singhal & Gupta 2010). Furthermore, the reported well yield from fractured shales in the Darwin Rural Area of Australia ranges from 1-3 L/sec.

2.3 Water quality challenges of fractured rock aquifer

Groundwater naturally contains mineral ions due to the slow dissolution of soil materials, sediments, and rocks when water moves across minerals within the voids or fractures of the unsaturated zone and the aquifer (Harter 2003). The suitability of groundwater for various purposes is influenced by its chemical properties (Ramesh & Elango 2012). Poor quality groundwater can result in substantial economic consequences by decreasing agricultural productivity, and also cause serious concern to human well-being (Geoscience Australia 2023). The chemical composition of groundwater in fractured rocks is influenced by regional climatic conditions and other local factors, such as surface water bodies and their chemical characteristics, micro-climate, precipitation quality, anomalies in rock composition, zone of discharge of deep-seated groundwater, and human activities (Gustafson & Krásný 1994).

According to Krásný & Sharp (2007), in temperate climatic regions, bicarbonate or sulphate and calcium are predominant ions found in groundwater drilled in hard rock aquifers. The concentration of total dissolved solids (TDS) is generally low, ranging from 100 to 300 mg/L, and is even less in certain areas. A decline in TDS and pH is observed as altitude increases, occasionally accompanied by elevated levels of sulphate, which could be related to acid rain contamination. Basic igneous rocks are typically characterised by high concentrations of magnesium, while marble is recognised by pure bicarbonate-calcium types, increased hardness, and pH levels of around seven. Higher levels of sulphate and TDS are typically found in some sediment rocks that may feature dispersed sulphide minerals. Some hard rock zones commonly exhibit high levels of certain minority and trace constituents. Near-surface hard rock aquifers frequently encounter bacteriological contamination originating from the surface.

The quality of groundwater in fractured rock aquifers located in arid and semi-arid regions is generally substandard due to the presence of elevated concentrations of bicarbonate, TDS, iron, sulphate, chloride, and sodium. In addition, the major issue regarding water quality in these climatic areas is the occurrence of brackish or saline groundwater (Gustafson & Krásný 1994). Groundwater exhibiting low TDS contents can be found only in areas where recharge is sufficient and natural groundwater discharge is relatively continuous (Krásný & Sharp 2007).

2.4 Treatment and alternative water supplies in areas with fractured rock aquifers

Emerging technologies in the field of water treatment have given rise to novel alternative resources capable of meeting the specific needs and requirements associated with water-related activities (Hardy et al. 2015). There are multiple approaches to treating groundwater, either from sedimentary or fractured rock aquifers (State of New South Wales NSW Ministry of Health, n.d.). The current technologies for groundwater treatment stated in the report for the National Water Grid Authority conducted by Doble et al. (2023) include disinfection, coagulation and flocculation, filtration, desalination, pH adjustment, and ion exchange.

Disinfection treatment is employed to eliminate pathogenic bacteria present in water to guarantee microbiological quality and ensure water safety for users (Collivignarelli et al. 2017). The predominant disinfection techniques applied to water treatment consist of physical disinfection, such as ultraviolet radiation, and chemical disinfection, including chloramine, chlorine, ozone, and dioxide (Gelete et al. 2019). Coagulation and flocculation are typically implemented to remove colloids, suspended particles, natural organic matter, and metal ions in water (Tzoupanos & Zouboulis 2008). The efficiency of these techniques involves the introduction of chemical agents such as aluminium sulphate or polyaluminium chloride into the water to induce the aggregation and sedimentation of particles, which are then removed via filtration (Doble et al. 2023). Filtration is a physical procedure to eliminate various impurities in water, including heavy metals, and organic matter (Tahir et al. 2023). Slow sand filters have extensive applicability and have been exploited globally for numerous decades, whereas membrane filtration systems have recently gained popularity due to their efficacy in the purification of potable water (Shammas 2015). Desalination is a process adopted to clean water with elevated concentrations of dissolved minerals or salt in order to make it suitable for diverse applications (Verma 2024), and reverse osmosis is currently the predominant technology utilised for desalination purposes (Curto et al. 2021). pH adjustment is a common practice to modify the pH of the water before undergoing treatment in order to minimise the risk of corrosion on the treatment infrastructure and create ideal conditions for subsequent stages of the treatment process, and the control of water pH is achieved by the addition of an acidic or alkaline substance (Doble et al. 2023). Finally, ion exchange is a technological approach employed for the purpose of removing hardness and a variety of contaminants such as nitrate, perchlorate, arsenic, bromide, dissolved organic carbon, cobalt, and uranium (Amini et al. 2015). The process of ion exchange involves the reversible transfer of ions between a solid ion exchange material, which is usually resin, and a solution (Shammas 2015).

2.5 Fractured rock aquifers and remote communities

Hard rock aquifers are highly suitable for providing groundwater to dispersed rural or remote communities, small-to-medium-size towns, and peri-urban regions (Lachassagne et al. 2014). The exploitation of fractured rock aquifers in remote areas is observed in many parts of the world. Shallow volcanic aquifers of the Ethiopian highlands play a vital role in providing water for a substantial number of the populations in the remote communities of Ethiopia (Shube et al. 2023). The residents typically use hand pump wells to access groundwater from these aquifers, which have moderate to high productivity. People living in the rural areas of Galicia in Spain mainly rely on groundwater extracted from weathered and fractured schist aquifers through spring catchments, shallow dug wells, and deep drilling wells as a public water supply system is unavailable (Samper et al. 2022). The fractured metamorphic rock aquifers serve as the primary source of water supply for remote rural regions in the Highlands of Scotland (Cobbing & Dochartaigh 2007). Although these metamorphic aquifers can yield groundwater with rates ranging from 0.01-0.1 L/sec, they are typically adequate for fulfilling domestic water requirements. Additionally, granite rock has become a vital aquifer for remote communities in Malaysia since the country experienced a prolonged dry period in the early 1980s (Sapari et al. 2010). The groundwater from this aquifer is appropriate for domestic water supply since it contains low levels of TDS, hardness, and iron.

CHAPTER THREE DESCRIPTION OF THE STUDY AREA

The communities of Iga Warta, Leigh Creek Station, Kakalpurannha, and Yappala were selected as study areas from the list of seven self-supplied remote communities, which are identified as having high vulnerability of water supplies for both potable and non-potable purposes in the next decade by the Department for Environment and Water. These four communities were targeted for further study on groundwater quality assessment in cooperation between the Department and Flinders University as part of a 2024 National Water Grid Authority project. These communities are Aboriginal Homelands located in hard rock areas of the northern Flinders Ranges (Figure 3.1).

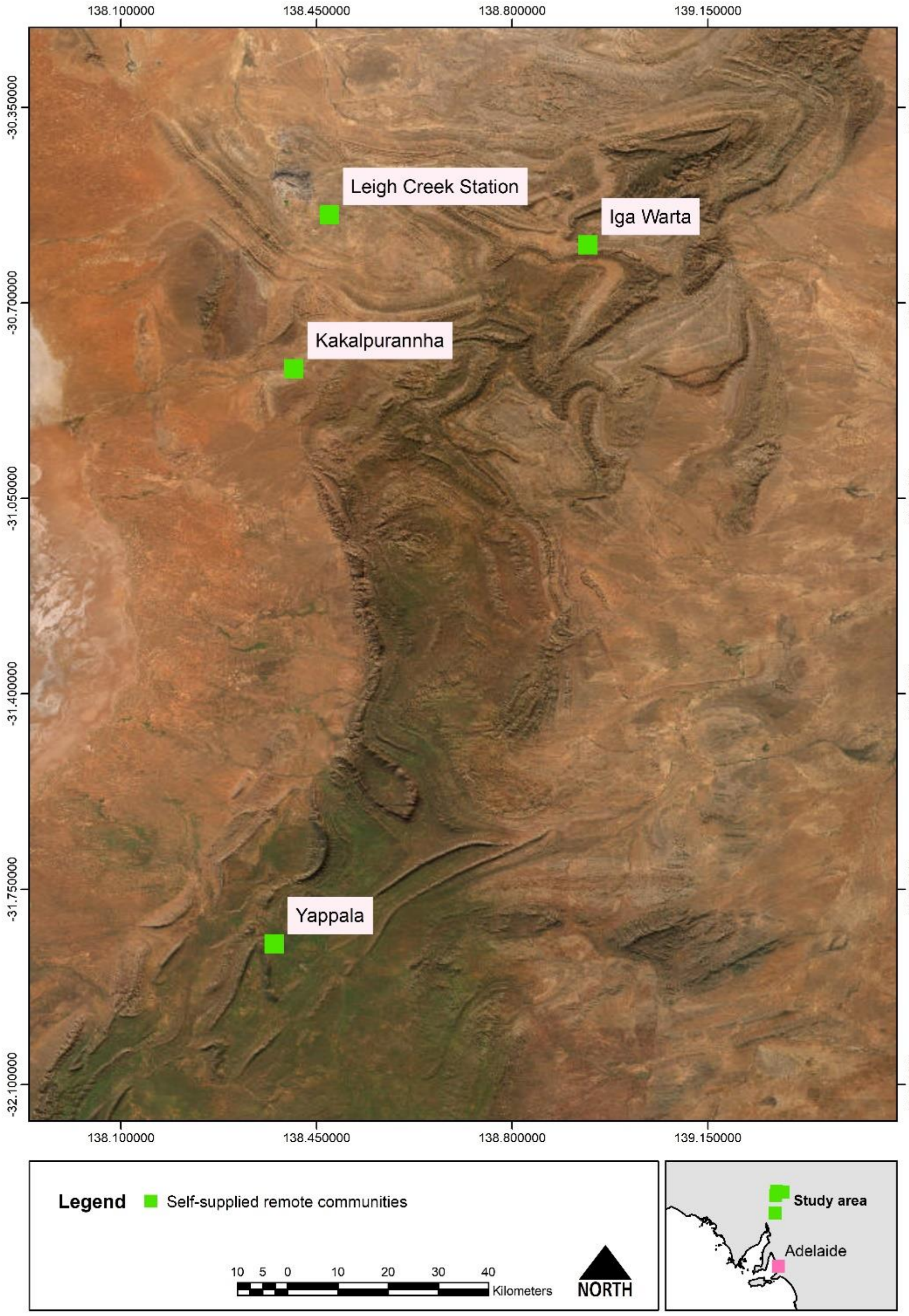

Figure 3.1 The location of four study sites.

3.1 Iga Warta

Iga Warta is approximately 600 km north of Adelaide at a latitude of -30.596086 and a longitude of 138.934722. It is situated on the south side of Gammon Ranges Road between two hills, Constitution Hill in the north and Cambell Bald Hill in the south, and its elevation is around 540 m above mean sea level (Figure 3.2). This village owns one sq km of land and is home to 25 permanent Adnyamathanha people; also, it is the first cultural centre of its kind in South Australia that is completely owned and operated by Aboriginal people (Department for Environment and Water 2024).

Figure removed due to copyright restriction.

Figure 3.2 Topographic map of Iga Warta. It is an extract from the Copley 1:250,000 topographic map (Geoscience Australia 2023).

3.1.1 Meteorology

The climate of Iga Warta is characterised by a hot, dry summer and a cold winter (Australian Government Bureau of Meteorology 2006). Long-term temperature data from the three weather stations near this community, including Gammon Ranges (Balcanoona), Arkaroola, and Leigh Creek Airport, indicates that the average annual temperature of Iga Warta falls within the range of 12-25 °C (Australian Government Bureau of Meteorology 2023). During the summer months, the maximum temperature typically reaches 35 °C while the minimum temperature stays around 10 °C (Figure 3.3). In contrast, winter months experience maximum temperatures above 30 °C and minimum temperatures of nearly 5 °C.

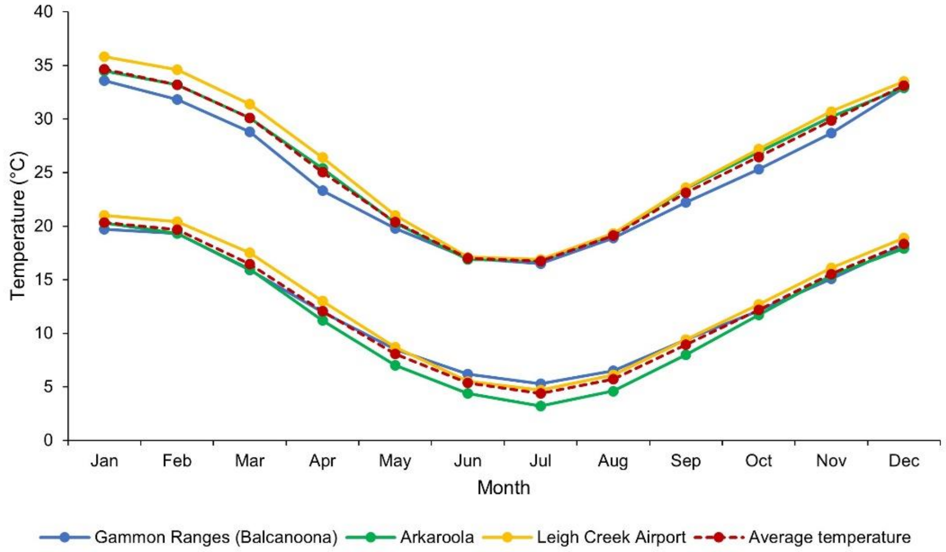

Figure 3.3 The mean maximum and minimum temperature each month in Iga Warta.

Rainfall data for Iga Warta was obtained from the three nearest stations, which are Leigh Creek (Maynards Well), Gammon Ranges (Balcanoona), and Wetaloona, and these stations were recording data for over a century from 1906 to 2015 (Australian Government Bureau of Meteorology, 2023). The yearly precipitation is highly variable and typically less than 250 mm (Figure 3.4). The average amount of rainfall per year is 197 mm. The minimum recorded annual rainfall is 36 mm, documented in 2002, while the maximum is 832 mm, observed in 1989.

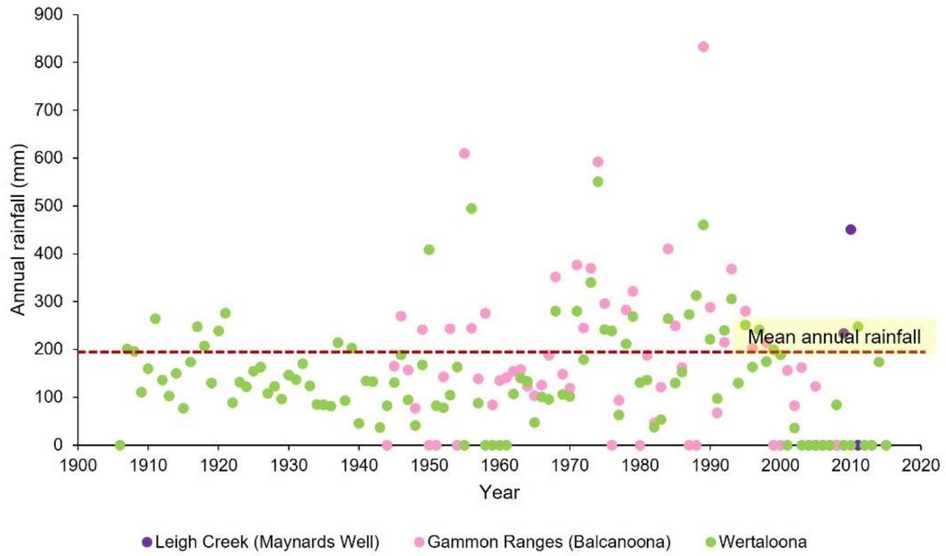

Figure 3.4 The annual rainfall of Iga Warta.

Every house in Iga Warta has a rainwater tank for drinking and cooking water (Department for Environment and Water 2024). The shortage of potable water generally occurs when rainwater is substituted for domestic use during an iron bacteria outbreak in a groundwater bore, and purchasing boxed water is often a solution. Rainwater has no record of quality concerns.

The only pan evaporation station is at Woomera Aerodrome in the northern region of South Australia; therefore, this evaporation measurement must be used for Iga Warta, Leigh Creek Station, Kakalpurannha, and Yappala (Australian Government Bureau of Meteorology 2023). Woomera Aerodrome station recorded evaporation data between 1967 and 2016 as shown in Figure 3.5. The evaporation rates vary moderately with the average annual evaporation of 3,200 mm, which can lead to rapid evaporation of surface water. In 2017, the evaporation reached its peak at 3,571 mm, while in 1974 it hit its lowest point at 2,709 mm.

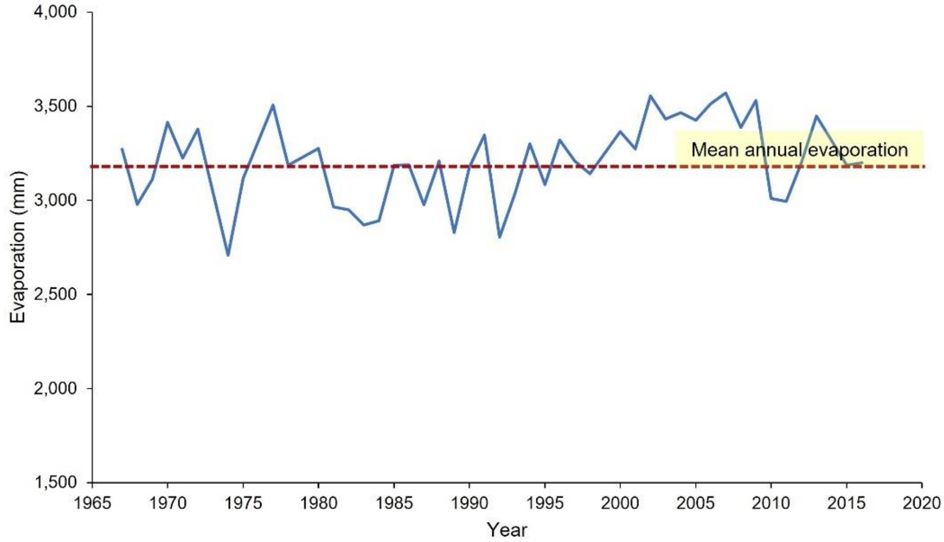

Figure 3.5 The average annual evaporation of the study areas.

3.1.2 Geology

Iga Warta community is located approximately at the axis of one of the synclines within Nepabunna Synclinorium (Department of Mines 1973). The axis trend is oriented in the northeast-southwest direction passing through Wilkawillina Limestone (Ehw), which is a member of the Early Cambrian Hawker Group, and the whole one-sq-km area of Iga Warta property is situated inside this rock formation (Figure 3.6). Furthermore, there is a fault running in a northeast-southwest direction at close distance to the community. The Wilkawillina Limestone was deposited in a carbonate shelf environment characterised by shallow water and the absence of clastic sediment (Langsford & Jago 2023).

The stratigraphy of Wilkawillina Limestone is divided into three distinct sections (Dyson 2009). The basal layer includes biothermal to stromatolitic, dolomitic, and oolitic limestone, which is interbedded with grey calcareous siltstone, limonitic siltstone, and minor thin-bedded sandstone. The middle layer transitions into an upward-fining sequence of interbedded calcareous siltstone and limestone. The uppermost layer of the formation consists of limestone with a thick bed, and it is overlain by interbedded layers of calcareous siltstone and limestone, which mark the transition to the Nepabunna Siltstone above.

Figure removed due to copyright restriction.

Figure 3.6 Geological map of Iga Warta's area. This map is created from shapefiles of 100K Geology - surface geology and linear structures (Geological Survey of South Australia 2022).

3.1.3 Hydrogeology

Iga Warta holds a total of 7 groundwater wells that have been drilled on its property but only one bore is presently being utilised (Figure 3.7). Well with number 6636-225 serves as the water source in this village, and it is used solely for non-drinking purposes, such as domestic usage, plantation of indigenous orchards, and tourism. (Department for Environment and Water 2024).

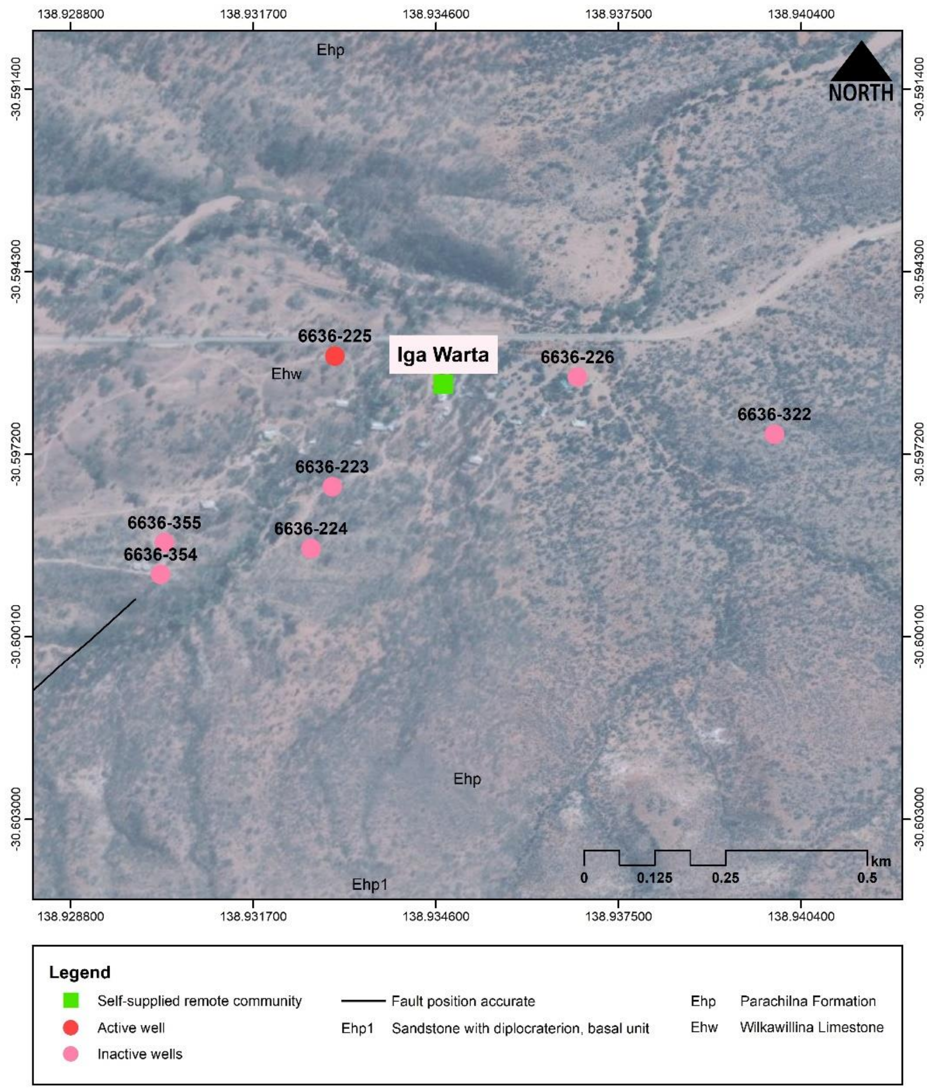

Figure 3.7 The location of groundwater wells in Iga Warta.

Wilkawillina Limestone (Ehw) is defined as the aquifer stratigraphic unit in almost all bores located in Iga Warta, including the active well (Appendix A). The details regarding the lithology and stratigraphy of this aquifer have previously been provided in the section on geology. The wells are relatively deep, ranging from 146 to nearly 170 m. These bores are designed with open holes for production zones, which span from 80 to 169 m. The water level is only documented in a single well, defined as 6636-322, with a depth of 96 m below the surface, indicating significant depth. The wells have a flow rate capacity ranging from 1.0 to 1.4 L/s.

The water quality data indicate that the groundwater from this aquifer has total dissolved solids (TDS) in the range of 944 to 1,083 mg/L. The electrical conductivity (EC) varies between 1,710 to 1,960 mg/L, and the pH data is only present in the active well with a pH of seven. Water chemistry information is absent in all wells. However, the Department for Environment and Water (2024) reported that water from the existing production well has high levels of calcium, causing a negative impact on home equipment and pipelines. Additionally, there are yearly occurrences of iron bacteria outbreaks, which cause severe skin rashes in the local population.

3.2 Leigh Creek Station

Leigh Creek Station is 545 km north of Adelaide, located at a latitude of -30.542258 and a longitude of 138.472402. It is located in a relatively flat area surrounded by small hills with an elevation of 280 m above mean sea level (Figure 3.8). This community has an area of 443 sq km, which has been leased for over two decades, and the number of permanent residents is 20 Adnyamathanha people; in addition, Leigh Creek Station is a habitat of numerous major floral and fauna species, as well as hosts culturally important places (Department for Environment and Water 2024).

Figure removed due to copyright restriction.

Figure 3.8 Topographic map of Leigh Creek Station. This map is extracted from the Copley 1:250,000 topographic map (Geoscience Australia 2023).

3.2.1 Meteorology

Leigh Creek Station is situated in a region with a hot dry summer and a cold winter climate (Australian Government Bureau of Meteorology 2006). The mean yearly temperature of this community fluctuates between 12 and 26 °C, as recorded by the three closest weather stations which are Leigh Creek Airport, Marree (Farina), and Gammon Ranges (Balcanoona) (Australian Government Bureau of Meteorology 2023). Over the summer season, the month of January receives the warmest temperature at 35 °C; however, in the winter season, the lowest temperature can drop to 4 °C in the month of July (Figure 3.9).

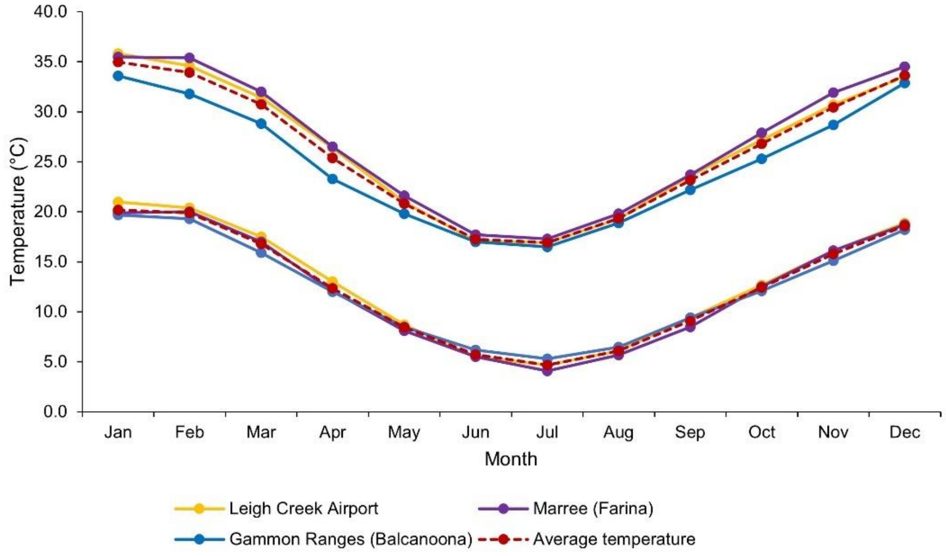

Figure 3.9 The mean highest and lowest temperature of Leigh Creek Station on a monthly basis.

The annual rainfall data of Leigh Creek Station is downloaded from the three weather stations, Leigh Creek Airport, Leigh Creek (North Moolooloo), and Leigh Creek (Pfitzners Well). The data has been recorded since 1982 (Australian Government Bureau of Meteorology 2023). The rainfall pattern exhibits significant annual fluctuations, with a mean annual precipitation of 220 mm (Figure 3.10). Additionally, there is a large gap between the lowest and highest yearly precipitation levels. The lowest recorded was 50 mm in 2019, whereas the highest was 496 mm in 2010.

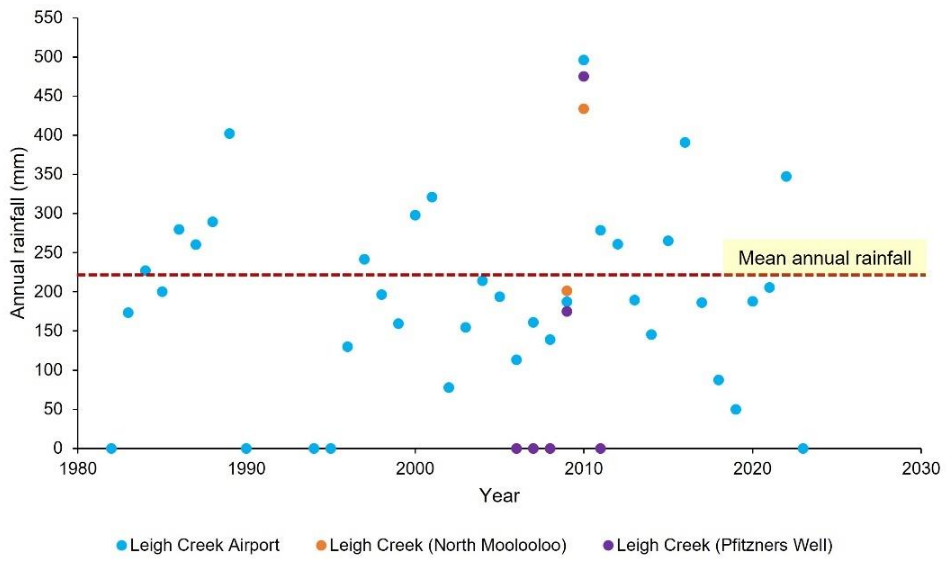

Figure 3.10 Total annual rainfall at Leigh Creek Station over the period of record.

Although each household in Leigh Creek Station has a tank to store rainwater for drinking and cooking, the supply is insufficient to meet domestic needs (Department for Environment and Water 2024). No issues with rainwater quality have been documented.

3.2.2 Geology

Leigh Creek Station is located on a limb of the syncline (Department of Mines 1973) within an area characterised by fault zones and various geological formations (Figure 3.11). The major orientation of the faults follows the northeast-southwest direction; however, a distinct north-south fault traverses through the community. Moreover, Leigh Creek Station occupies an area that serves as a contact boundary between the Amberoona Formation (Nib) and the Angepena Formation (Nia).

Figure removed due to copyright restriction.

Figure 3.11 A geological map of the Leigh Creek Station. This map is created from shapefiles of 100K Geology - surface geology and linear structures (Geological Survey of South Australia 2022).

The Amberoona and Angepena formations belong to the Upalinna Subgroup deposited in a transgressive-regressive environment, dating back to the Early Marinoan times, with a maximum age of 724 ± 40 Ma (Preiss et al. 1998). The features of each formation below are provided in ascending order according to the age from most recent to oldest.

The Amberoona Formation comprises finely laminated siltstones and shales that are green and grey-green in colour (Geological Survey of South Australia 1973). It also contains minor sandy and stromatolitic limestone, as well as minor purple shale. Additionally, there are areas with local slump structures within the formation. Its stratigraphic thickness rarely exceeds 100 m in occurrences above shallow water succession (Fromhold & Wallace 2011). Conversely, within the basinal setting, the formation reaches a thickness of over 240 m.

The Angepena Formation is a group of flaggy red or purple ripple-marked micaceous siltstone and shales, along with minor green shales, red and grey dolomites, and limestones containing oolites and stromatolitic features. (Geological Survey of South Australia 1973). The existence of sedimentological features such as mudcracks, tepees, bidirectional crossbedding, and mud drapes in this sedimentary rock formation provides evidence of its deposition in a peritidal environment (O'Connell et al. 2020).

3.2.3 Hydrogeology

The groundwater wells are positioned at a considerable distance from the residential area of Leigh Creek Station (Figure 3.12). The total number of boreholes in this community is 10, and the main objective of drilling these bores is to provide water for livestock. The primary water resources are wells 6536-422 and 6536-3, which are utilised for domestic and cattle purposes (Department for Environment and Water 2024).

The aquifer information from four groundwater bores reveals that the wells at Leigh Creek Station are dug in two different aquifer formations (Appendix B). Two bores, 6536-5 and 6536-6, are categorised as aquifer units in the Amberoona Formation (Nib), whereas two other wells, 6536-204 and 6536-3209, extract water from the Angepena Formation (Nia) aquifer. The remaining wells, including the two operating ones, have not been classified with regard to aquifer formation. Detailed information about the lithology and stratigraphy of these two aquifer units can be found in the previous section on geology.

The Amberoona Formation is largely siltstone and shale. There is a lack of information regarding the depth, production zones, water levels, and capacity of bores pumping water from this aquifer at Leigh Creek Station. There is a difference in the quality of water between two groundwater wells, 6536-5 and 6536-6, that have been drilled in this aquifer. Well 6536-5 has excessive levels of TDS, EC, chloride, hardness, sodium, and sulphate. In contrast, well 6536-6 presents good quality groundwater. There is no pH data available for this specific aquifer formation.

Figure removed due to copyright restriction.

Figure 3.12 The location of groundwater wells in Leigh Creek Station.

The Angepena Formation mainly consists of mudstone, dolomite, and limestone, as described in section 3.2.2 geology. The data obtained from two boreholes, 6536-204 and 6536-3209, provide different sets of information regarding this aquifer. The bore with the number 6536-204 has only drilling data, whereas the well identified as 6536-3209 is solely recorded for water quality. The well has a depth of 133 m, which is relatively deep, and the water level is located 38.5 beneath the surface. Furthermore, the well holds production zones at a depth of 121.5 to 133.0 m. with the capacity to discharge water at 1 L/s. The water quality exhibits significantly high levels of TDS and EC, surpassing 4,500 mg/L and 8,000 mg/L, respectively. There is no information available for the pH measurements. The groundwater analysis reveals high concentrations of various elements of concern, including chloride, hardness, sodium, and sulphate.

According to the Department for Environment and Water (2024), the majority of wells in Leigh Creek Station currently suffer from depletion after a few hours of pumping, and it may take days for these wells to recover before they are once again usable. The data from four wells drilled in the community indicate a significant decrease in water levels of 25 m between the years 1954 and 1996. The decline may be attributed to the operation of coal mines near this community. Insufficient water limits the ability to sustain a large number of cattle, leading to a scarcity of job opportunities and prompting people to relocate from the village. Moreover, the active wells yield elevated calcium levels, resulting in a harmful impact on home equipment.

3.3 Kakalpurannha

Kakalpurannha is the Adnyamathanha community located 515 km from Adelaide at a latitude of -30.817885 and a longitude of 138.409082. It is situated in relatively flat topography with an elevation of approximately 240 m above mean sea level and is surrounded by Beltana Hill in the southwest and a 400 m high hill in the southeast (Figure 3.13). This village is home to 20 permanent residents, and these people are closely connected to the Beltana area's culture (Department for Environment and Water 2024).

Figure removed due to copyright restriction.

Figure 3.13 Topographic map of Kakalpurannha. This map is obtained from the Copley 1:250,000 topographic map (Geoscience Australia 2023).

3.3.1 Meteorology

Kakalpurannha also has a climate characterised by hot and dry summer as well as cold winter (Australian Government Bureau of Meteorology 2006). The temperature record obtained from the Leigh Creek Airport, Wilpena Pound, and Marree (Farina) weather stations, exhibits that the average annual temperature of this village varies from 11 to 25 °C (Australian Government Bureau of Meteorology 2023). January experiences the highest temperatures, with an average of almost 35 °C, whereas July is the coldest month with temperatures dropping below 5 °C (Figure 3.14).

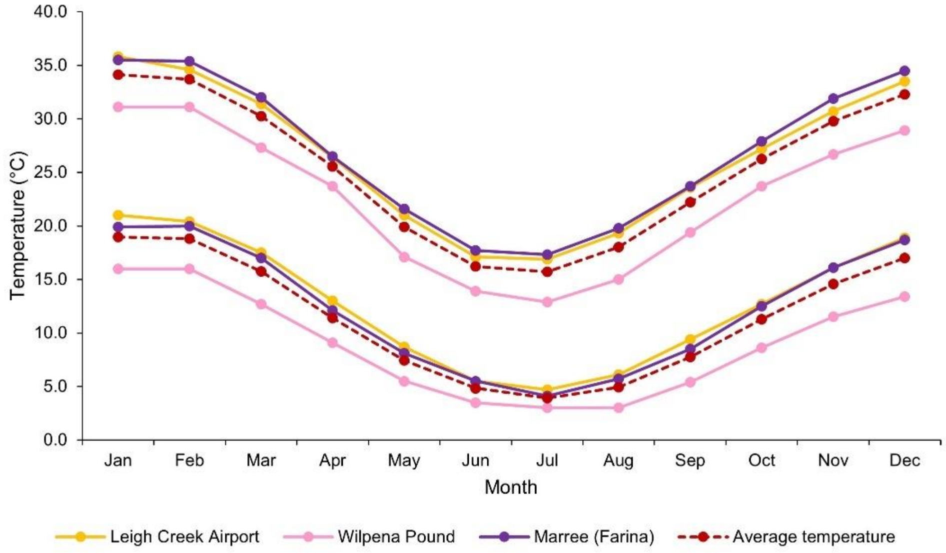

Figure 3.14 The average highest and lowest temperature each month of Kakalpurannha.

The yearly precipitation data of Kakalpurannha is gathered from Beltana Station, Beltana Roadhouse, and Leigh Creek (Pfitzners Well). These stations have been observing the data since 1872 (Australian Government Bureau of Meteorology 2023). Forecasting the quantity of rainfall is challenging due to the high variation of rainfall patterns (Figure 3.15). The average annual rainfall is 210 mm. In 1902, the lowest yearly rainfall on record was monitored at 57 mm, while the highest recorded annual rainfall of 508 mm was found in 1989.

Rainwater is typically harvested for domestic consumption at Kakalpurannha, with each household installing one or two tanks for storage; however, these containers are unable to collect all runoff from the roof (Department for Environment and Water 2024). There is no historical record of any concerns regarding the quality of rainwater.

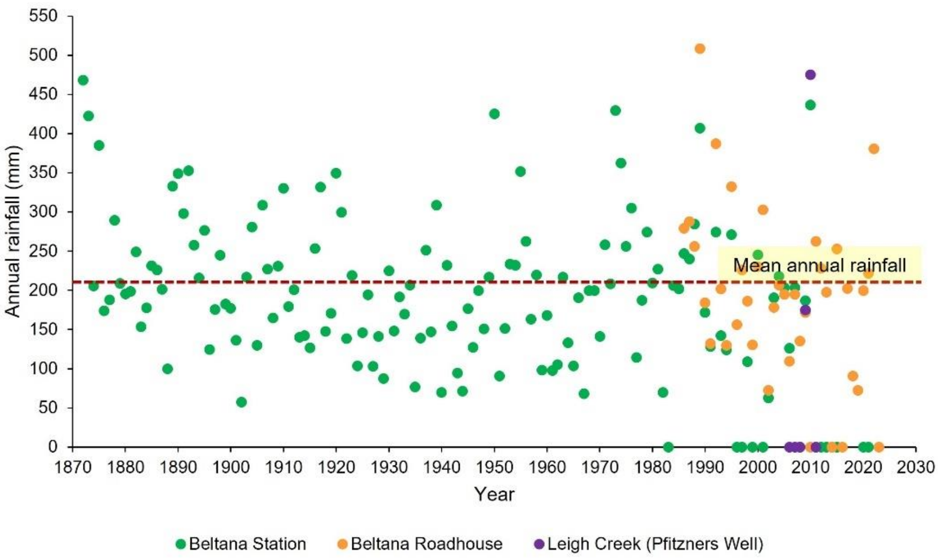

Figure 3.15 The yearly precipitation of Kakalpurannha.

3.3.2 Geology

The Kakalpurannha community is located on a limb of the anticline where its axis passes through Mountain Stuart in the east-west direction and crosses the Mountain Stuart Fault (Department of Mines 1973). It is also situated within the geological unit of the Wonoka Formation (Nww), which is a part of the Wilpena Group from the late Precambrian period (Figure 3.16). Furthermore, neither faults nor fractures are found nearby to the community. The Wonoka Formation was deposited in a shallow marine environment, specifically a carbonate shelf that gradually becomes shallower from the lower shoreface to the foreshore (Kerne et al. 2019).

The type section of the Wonoka Formation has a thickness of roughly 620 m at Bunyeroo Gorge in the Central Flinders Ranges (Kerne et al. 2019). This formation observed in the central Flinders Ranges exhibits a thickness of 500 m, and its lithology reveals an upward shallowing and coarsening sequence of calcareous shale, siltstone, and fine sandstone (Gehling & Droser 2012). Notably, in the northern and southern parts of the Flinders Ranges, canyon incisions through the formation's basal layers suggest a fluvial cut followed by marine sediment. Beyond the canyon regions, the Wonoka Formation demonstrates a stratigraphic sequence comprising turbidites transitioning into hummocky cross stratified, silty limestone. Subsequently, it features green stylolitic, cryptomicrobial limestone interleaved with sandy limestone, notable for its soft-sediment deformation and the presence of intraformational breccias. The formation ends up with two distinct parasequences of red, clayey sandstone succeeded by an overlay of a carbonate unit.

Figure removed due to copyright restriction.

Figure 3.16 A map of the geology of Kakalpurannha. This map is created from shapefiles of 100K Geology - surface geology and linear structures (Geological Survey of South Australia 2022).

3.3.3 Hydrogeology

A total of 29 groundwater bores have been drilled near Kakalpurannha, although only two of these wells are now in use. (Figure 3.17). The primary bore, 6536-4427, is powered by solar cells to supply water to two large tanks, which are then discharged to every household within the community (Department for Environment and Water 2024). The second bore, which has no identification number, operates specifically in situations when the main bore fails to function as a result of inadequate sunlight, insufficient productivity, or the installation of a substitute pump. These operating bores are generally utilised for non-potable activities such as domestic use, watering plants, and supporting animal life.

Figure removed due to copyright restriction.

Figure 3.17 The location of groundwater wells in Kakalpurannha.

Almost half of the bores in Kakalpurannha have been identified for aquifer stratigraphic units, including the primary bore, while aquifer formations of other wells are missing due to a lack of lithologic data (Appendix C). Based on groundwater wells data, most bores extract groundwater from a fractured-rock aquifer known as the Wonoka Formation (Nww). The major lithology of this aquifer includes shale, limestone, siltstone, and sandstone. Further information regarding this rock formation can be found in the geological section 3.3.2. The boreholes have a range of depth, spanning from 12 to 129 m. The production zone extends from 2.4 to 129.0 m. The depth of groundwater levels ranges from 6 to 14 m below the surface and the wells have a flow rate capacity ranging from 0.13 to 8.00 L/s.

The groundwater from this specific aquifer has TDS ranging from 1,770 to 5,343 mg/L. EC varies from 3,190 to 9,400 mg/L, whereas the pH levels range from 6.7 to 8.2. Although there is no existing water chemistry data for the bores, the presence of calcification of the header tanks indicates that active bores have high calcium concentrations, which can lead to a reduction in the longevity of household appliances (Department for Environment and Water 2024).

3.4 Yappala

Yappala is 390 km north of Adelaide at a latitude of -31.847382 and a longitude of 138.37366, and it is not far from Hawker. This community is located in a flat area between Wonoka Hill in the northeast and Yappala Range in the west with an elevation of 290 m above mean sea level, and it is also in an area of Yappala managed resource, which is an aboriginal protected area (Figure 18). Yappala has 30 permanent residents, and it functions as the main area of residence within an expansive property consisting of three distinctive sections, which are Yappala itself, along with Worro Downs and Cotabena (Department for Environment and Water 2024).

Figure removed due to copyright restriction.

Figure 3.18 Topographic map shows the location and topology of Yappala. This map is an extract from the Parachilna 1:250,000 topographic map (Geoscience Australia 2023).

3.4.1 Meteorology

Similar to the other three study locations, Yappala has a hot dry summer and a cold winter climate condition (Australian Government Bureau of Meteorology 2006). The mean annual temperature is 11-25 °C, as determined by data obtained from Hawker, Wilpena Pond, and Port Augusta Aero, the three stations situated at close distance to Yapala, which have been operational since 1965 (Australian Government Bureau of Meteorology 2023). January has the warmest air temperatures, reaching a maximum of 34 °C during the day and 18 °C at night. July is the coldest month, with nighttime temperature dropping to 4 °C and daytime temperature reaching 16 °C (Figure 3.19).

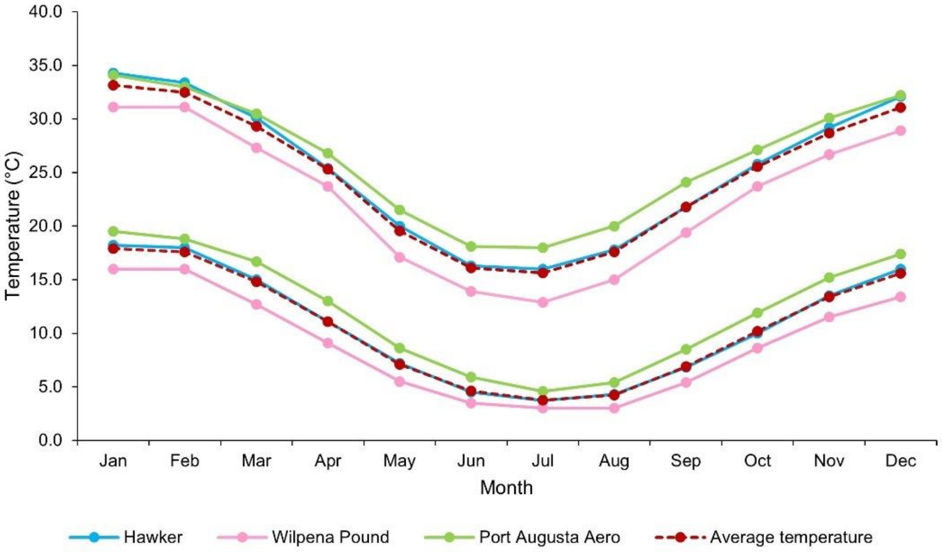

Figure 3.19 The monthly average maximum and minimum temperature per month of Yappala.

The annual precipitation of Yappala is collected from Hawker, Hawker (Wilson), and Cradock stations, and available data provides information on the amount of rainfall each year covering the period from 1882 to 2023 (Australian Government Bureau of Meteorology 2023). The yearly rainfall is highly variable, making rainwater an unreliable source of water supply, and the mean annual rainfall is recorded at 293 mm (Figure 3.20). The minimum rainfall on record was found in 1940 at 60 mm, whereas the maximum was observed at 677 mm in 1920.

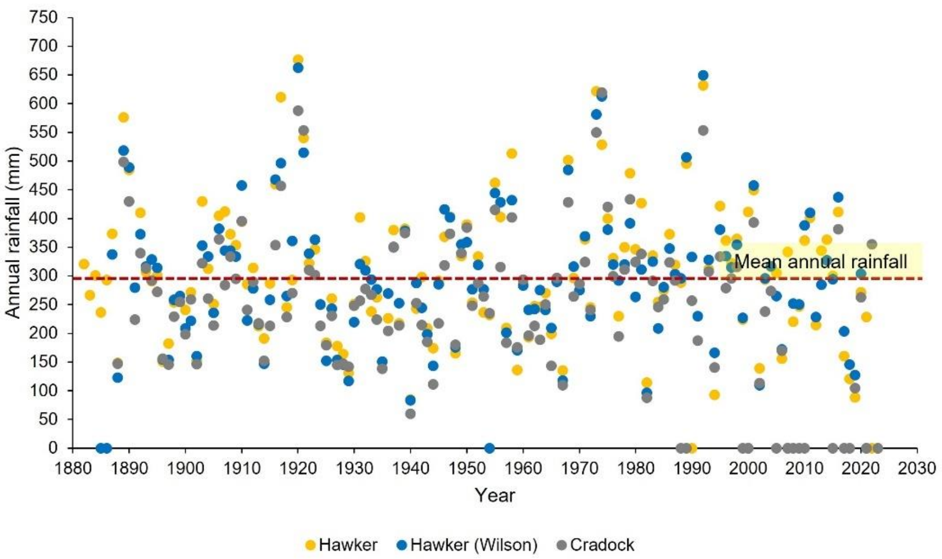

Figure 3.20 The annual precipitation of Yappala.

Yappala community relies mainly on rainwater for drinking and cooking (Department for Environment and Water 2024). Each house is equipped with an individual rainwater tank that is linked to an underground reticulation system, allowing the transfer of water between tanks when water is needed. However, the insufficient capacity of rainwater containers has resulted in a limitation of the frequency of community events and other activities because of the restricted quantity of rainwater. Moreover, water carting is sometimes necessary to serve water for people during periods of drought. The historical concerns regarding the quality of rainwater are absent at Yappala.

3.4.2 Geology

Yappala is positioned within the area bounded by the northeast-southwest axis of the anticline and the Yappala syncline (Department of Primary Industries and Resources 1999). The community is also located in the sedimentary formation of alluvial fans (Qa2), which were deposited throughout the Pleistocene and Holocene (Figure 3.21). Additionally, the east-west fault is present near the community.

Figure removed due to copyright restriction.

Figure 3.21 Yappala's geological map. This map is generated using shapefiles of 100K Geology - surface geology and linear structures (Geological Survey of South Australia 2022).

According to the geological map of the Parachilna sheet at a scale of 1:250,000 (Department of Primary Industries and Resources 1999), the lithology of the alluvial fans consists of flanking bedrock outcrops, which are consolidated but not cemented; and have varying degrees of soil horizon development. The sediment is poorly sorted, consisting of boulder to gravel, and is located close to its origin. Older fans are sizable and have been analysed in detail.

3.4.3 Hydrogeology

The groundwater wells in Yappala are situated at a considerable distance from the residential area. There are a total of seven boreholes surrounding the village, as shown in Figure 3.22. The currently operational well, 6534-204, is located 2.5 km in the southwest direction from the main property (Department for Environment and Water 2024). The water is pumped to three containers near the bore and then distributed to each house by gravity. This bore functions as the primary water source for non-potable activities, including home use, cultivation of native orchards, and livestock.

Figure removed due to copyright restriction.

Figure 3.22 The location of groundwater wells in Yappala.

Bonney Sandstone (Npb) and Rawnsley Quartzite (Npr) are identified as aquifer units for the active well and the bore number 6534-179, respectively, while six other boreholes have not been recognised as being part of an aquifer formation (Appendix D). These formations belong to the Pound Subgroup and date back to the late Precambrian or late Adelaidean period, with an estimated age of 676 ± 204 Ma (Preiss & Forbes 1981). The characteristics of each aquifer formation below are detailed in ascending order based on the age of the rock formation from youngest to oldest.

The Rawnsley Quartzite is approximately 250 m thick. This formation formed near the shore and was influenced by the impact of waves and tides in a deltaic environment (Gehling & Droser 2012). Its deposit signalled a period of uplift and erosion on the Gawler Craton and coincided with the beginning of the Petermann Orogeny. The lithology of this formation is predominantly pale, medium to coarse-grained sandstone with a high feldspar content. However, in the areas where the formation is deeply incised, the sand grains become stained with iron, giving the sandstone a reddish appearance. The well 6534-179 drilled in this formation lacks data regarding its depth, production zone, water level, and capacity. Nevertheless, it has a documented history of water quality data. The level of TDS is above 2,400 mg/L, while EC is more than 4,400 mg/L. In addition, this well exhibits a significant presence of chloride, hardness, sodium, and sulphate. There is a lack of pH data for this aquifer unit.

Bonney Sandstone has a thickness ranging from 300 to 400 m in the middle Flinders Ranges, and it consists of three unique rock sequences (Gehling & Droser 2012). Transgressive shallow marine sandstone and carbonate deposits are present in the bottom layer. The middle layer is composed of deeper water siltstone and fine sandstone that is shallowing and coarsening upward in response to a period of high eustatic sea level. Alluvial, red, poor sorted sandy mudstone forms the top layer of this formation. The data from the operation bore indicates that the well was drilled to a depth of 70 m in this aquifer formation, with a water level of 63 m below the surface. The information regarding the production zone and capacity of the well is unavailable. The water has a concentration of TDS over 2,000 mg/L and EC surpassing 4,000 mg/L. The pH and water chemistry data are not provided. However, high calcium concentration is recognised as it damages various household items, including pumps, header tanks, pipework, taps, and shower heads (Department for Environment and Water 2024).

3.5 Previous studies

The previous studies on water quantity and quality have been conducted on a large scale covering the entire northern Flinders Ranges, as well as on a smaller scale, specifically focused on the individual communities of Iga Warta, Leigh Creek Station, Kakalpurannha, and Yappala, which are the targeted sites for this study. These prior studies provide valuable and beneficial information for enhancing understanding and for making comparisons with other findings.

3.5.1 Large-scale studies

Watt et al. (2012) carried out a hydrological report for the area that is not prescribed for groundwater resources assessment involving the northern Flinders Ranges, South Australia. According to Watt et al. (2012), the northern Flinders Ranges remain within the area of Adelaide Geosyncline, which refers to the complex system of basins of thick Neoproterozoic sedimentary layers in central-eastern South Australia. The quality and amount of groundwater in the fractured rock of the Adelaide Geosyncline are mainly influenced by several key factors, including the magnitude and distribution of joints and fractures, lithological characteristics, recharge dynamics, and the degree of weathering.

In the northern Flinders Ranges, the greatest amount of water is found near faults, which are the locations of most springs. However, most wells are drilled in valleys where the subsurface is made up of easily erodible slates and shales. These bores are shallow and produce a small amount of water, which is usually enough for livestock, but they do not give a good estimate of the potential water yield that could be obtained by deeper drilling into more favourable rock formations. Mineral exploration has revealed some of the highest quantities of groundwater at deeper drilling, but the availability of resources varies greatly depending on factors such as the number and magnitude of fractures intersected, the kind of rock as well as structural setting. Limestones typically generate a large volume of roughly 30 L/s, whereas shales and siltstones yield a far lower volume of less than 0.1 L/s. The salinity of groundwater shows significant variability, with values ranging from 214 to 92,000 mg/L. Wells with low salinity are generally distributed in the central regions of the Flinders Ranges. The depth of groundwater ranges from 127 m below the surface to a median of 13 m.

3.5.2 Small-scale studies

Self-supplied remote communities in South Australia, including Iga Warta, Leigh Creek Station, Kakalpurannha, and Yappala, were the subject of a stocktake and water security assessment report published by the Department for Environment and Water (2024). Each of these communities relies on one or two groundwater bores for water supply, primarily allocated for non-potable purposes such as domestic activities, livestock, and plantation. The available groundwater resources prove insufficient to fulfill the needs of the local population, while a major water quality issue in all examined communities is high calcium concentrations. This calcium-rich water negatively affects home appliances, tap heads, and pipework, reducing equipment lifespan and requiring regular replacement due to the buildup of calcium deposits.

Grey-Gardner (2008) investigated the concerns regarding the adequacy and availability of water resources in Yappala as a part of the Remote Community Water Management project. Prior to 2001, Yappala obtained water for domestic purposes from a groundwater bore sited three km away and entered into an agreement to distribute water from this bore to their neighbour due to its abundant supply. After a duration of two years, the water supply was limited, and the storage tanks were frequently emptied because of the bush tucker plot that was equipped with a water-conserving irrigation system but evidently required a greater amount of water than initially expected. In 2004, a new well was drilled approximately two km west of the main residence with an estimated yield of 400 gallons per hour to cover the water demand of the local population. The presence of E. Coli was not identified in the water; however, the TDS, hardness, chloride, iodide, sodium, and sulphate levels were above the recommended limits set by the Australian Drinking Water Guidelines.

Fildes et al. (2020) conducted a study on mapping the potential groundwater zones within a 10 km radius of the Hawker township covering the Yappala community area in the Southern Flinders Ranges. The study utilised remote sensing and geospatial techniques, together with multi-criteria analyses, as the primary methods for identifying the zones. These approaches were selected with the goal of implementing a fast and cost-effective strategy to help pinpoint areas for additional field investigations in order to minimise the expense associated with exploratory drilling. Thematic layers in GIS integrated in this study included rainfall, lithology, lineament density, topographic wetness, slope, and aspect. Furthermore, the study incorporated field-collected data to validate the groundwater potential zone map generated by the GIS-based technique. The map was categorised into five groundwater potential zones, which are very high, high, moderate, low, and very low. The findings indicated that Yappala is located in a zone of high-potential groundwater.

CHAPTER FOUR METHODOLOGY

Initially, the methods for this study were divided into two distinct phases, desktop study and fieldwork. Desktop study is a process that involves gathering available data in the study area from various sources to early assess groundwater resources in four self-supplied remote communities, namely Iga Warta, Leigh Creek Station, Kakalpurannha, and Yappala. Fieldwork was designed to collect raw data in the targeted study site in order to acquire recent information on the capacity of fractured rock aquifers through hydraulic tests, a potential area of the aquifers for both extent and depth using geophysical surveys, and physical, chemical, and microbial quality from groundwater analysis. However, fieldwork has been delayed due to unexpected issues, resulting in the inability to access the four study sites. Consequently, desktop study is the only process implemented in this study to achieve its objectives.

4.1 Data sources

The limitation of groundwater well data indicated in Chapter 3 presents challenges when evaluating the quantity and quality of groundwater from fractured rock aquifers in each targeted study site. In order to achieve the study's aims, additional data is required for each unit of aquifers, which are primarily distributed in the Flinders Ranges. Therefore, the area of interest is expanded to cover the entire ranges shown as a red rectangle in Figure 4.1, with 155 km width and 360 km length. The data on groundwater wells is obtained from two major sources managed by the Department for Water and Environment of the South Australian government, which are the WaterConnect website and scanned microfiche images.

The WaterConnect website contains comprehensive groundwater data for South Australia, allowing users to easily download data on permit and observation wells by using unit numbers, coordinates, or specific areas. It also features a user interface map that visually presents the selected well locations, and the total count of wells discovered. Furthermore, there is a table that provides a short summary of information on the chosen bores. The available data for download includes well summary, water chemistry, construction summary and details, driller, lithological, hydrostratigraphic, as well as stratigraphic logs, and is provided in various formats, such as CSV, XML, KML, TXT, and PDF. The website also provides long-term data, for example, water levels from monitoring well networks, and salinity concentration in groundwater. The scanned microfiche images are another valuable resource for accessing historical data regarding groundwater wells. Handwritten records of individual wells were digitised by scanning paper documents and transforming them into digital files that are more convenient and easier to manage. The images generally offer similar data on groundwater wells to that available on the WaterConnect website; however, this image data was recorded in earlier periods.

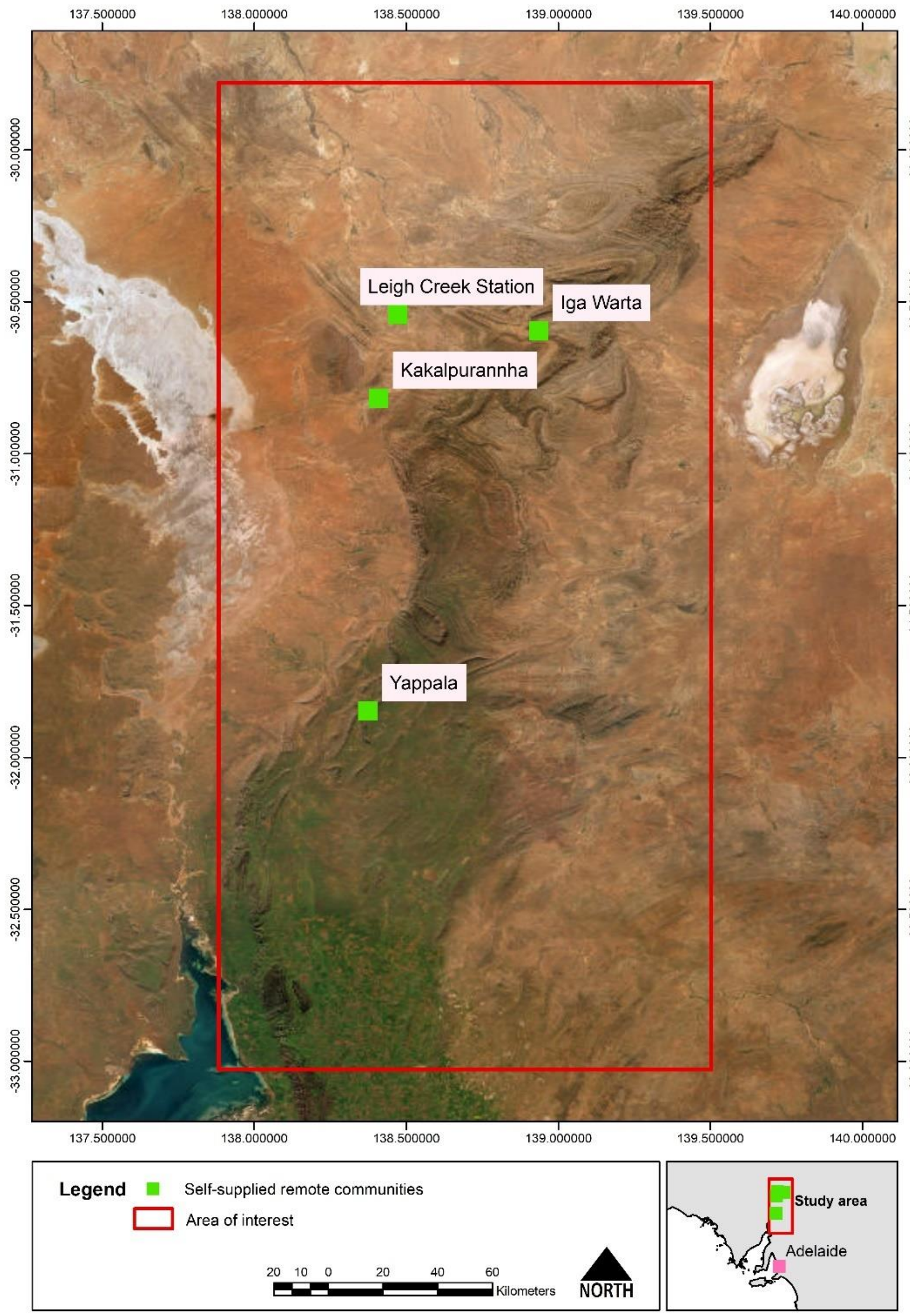

Figure 4.1 The area of interest.

Well summary provides groundwater well data regarding aquifer unit, drilled depth, casing, production zone, water level, physical quality of groundwater, well yield, and coordinates. Physical quality data includes Total Dissolved Solids (TDS), Electrical Conductivity (EC), and pH. Well yield data was acquired through the air testing approach conducted by drillers. This testing can be undertaken while either drilling a partially completed open hole or on a fully completed bore that is cased, slotted, or screened for production purposes (NUDLC 2020). In addition, inadequate submergence during airlift pumping may result in inefficiency; therefore, air testing may not always provide data on the complete amount of water available in the bore. Water chemistry contains concentration data of partial chemicals in groundwater, and the date of measurement. This partial water chemistry generally includes calcium (Ca), chloride (Cl), carbonate (CO_3), hardness, magnesium (Mg), sodium (Na), sulphate (SO_4), and Total Dissolved Solids (TDS). Other chemical parameters that are infrequently documented in the record consist of alkalinity, bicarbonate (HCO_3), potassium (K), and nitrate (NO_3).

Construction summary and details offer essential data on well construction, such as the completion date of well construction, drilled depth, well diameter, and method used for drilling. In the regions characterised by hard rock, such as the areas where the four self-supplied remote communities are situated, the rotary air method is predominantly utilised for drilling boreholes, and the open-hole approach is typically employed for well construction in rock formations that exhibit consistent firmness and stability (NUDLC 2020). Driller, lithological, hydrostratigraphic, and stratigraphic logs supply detailed information on the stratigraphy and lithology encountered during well drilling. These logs offer insights into the thickness of geological layers and the type of rocks that serve as groundwater reservoirs.

Another beneficial dataset gathered from an online source includes shapefiles of surface geology and linear structures at a 100:000 scale prepared by the Geological Survey of South Australia and released in 2022. These two shapefiles can be imported into Geographic Information System (GIS) software and are useful for the evaluation of borehole data. Other related data for this study collected during the desktop study phase include a digital format of a hydrogeology map of Australia, a groundwater resource map of South Australia, geological maps, and topographic maps, as shown in Table 4.1.

Table 4.1 Digital maps of hydrogeology, geology, topography, and gathered from online platforms.

No.	Data	Scale	Year	Source
1	Hydrogeology map of Australia	1:5,000,000	1987	Department of Resources and Energy
2	Groundwater resource map of South Australia	1:2,000,000	1982	Department of Mines and Energy, Geological Survey of South Australia
3	Geological map of Copley	1:250,000	1973	Department of Mines, Geological Survey of South Australia
4	Geological map of Parachilna	1:250,000	1999	Department of Primary Industries and Resources, Geological Survey of South Australia
5	Geological map of Orroroo	1:250,000	1968	Department of Mines, Geological Survey of South Australia

No.	Data	Scale	Year	Source
6	Topographic maps of Copley, Parachilna, and Orroroo	1:250,000	2023	Geoscience Australia

The hydrogeology map of Australia presents data regarding the type and productivity of aquifers, while the groundwater resource map of South Australia offers information on aquifer types with their description, yield, and quality of groundwater resources. In comparison, these two maps provide consistent information on both aquifer types and their potential to produce groundwater. The Flinders Ranges are characterised as fractured or fissured aquifers with low to moderate productivity. These fractured rock aquifers consist of various types of rocks, including quartzite, sandstone, limestone, dolomite, slate, marble, siltstone, phyllite, schist, and gneiss. Generally, the groundwater has salinity levels over 1,500 mg/L, which is appropriate for all livestock. However, there are still certain areas where groundwater of good quality with salinity concentration below 1,500 mg/L can be found.

The geological maps of Copley, Parachilna, and Orroroo at a 1:250,000 scale provide essential geological information for the four communities and the Flinders Ranges. This information encompasses stratigraphy, descriptions of rock formations, rock relation, structural geology, tectonics of the area, and geological cross-sections. Based on the hydrogeology and groundwater resource maps, the primary aquifers in this region are within hard rock formations. Therefore, this geological data enhances comprehension of geological characteristics and the orientation of the aquifers in this area, as well as fracture and fault systems that significantly impact the spaces or voids to store groundwater within hard rocks. Topographic maps of the same map sheet and scale as the geological maps reveal detailed insights into the geomorphology of the area of interest. These maps highlight elevations that indicate recharge and discharge zones, as well as drainage patterns typically controlled by fractures and rock types in consolidated rock regions. Additionally, these topographic maps offer specific information, such as cadastral data, which explains why certain wells are drilled at some distance from communities.

4.2 Data analysis

This process employs ArcMap version 10.7.1 as a major tool for visualising and querying borehole data obtained from the WaterConnet website and the Department for Environment and Water. It also involves analysis of the borehole data alongside geological, topographical, and hydrogeological maps to address study questions regarding major fractured rock aquifers of Iga Warta, Leigh Creek Station, Kakalpurannha, and Yappala, as well as their quantity and quality.

ArcMap is a GIS software that enables users to manipulate geographic data through maps, and it also offers a wide range of GIS tools utilised for geoprocessing tasks (Booth & Mitchell 2001). This study applies only a straightforward tool called clip analysis to select desired well data. This tool is used to perform a spatial operation known as clip, where a portion of one feature class is extracted based on the boundaries of one or more of the features from another feature class (ESRI 2021). More than 15,000 wells within the area of interest or across the Flinders Ranges were imported to ArcMap software using their coordinates in CSV format. This facilitated the visualisation of their spatial distribution and conversion of their data into point features. The clip analysis tool under ArcToolbox on ArcMap was employed to clip the point features representing the well location with the polygon feature denoting surface geology, which is specifically identified as major fractured rock aquifers of the four self-supplied remote communities. Consequently, there has been an increase in groundwater well data of the interested fractured rock aquifers, leading to greater availability of data to support the achievement of the study goals. The integration of all these diverse existing datasets, including well data and various types of maps, enables a comprehensive assessment of groundwater resources in Iga Warta, Leigh Creek Station, Kakalpurannha, and Yappala communities.

CHAPTER FIVE RESULTS

The findings from analysis of various existing data, including groundwater well data, and hydrogeological, geological, as well as topographic maps, in the desktop study reveal the major fractured rock aquifers of the Iga Warta, Leigh Creek Station, Kakalpurannha, and Yappala communities, the amount of groundwater that can be pumped from the wells, and the quality of groundwater in each fractured rock aquifer, even though well yield and water chemistry data are very limited in certain types of aquifers.

The major aquifers specified based on existing hydrogeological data and currently active wells of the four communities as well as the total number of wells in each aquifer across the Flinders Ranges are presented in Table 5.1. Iga Warta has Wilkawillina Limestone (Ehw) as a primary aquifer. Leigh Creek Station extracts groundwater from the main aquifer named Angepena Formation (Nia), which mainly consists of shale and siltstone. Kakalpurannha exploits the fractured rock aquifer of Wonoka Formation (Nww), which is composed of shale and limestone, for the main groundwater supply, whereas Yappala has a major aquifer known as Bonney Sandstone (Npb). Even though hydrogeological data is generally more available when the area of interest is extended to include the surface boundary of the geological formation of the major fractured rock aquifers present in the Flinders Ranges, however constraints on data still exist. The Bonney Sandstone aquifer has the least number of drilled wells compared to the other three hard rock aquifers, while the highest number is found in the Wilkawillina Limestone. Furthermore, all aquifers have limited available data in the case of water chemistry.

Table 5.1 The total number of wells in each aquifer across the Flinders Ranges.

Study site	Active wells	Aquifer	Total wells across the Flinders Ranges	Depth data (wells)	Yield data (wells)	Water chemistry data (wells)	TDS and EC data (wells)
Iga Warta	6636-225	Ehw	173	168	28	9	26
Leigh Creek Station	6636-3 and 6536-422	Nia	93	79	49	13	67
Kakalpurannha	6536-4427	Nww	122	115	41	7	57
Yappala	6534-204	Npb	24	19	8	2	20
Total wells			**412**	**381**	**126**	**31**	**170**

5.1 Iga Warta

The Wilkawillina Limestone formation is found not only in the Iga Warta community but also in the other parts of the Northern Flinders Ranges (Figure 5.1). Numerous groundwater wells were drilled in this formation, and they are mostly concentrated in the northern area of the ranges.

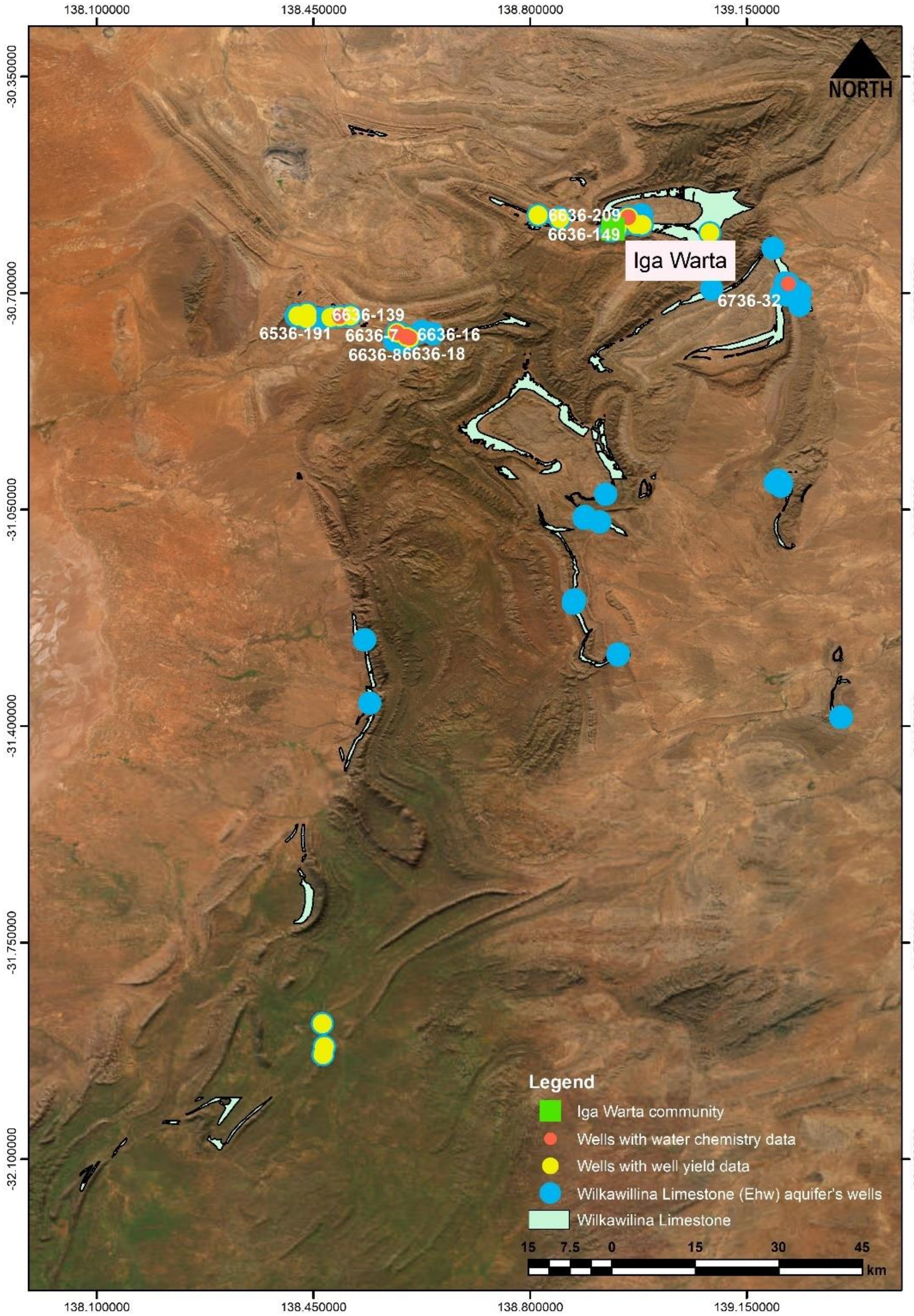

Figure 5.1 The location of groundwater wells in the Wilkawillina Limestone aquifer.

The Wilkawillina Limestone aquifer has been defined for a total number of 173 bores, including the seven wells installed in the Iga Warta area. However, only a small number of these wells have data regarding their yield and water chemistry. There are an overall number of 28 boreholes containing well yield data, and the majority of these wells are primarily found in the north of the ranges. Although, there are also a few wells in the southern region that offer this type of data. The water chemistry data is restricted to nine bores, and the location of these wells is only present in the northern area of the ranges outside the Iga Warta community.

The wells drilled in the Wilkawillina Limestone aquifer typically have significant depth. The minimum depth of a groundwater well is 1 m, while the maximum depth is 282.1 m. The mean depth is 75.5 m, calculated from the data of 168 wells that provide information on their individual depths. The water level can be found at several depths. The data gathered from 30 wells indicates that water tables vary greatly from 1.2 to 96.0 m below the surface, with an average depth of 28.8 m. The wells have a wide range of water discharge capacity, spanning from 0.19 to 65 L/sec. Additionally, the average well yield is 6.73 L/sec.

The existing groundwater analysis data reveals that the pH levels of the wells in the Wilkawillina Limestone aquifer vary between 7 and 8.6, evidenced by the pH data from nine wells. The pH level has an average value of 7.5. TDS were analysed in 26 groundwater wells and generally exceeded 1,000 mg/L. The concentration of TDS ranges from approximately 600 to nearly 6,000 mg/L, with a mean concentration of 1,782 mg/L. The water chemistry data exists only in nine wells (Appendix E), and the concentrations of commonly analysed constituents are shown in Figure 5.2. Most of the wells in this limestone aquifer have a groundwater nature with remarkable hardness levels, varying from around 550 to almost 900 mg/L. The concentration patterns of these constituents are similar in five wells, including well numbers 6636-16, 6636-18, 6636-7, 6636-8, and 6736-32, as these wells exhibit outstanding concentrations of hardness, chloride, sodium, and sulphate. An analysis was conducted on groundwater samples from a few wells to determine their alkalinity, bicarbonate, potassium, and nitrate levels. The alkalinity values from the two wells are 406 and 557 mg/L, respectively. Bicarbonate levels in the four wells range from 177 to 613 mg/L. Potassium concentration data is contained in three wells, with the values of 3,4 and 5 mg/L. Lastly, nitrate data found in three wells reveals concentrations of 0 and 11 mg/L.

5.2 Leigh Creek Station

The presence of groundwater wells in the Angepena Formation is limited to the Northern and Southern Flinders Ranges as a result of the unique appearance of this rock formation in these two particular regions (Figure 5.3). The Angepena Formation aquifer has been identified in a total of 93 bores across the Flinders Ranges. This includes two currently operational and two abandoned wells drilled in the Leigh Creek Station community. Furthermore, the distribution of these bores exhibits a higher density in the southern part of the ranges compared to the northern area. There are records of well-yield and water chemistry in 49 and 13 groundwater bores, respectively. Most wells are predominantly situated in the Southern Flinders Ranges.

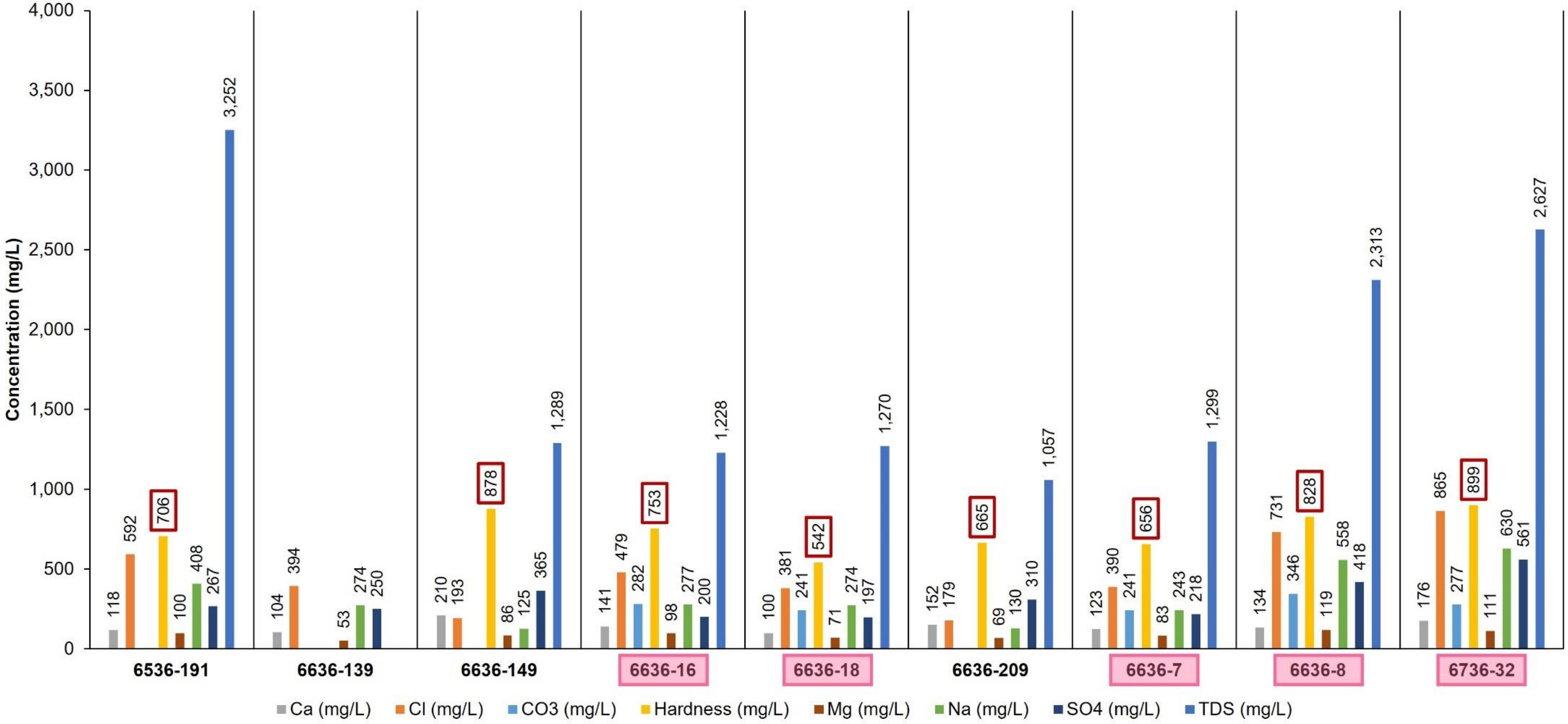

Figure 5.2 Water quality of individual well drilled in the Wilkawillina Limestone aquifer across the Flinders Ranges.

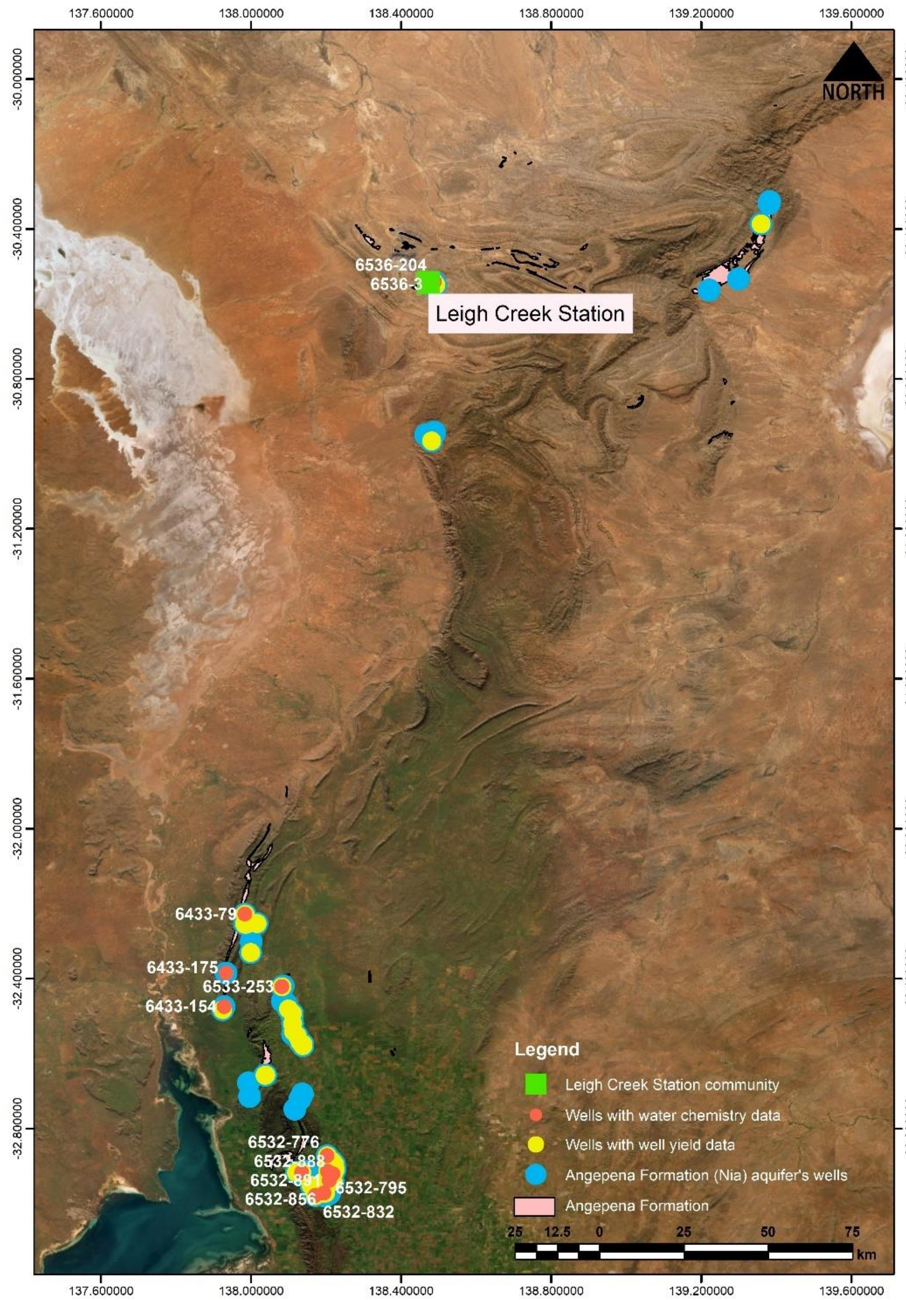

Figure 5.3 The distribution of groundwater wells drilled in the Angepena Formation.

Groundwater wells were drilled at various depths within the Angepena Formation aquifer, as evidenced by 79 wells in this aquifer. The recorded depths range from a minimum of 3.8 m to almost 201.0 m., with a mean depth of 66.5 m. The water level can be observed from shallow to great depths below the surface, with measurements ranging from 1 to 92 m. The average depth of these water tables is 22.0 m., derived from water level data of 49 wells. The wells in this aquifer typically produce a yield rate of less than 3 L/sec. However, the well yield can range from 0.01 to 14.0 L/sec, with an average rate of 1.3 L/sec.

Groundwater samples were previously taken from multiple wells in the Angepena Formation aquifer to analyse their physical and chemical quality. The pH data recorded from 46 wells indicates that groundwater in this specific aquifer has pH values ranging from 6.9 to 8.7, with a mean pH of 7.7. The TDS data present in 67 wells exhibits an extremely wide range of concentrations varying from around 400 to over 16,000 mg/L. The average concentration of TDS was calculated to be nearly 3,200 mg/L. The water chemistry data was collected from 13 wells, with only one bore located within the Leigh Creek Station community (Appendix F). The concentrations of eight characteristics commonly found in records of these 13 groundwater bores are shown in Figure 5.4. Most wells in this aquifer exhibit notable chloride levels in their groundwater. The similarity in concentration patterns of chloride, hardness, and sodium is observed in wells, 6433-175, 6632-856, 6632-888, and 6632-891. Only a few groundwater samples were collected for nitrate analysis, and the results suggested that concentrations of nitrate in groundwater were 0 and 63 mg/L. The wells drilled in this aquifer lack historical data regarding the concentration of other constituents.

5.3 Kakalpurannha

The Wonoka Formation is present over the entire Flinders Ranges in a folded ribbon-like shape, and covers over the Kakalpurannha community (Figure 5.5). A total of 118 wells were constructed in the Wonoka Formation aquifer, consisting of one operational bore and the other 16 bores located in Kakalpurannha. The wells are distributed extensively across most parts of the Flinders Ranges, excluding the central section of the ranges. The data on well yield is available for 41 wells appearing in both the northern and southern areas of the ranges. However, the information on water chemistry is only recorded in seven boreholes, mostly concentrated in the northern part of the ranges.

The wells in the Wonoka Formation aquifer typically have a depth of less than 90 m. The shallowest well discovered in this aquifer is approximately 2.5 m, whereas the deepest well has a recorded depth of 484 m. The average depth is 57.3 m, calculated from well-depth data of 115 bores. Water levels can be found in a wide range of depths, ranging from half a meter to 76 m. The mean water level is calculated from 48 wells with a result of almost 16 m. The wells drilled in this aquifer generally yield groundwater less than 2 L/sec. The wells have the capacity to discharge water at a wide range of rates, varying from 0.02 to 11.5 L/sec, with an average of 1.3 L/sec.

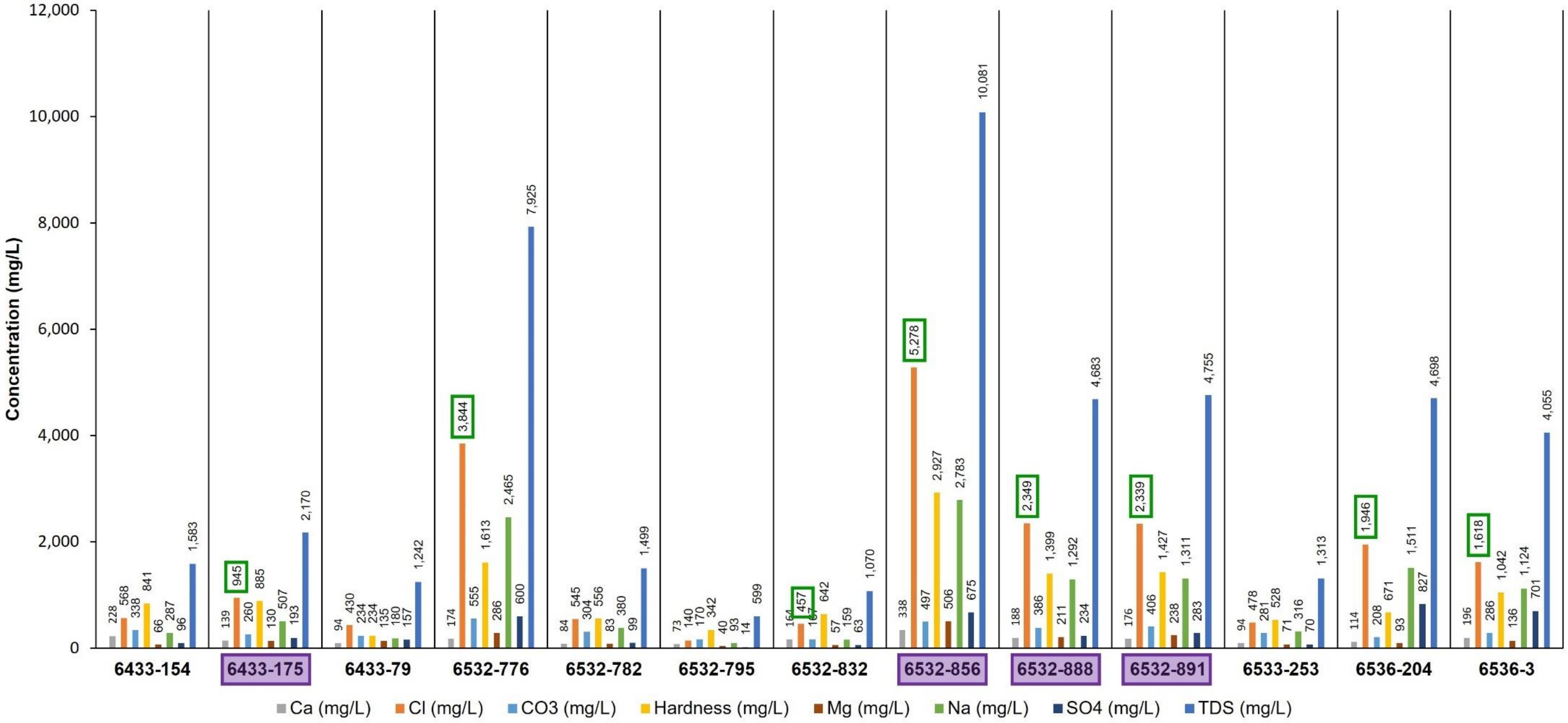

Figure 5.4 The concentration of eight constituents in groundwater from the Angepena Formation aquifer.

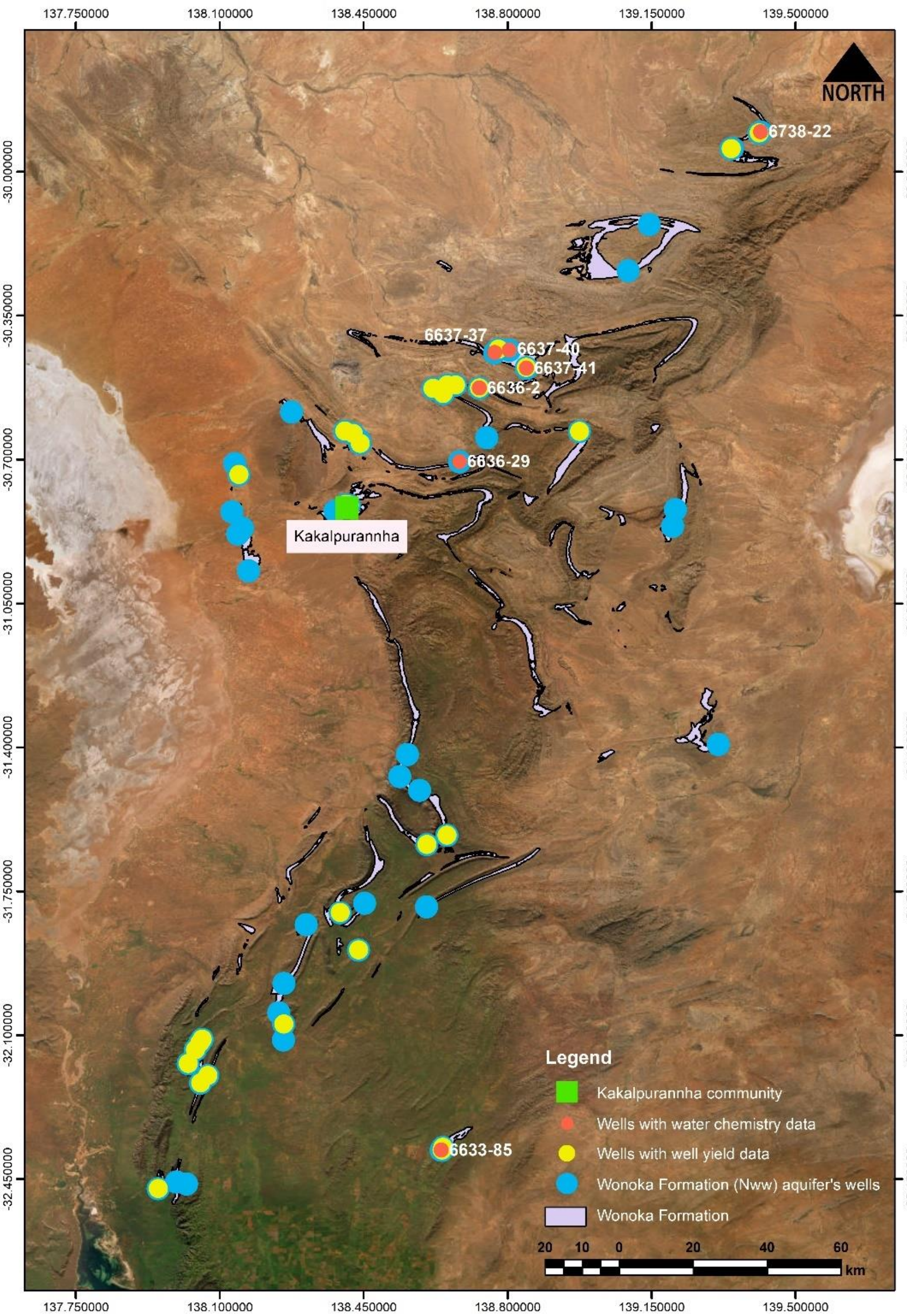

Figure 5.5 Groundwater wells extracted water from the Wonoka Formation aquifer.

The pH, TDS, and water chemistry data for the Wonoka Formation aquifer are available in varying numbers of wells. The pH data existing in 15 wells exhibits pH values ranging from 6.7 to 8.2, with an average pH of 7.3. The TDS concentrations in 26 groundwater wells were found to vary greatly, spanning from approximately 500 to over 7,000 mg/L. The mean TDS concentration across these wells is 2,420 mg/L. The water chemistry data is limited exclusively to seven wells situated outside the Kakalpurannha community (Appendix G), and Figure 5.6 displays concentrations of the eight constituents usually found in the records of these wells. Three wells have remarkable hardness concentrations, including well numbers 6633-85, 6636-29, and 6637-37. Another three wells, namely 6633-85, 6636-29, and 6637-3, are notable for their exceptionally high chloride levels. Moreover, these three wells exhibit comparable concentration patterns in outstanding levels of chloride, hardness, sodium, and sulphate. Well 6738-22 has a concentration signature that is dissimilar to those of the other wells. Nitrate concentration data exists for a single well, which has a nitrate level of 90 mg/L. No other characteristics have been recorded in any wells.

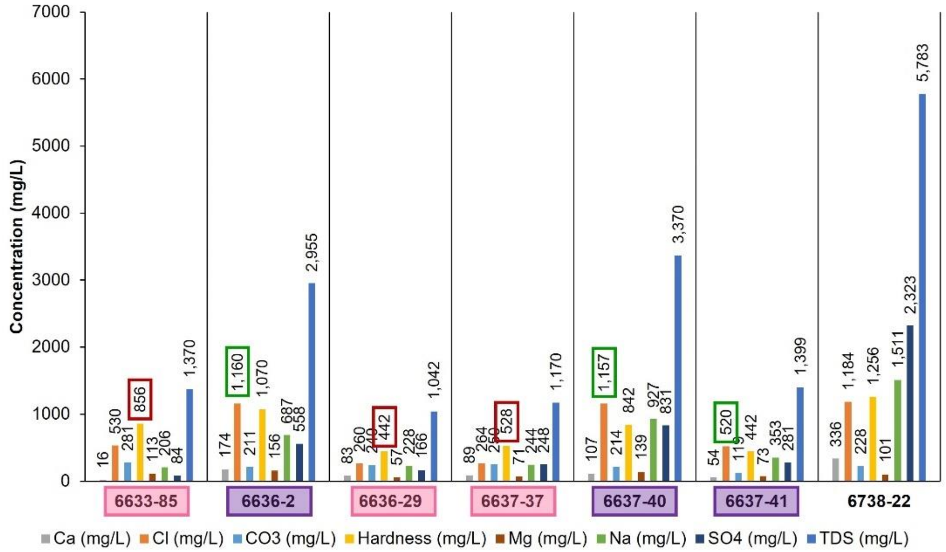

Figure 5.6 The water chemistry of seven individual wells in the Wonoka Formation aquifer.

5.4 Yappala

Bonney Sandstone formation exists in the Northern Flinders Ranges, and the boundary of this rock formation appears like a thin-folded noodle shape throughout the ranges (Figure 5.7). The number of wells drilled in the Bonney Sandstone aquifer is significantly lower in comparison to the other three aquifer formations. There are only 24 wells that exploit groundwater from this formation, and these bores are concentrated in small, dense clusters in certain areas of this part of the Flinders Ranges. Well-yield and water chemistry data is limited to a small number of wells. Well-yield data is obtained from a total of eight wells which are located in both the north and south of the ranges. In addition, water chemistry data is available only in two wells present in the north region of the range.

The groundwater wells were drilled in the Bonney Sandstone aquifer at depths, ranging from 2.3 to 196.3 m. Analysis of the depth data from 19 wells reveals that the average depth of the wells is 46 m. The water table measurement data exhibits a range of depth from shallow to deep levels beneath the ground surface, evidenced by the data from 14 wells. The minimum depth of water level is almost 2 m, while the maximum water level is recorded at 81 m, with a mean level of 22.5 m. The wells in the Bonney Sandstone aquifer typically have a very low yield rate. The lowest recorded rate is 0.25 L/sec, and the highest is 2.2 L/sec. The calculated average well yield is 0.7 L/sec.

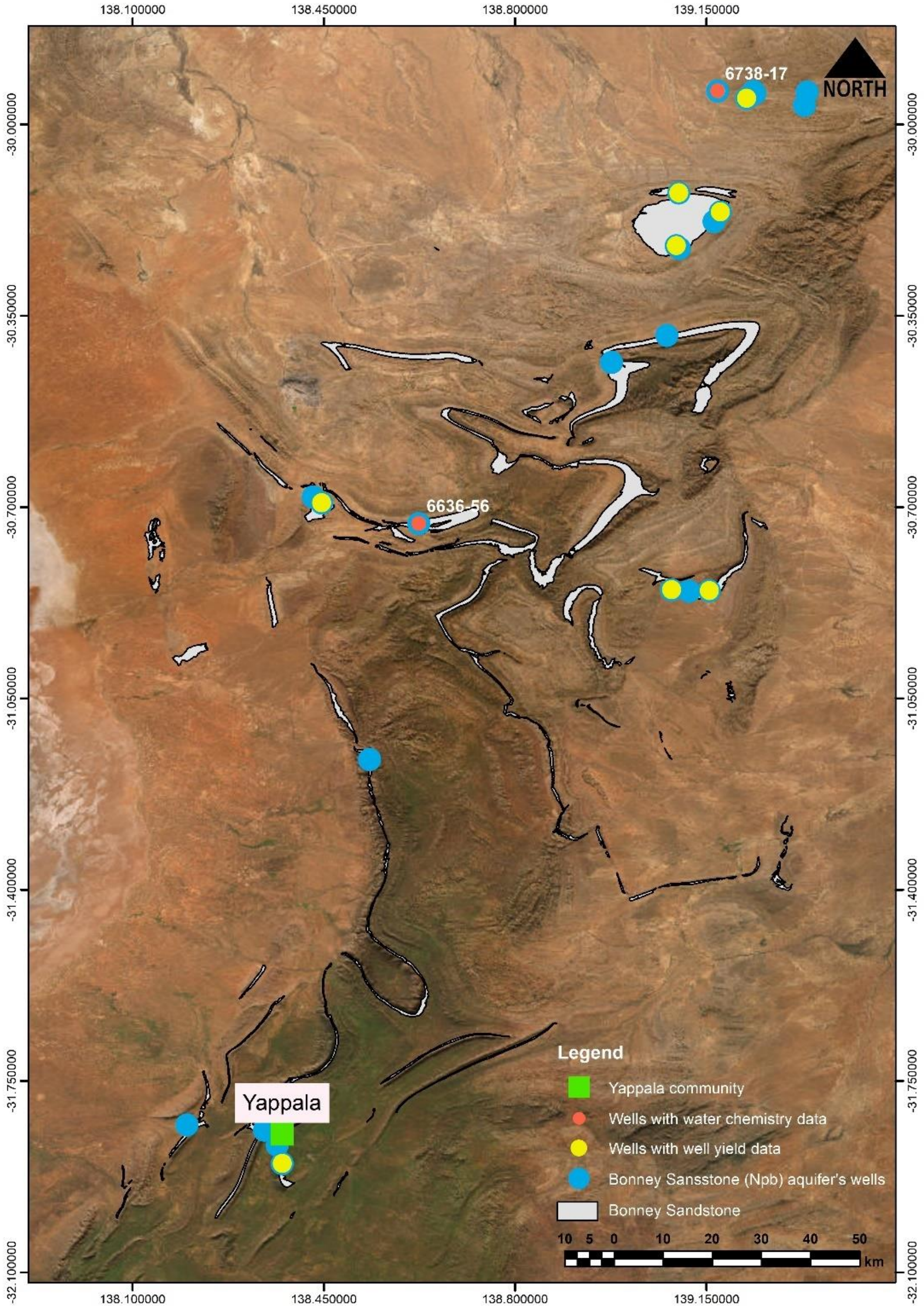

Figure 5.7 The position of the Bonney Sandstone aquifer's groundwater wells.

Water quality data for the Bonney Sandstone aquifer is only available in a minority of wells, and only a few also have water chemistry data. According to pH data found in ten bores, groundwater in this sandstone aquifer has a pH range of 6.4 to 7.9, with an average value of 7. The concentrations of TDS were measured in 20 wells, revealing levels spanning from over 1,100 to nearly 9,400 mg/L. The mean TDS concentration calculated from these wells is 3,450 mg/L. The water chemistry data is available for only two wells (Appendix H), and the composition of groundwater of these two wells based on eight frequently analysed characteristics is shown in Figure 5.8. The concentration patterns observed in the two wells, 6636-56 and 6738-17, are dissimilar. The well number 6636-56 has a notable level of chloride, whereas another well, 6738-17, has a signature of a high concentration of sulphate. Other constituents are not recorded in these two wells.

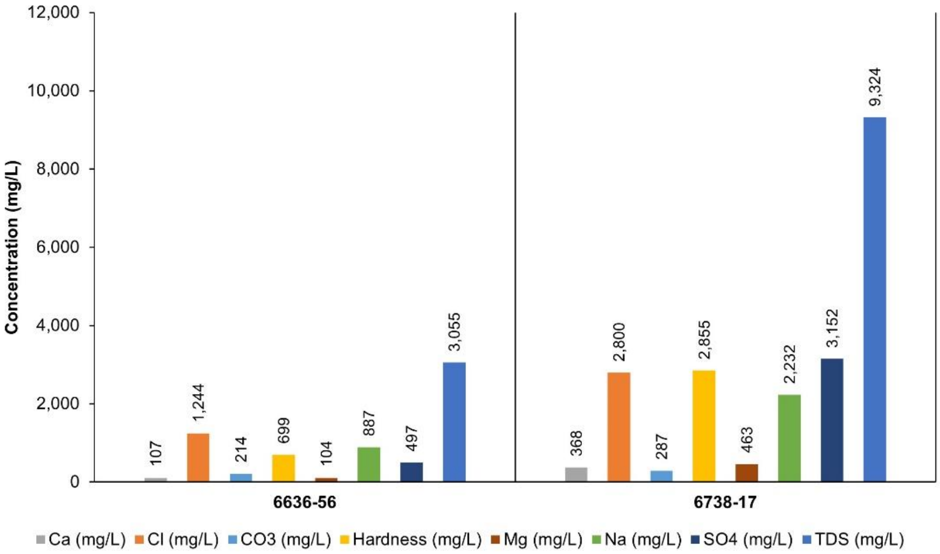

Figure 5.8 The groundwater composition of two individual wells drilled in the Bonney Sandstone aquifer.

5.5 Comparison of the four fractured rock aquifers

The four fractured rock aquifers, which are the Wilkawillina Limestone, Angepena Formation, Wonoka Formation, and Bonney Sandstone, are being compared based on their depth, water level, yield, as well as physical and chemical quality in order to identify their distinct characteristics. The results not only offer an understanding of the unique nature of each hard rock aquifer but also give helpful information for future comparison and interpretation with the fieldwork findings.

5.5.1 Groundwater well data and quantity

The depth of groundwater wells in the four unique fractured rock aquifers is generally shallow (Figure 5.9). The wells in the Wilkawillina Limestone aquifer have greater depths compared to the wells in other aquifers. Shallow wells were commonly drilled in the Wonoka Formation and the Bonney Sandstone. The median well depth can be categorised into two groups, which are greater than 50 and less than 50 m. Wilkawillina Limestone and Angepena Formation both have median depths over 50 m, with similar values of 58 m and 55 m., respectively. In contrast, the Wonoka Formation and Bonney Sandstone belong to the group with a median depth of less than 50 m, with depths of 27 m and 36 m.

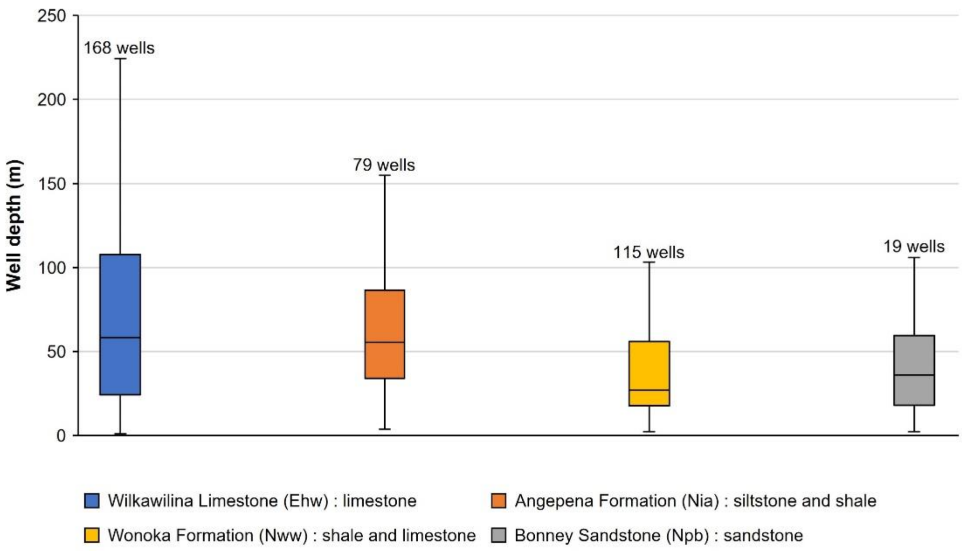

Figure 5.9 Total depth of groundwater wells in four different fractured rock aquifers.

The water level in four different rock-type aquifers can be found at depths ranging from less than one metre to over 60 m below the surface (Figure 5.10). Groundwater wells in the Bonney Sandstone aquifer have deeper water levels than the wells in other aquifers. The wells in the Wonoka Formation aquifer have comparatively shallower water tables. The water levels of the four aquifers exhibit small variations in their medians. The Wilkawillina Limestone aquifer has a median water level of 23 m, which is the greatest depth. It is followed by the Angepena Formation aquifer, which has a median water level of 19 m. The Bonney Sandstone aquifer has a median water level of 14 m, and the Wonoka Formation aquifer has the shallowest median water level at 11 m.

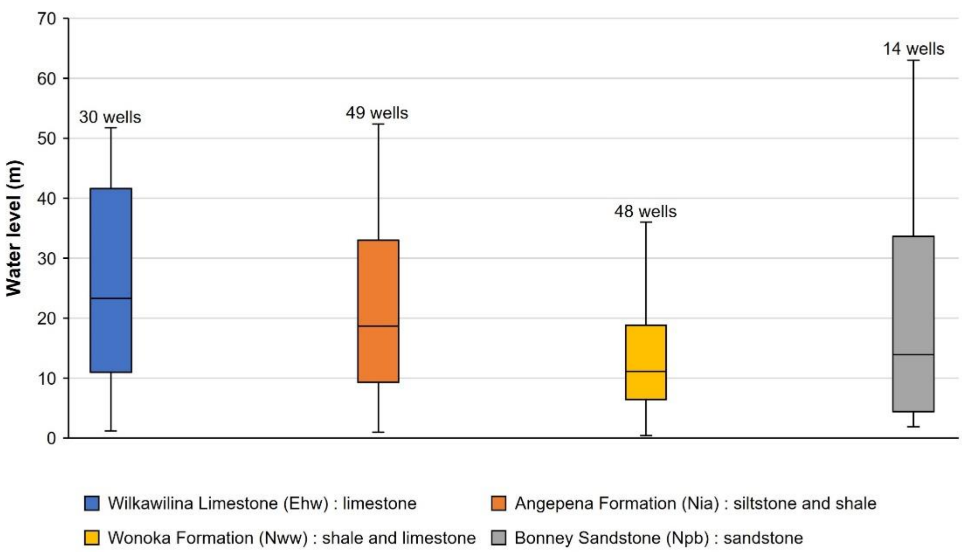

Figure 5.10 The difference in water level of four major aquifers.

A clear distinction of well yield is observed among the four fractured rock aquifers (Figure 5.11). The Wilkawillina Limestone aquifer exhibits significantly greater water yield compared to the three other aquifer types. The wells within the limestone aquifer demonstrate the capacity to discharge groundwater ranging from less than 5 to a maximum of 20 L/sec. In contrast, the wells in the Angepena Formation, the Wonoka Formation, and the Bonney Sandstone often have a well yield of less than 3 L/s. The median well yield reveals a high degree of similarity across the four rock units, with all aquifers having a median well yield of approximately 1 L/sec.

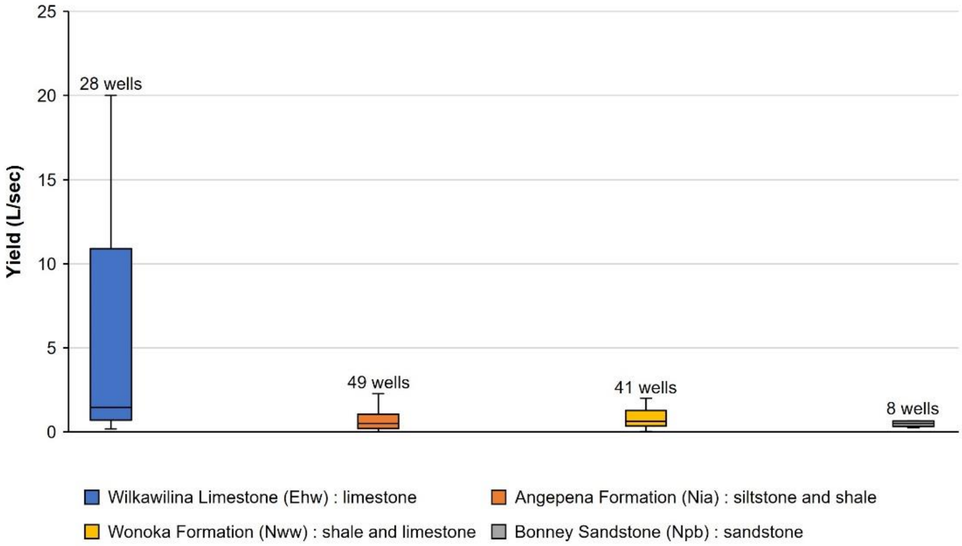

Figure 5.11 The comparison of well yield in four types of fractured rock aquifer.

The well yield of the four fractured rock aquifers has an independent variation with depth (Figure 5.12). The wells in all types of fractured rock aquifers typically yield low volumes of water with a rate of less than 5 L/sec. These low yields can be found in both shallow and deep groundwater wells across the four aquifers. High well yields are predominantly associated with wells drilled to depths exceeding 100 m within the Wilkawillina Limestone aquifer. The Angepena and Wonoga Formation aquifers also demonstrate the capacity for high groundwater production, particularly in wells drilled to depths of less than 100 m. High well yield is not observed in the sandstone aquifer.

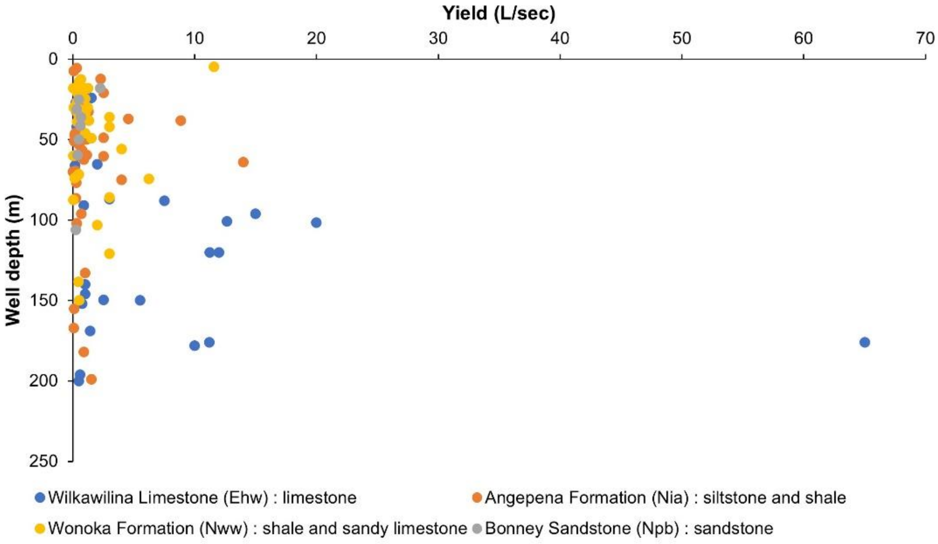

Figure 5.12 The well depth versus yield for boreholes in four fractured rock aquifers.

5.5.2 Groundwater quality

Analysis of historical data reveals that groundwater pH levels in the four fractured rock aquifers fall between 6.5 and 8.5 (Figure 5.13). Despite this similarity, slight variations in the median were observed across the different rock unit aquifers. Specifically, both the Wilkawillina Limestone and the Wonoka Formation aquifers demonstrate an identical median pH level of 7.3. The highest median of pH levels is present in the Angepena Formation, with a value of 7.7, whereas the lowest pH median value of 6.8 is observed in the Bonney Sandstone aquifer.

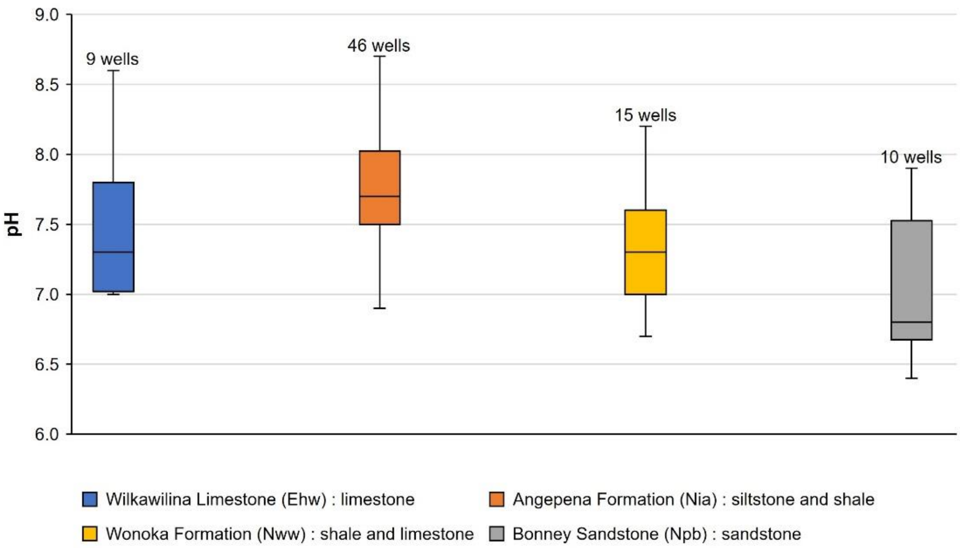

Figure 5.13 The pH levels in the groundwater of each major fractured rock aquifer.

The concentration of TDS in groundwater from all four fractured rock aquifers generally exceeds 1,000 mg/L, but high variation in TDS levels exists when comparing individual rock aquifers (Figure 5.14). Extremely high TDS concentrations are present in two aquifers, namely the Angepena and Wonoka Formations. Groundwater within the Wilkawillina Limestone aquifer contains comparatively lower levels of TDS concentration than the other aquifers. The median TDS concentration is similar in the three aquifer units, including the Angepena Formation, Wonoka Formation, and Bonney Sandstone, with respective medians of 2,369 mg/L, 2,070 mg/L, and 2,445 mg/L. Conversely, the limestone aquifer has the lowest median TDS concentration among the four aquifers, with a median value of 1,329 mg/L.

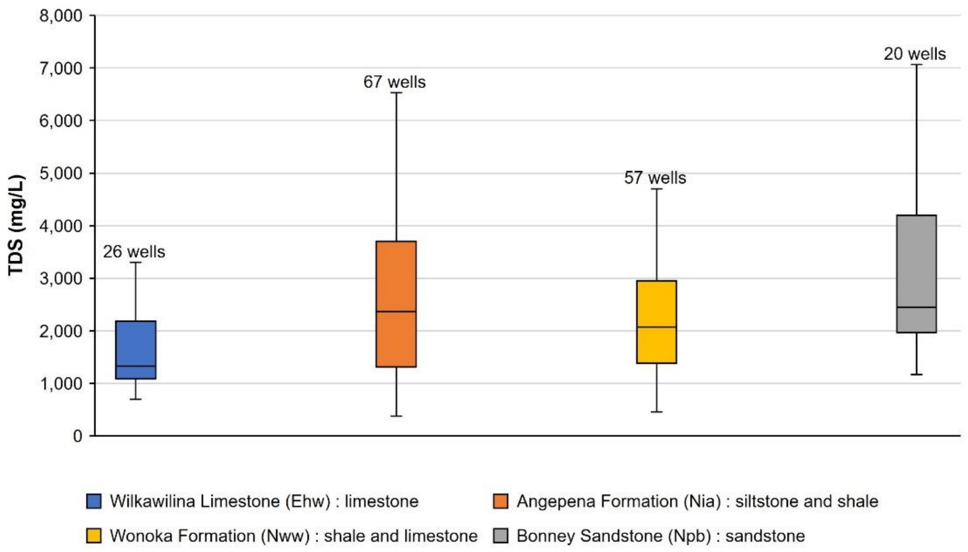

Figure 5.14 The difference between concentrations of TDS in four fractured rock aquifers.

The groundwater of four fractured rock aquifers exhibits a unique signature in water chemistry. The Wilkawillina Limestone aquifer has lower levels of physical and chemical constituents compared to the other hard rock aquifers (Figure 5.15). The concentrations of constituents in groundwater from the Wilkawillina Limestone aquifer are generally less than 1,000 mg/L, with the exception of TDS. The water quality of this limestone aquifer exhibits unique characteristics in high concentrations of hardness, chloride, and sodium. Groundwater sourced from the Angepena Formation aquifer, which mainly consists of siltstone and shale, has levels of some constituents, such as calcium, carbonate, magnesium, and sulphate, lower than 1,000 mg/L. The distinct signature of notable concentrations of chloride, sodium, and hardness are observed in groundwater from this rock unit. The groundwater quality derived from the Wonoka Formation aquifer shows concentrations below 1,000 mg/L for the constituents that paralleled those observed in the Angepena Formation aquifer. The Wonoka Formation aquifer, characterised primarily by shale and limestone, presents high sodium, hardness, and chloride. Finally, the concentration of constituents in the Bonney Sandstone aquifer typically exceeds 1,000 mg/L. The signature of groundwater in this sandstone aquifer remains ambiguous due to the scarcity of available data.

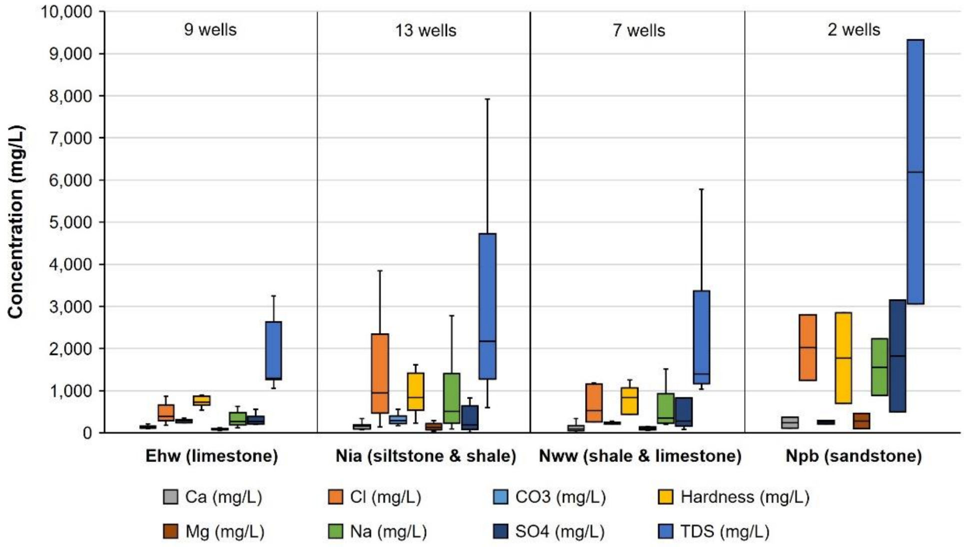

Figure 5.15 The quality of groundwater in the four fractured rock aquifers.

CHAPTER SIX DISCUSSION

The distinct characteristics in groundwater quantity and quality of the four fractured rock aquifers located at the Flinders Ranges, namely the Wilkawillina Limestone, Angepena Formation, Wonoka Formation, and Bonney Sandstone, are likely to relate to the lithology of these formations. The excessive concentration of minerals in groundwater compared with the Australian Drinking Water Guidelines seems to have a connection with the climatic conditions of the area. However, a limitation on available data regarding groundwater wells and water chemistry obstructs the ability to provide comprehensive answers to the study questions.

6.1 Water quantity and quality with lithology

The four fractured rock aquifers in the Flinders Ranges have varying groundwater production capacities due to their lithology. The rock formations in these ranges are dated from the early Cambrian in the Palaeozoic to Marinoan in the Proterozoic and have undergone numerous significant tectonic events over geological timescales, as evidenced by the presence of geological structures such as anticlines, synclines, and faults throughout the areas. Consequently, secondary porosity, comprising voids, fractures, and fissures, has developed in the rock formations and serves as favourable reservoirs for groundwater storage. Therefore, the existence of larger voids and interconnected fractures within the rock formations correlates with the increased yield potential of the fractured rock aquifers.

The Wilkawillina Limestone aquifer is likely to provide larger quantities of groundwater than the other aquifers because large voids easily form in this massive limestone. Calcite is the primary mineral composition of limestone, and its chemical interaction with rainwater during infiltration leads to the dissolution and development of voids to hold groundwater. Thus, numerous wells within this aquifer have significant groundwater yield rates exceeding 10 L/sec. The Angepena and Wonoka Formation aquifers demonstrate the capacity to yield groundwater at comparable volumes, typically below 3 L/sec. However, a small number of wells from these two aquifers have been observed to produce groundwater at rates of 10 L/sec. The Angepena Formation primarily comprises shale and siltstone lithologies, while the Wonoka Formation is characterised by shale and limestone as its predominant rock types. Shale and siltstone generally do not exhibit large space development since their mineral compositions are resistant to dissolution by water; similarly, limestone in the Wonoka Formation is mixed with sand, which restricts its ability to create large voids for storing groundwater. Hence, low-productivity wells are generally found in these two aquifers. Lastly, the Bonney Sandstone aquifer has the lowest well yield among the four aquifers, typically yielding less than 1 L/sec. Sandstone has high resistance against erosion and weathering processes. As a result, the sandstone aquifer is unsuitable for groundwater storage because of its limited capacity in this regard.

Lithology also plays an important role in the unique characteristics of groundwater quality in the four fractured rock aquifers. The distinguished hardness levels observed in groundwater from the Wilkawillina Limestone and the Wonoka Formation aquifers may be associated with the limestone. This connection arises from the dissolution of calcite or calcium carbonate in limestone, which can elevate the hardness levels in groundwater. Conversely, the high content of chloride and sodium in these two aquifers appears unrelated to this limestone unit. A pronounced presence of chloride, hardness, and sodium in the Angepena Formation aquifer does not appear to be directly influenced by the lithology of this aquifer, which consists mainly of shale and siltstone. The signature groundwater quality of the Bonney Sandstone remains unknown due to limited water chemistry data. In addition, the introduction of lithologically unrelated constituents in the groundwater may occur from mineral uptake during water infiltration to aquifers through fractures in rocks.

6.2 Water quality and Australian Drinking Water Guidelines

The water quality data of the four major fractured rock aquifers across the Flinders Ranges records the concentrations of some constituents specified in the Australian Drinking Water Guidelines. These constituents include nitrate, chloride, hardness, sodium, sulphate, Total Dissolved Solids (TDS), and pH. Nitrate is the only chemical that is considered harmful and can cause health problems in humans, while the remaining constituents are categorised within a group of aesthetic parameters. The levels of nitrate exceeding the guidelines' maximum limit of 50 mg/L were detected in two wells drilled in the Angepena Formation (Nia) and Wonoka Formation (Nww) aquifers, with concentrations of 63 and 90 mg/L, respectively. The chloride, hardness, sodium, sulphate, and TDS concentrations are generally higher than the maximum limits set in the drinking water guidelines in groundwater from all aquifers (Figure 6.1 (a)-(e)). Conversely, pH levels in the four aquifers typically remain within the permissible range of 6.5 and 8.5, as seen in Figure 6.1 (f).

Groundwater sourced from the four fractured rock aquifers has poor quality, proving it unsuitable for human consumption due to its failure to meet the established drinking water quality standard. High levels of nitrate in groundwater are a matter of concern as nitrate has the ability to convert to nitrite through a reduction process. Nitrite has a significant biological impact on people by oxidising normal haemoglobin to methaemoglobin, which impairs the transport of oxygen to tissues - a condition known as methaemoglobinaemia (NHMRC & NRMMC 2011). Excessive concentrations of chloride, hardness, sodium, sulphate, and TDS are not directly associated with adverse effects on human health. However, they can offer unpleasant sensory experiences and cause serious damage to household infrastructure and equipment. According to the Australian Drinking Water Guidelines (NHMRC & NRMMC 2011), high content of chloride, hardness, and TDS potentially induce corrosion and formation of excessive scaling in plumbing systems, fittings, and domestic appliances. Similarly, heightened concentrations of sodium and sulphate may contribute to distinct taste characteristics of groundwater.

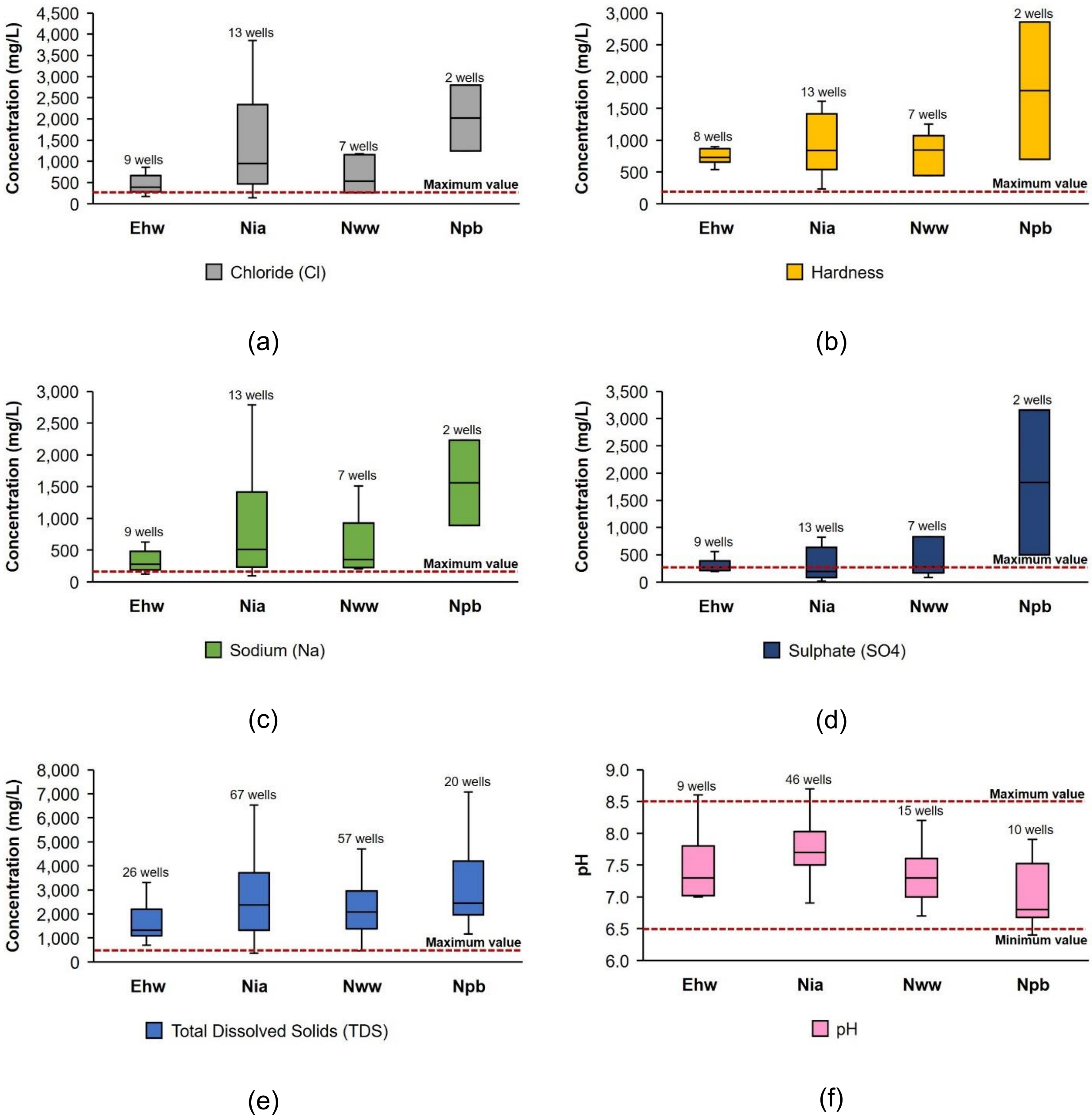

Figure 6.1 (a)-(f) The comparison of individual constituents in groundwater from the four aquifers with the Australian Drinking Water Guidelines.

Poor groundwater quality across all four fractured rock aquifers may be attributed to climate factors. The higher topographic regions of the Flinders Ranges serve as groundwater recharge zones where precipitation infiltrates the aquifers via fractures in the rock formations. Groundwater in recharge areas often exhibits good quality water, characterised by low concentrations of the most common ions and salts from the soil and bedrock material through which it travels, making it appropriate for both potable and non-potable uses. Since the Flinders Ranges are in the arid and semi-arid regions of South Australia, the amount of rainfall varies greatly from year to year, with an average annual rate of 250 mm. In addition, the high temperatures in the regions lead to high levels of evapotranspiration. This means that a very limited volume of rainfall can infiltrate these fractured rock aquifers to dilute the high mineral concentration in groundwater that occurs during a chemical exchange process when water travels through fractures in rocks. As a result, groundwater originating from hard rock aquifers in these areas has excessive mineral content and is of poorer water quality.

The groundwater in the communities of Iga Warta, Leigh Creek Station, Kakalpurannha, and Yappala requires treatment before consumption as it contains elevated concentrations of nitrate, chloride, hardness, sodium, sulphate, and TDS, over the limit specified in the Australian Drinking Water Guidelines. According to the report conducted by Doble et al. (2023) on remote communities in Australia, various water treatment technologies are suitable for improving poor-quality groundwater to acceptable standards in small communities. These technologies include ultraviolet (UV) disinfection, filtration systems, reverse osmosis systems, ion exchange systems, and solar distillation systems. Thus, small-scale reverse osmosis and ion exchange systems could be the most suitable water treatment techniques for the four communities since these two methods are effective in eliminating the chemicals which exceed the levels specified in the guidelines. However, it is crucial to consider maintenance, wastewater from the treatment process, and water losses while determining appropriate treatment options.

6.3 Limitation

The limited available datasets on groundwater wells and water chemistry made it difficult to accurately assess both the quantity and quality of the groundwater in each of the four fractured rock aquifers. The assessment of the water quality in each fractured rock aquifer is based on historical data, which may miss key measurements. Only hardness, TDS, and pH are provided for physical quality. Chemical quality analysis was performed on specific parameters; therefore, water type cannot be determined by the Piper Diagram. A full chemical analysis is required to identify other concerned constituents present in groundwater. For example, the Bonney Sandstone aquifer only had a very small number of wells.

The well yield data of the four aquifers determined using the airlifting method does not reflect the total capacity of wells, and the calculation for the hydraulic properties of the aquifers is unachievable due to lacking data from pumping tests. The absence of new data from hydraulic tests prevents the opportunity to determine the current quantity of groundwater that can be pumped from each aquifer, as well as a chance to calculate the hydraulic properties of the aquifers. A lack of geophysical data obtained from field survey results in an uncertain understanding regarding the extent of the aquifer in each study community, as well as the depth and location for future drilling of groundwater wells. A lack of water quality analysis data constrains the ability to evaluate the current physical, chemical, and microbial quality of groundwater within the four aquifers. Moreover, it is impossible to make a comparison between the findings obtained from historical groundwater data and field data.

CHAPTER SEVEN CONCLUSIONS AND RECOMMENDATIONS

Four self-supplied remote communities located in the Northern Flinders Ranges have different fractured rock aquifer units. The findings from the analysis of existing data collected across the Flinders Ranges during the desktop study indicate that these four hard rock aquifers have the capacity to produce groundwater in varying quantities, suggesting potential for future development. Groundwater from each fractured rock aquifer exhibits unique water chemistry characteristics, and its quality fails to align with acceptable levels outlined in the Australian Drinking Water Guidelines. Therefore, groundwater from all four aquifers is unsuitable for human consumption; however, it remains suitable for non-potable purposes such as household uses, watering plants, and supporting livestock.

Iga Warta is characterised by the Wilkawillina Limestone (Ehw) as its primary aquifer, which is mainly composed of massive and clean limestone. This fractured rock aquifer generally yields a high volume of groundwater and has a significant well depth. The groundwater exhibits a signature of pronounced hardness, chloride, and sodium. It also contains exceeding concentrations of many constituents defined in the drinking water standard, including chloride, hardness, sodium, sulphate, and Total Dissolved Solids (TDS). Thus, groundwater sourced from the Wilkiwillina Limestone aquifer is of poor quality and not recommended for potable usage.

The primary aquifer at Leigh Creek Station is the Angepena Formation (Nia), consisting mainly of siltstone and shale. A low yield of groundwater is generally expected from this aquifer. However, a significant volume is possible to extract under certain conditions. This fractured rock aquifer typically has shallow well depths and displays unique characteristics, including high contents of chloride, hardness, and sodium in the groundwater. The quality of groundwater is unsafe for consumption due to the concentrations over the limit set by the Australian Drinking Water Guidelines for chloride, hardness, sodium, sulphate, TDS, and nitrate.

Kakalpurannha is situated within the Wonoka Formation (Nww) area, which is defined as a principal aquifer predominantly composed of shale and limestone. The aquifer typically exhibits a low yield of groundwater production. Nevertheless, the Wonoka Formation aquifer presents a potential for achieving a high discharge rate. The depth of wells in this aquifer is typically shallow. The groundwater in this aquifer has high sodium, hardness, and chloride. Moreover, its quality is classified as unsuitable for consumption as the concentrations of chloride, hardness, sodium, sulphate, TDS, and nitrate exceed the standard specified in the drinking water guidelines.

Yappala extracts groundwater from the major aquifer formation known as Bonney Sandstone (Npb), which mainly consists of sandstone. This sandstone aquifer has the capacity to yield groundwater at a low rate, with the well depth being generally shallow. The determination of a groundwater quality signature is not possible due to the scarcity of available water chemistry data. Furthermore, the groundwater quality of this aquifer falls below the standard outlined in the Australian Drinking Water Guidelines due to high levels of chloride, hardness, sodium, sulphate, and TDS detected in groundwater. As a consequence, it is unsuitable for human consumption.

Although existing data can reveal the groundwater quantity and quality of the four fractured-rock aquifers, fieldwork is necessary to obtain recent data from hydraulic tests, geophysical surveys, and groundwater sampling and analysis. Residents of Iga Warta, Leigh Creek Station, Kakalpurannha, and Yappala should be advised of the negative consequences associated with using groundwater with high mineral content. This includes the risk of financial losses incurred for the routine maintenance of pipelines and household equipment due to corrosion and the formation of excessive scaling. The removal of excessive concentrations of chloride, hardness, sodium, sulphate, TDS, and nitrate in groundwater is required to ensure its safety and compliance with the drinking standard when utilised for consumption; therefore, the installation of water treatment plants is necessary across all communities. Moreover, it is essential to treat groundwater for domestic purposes to prevent damage from calcium accumulation on household equipment, minimise maintenance expenses, and enhance the overall user experience.

BIBLIOGRAPHY

Adelana, S M A 2009, 'Monitoring groundwater resources in Sub-Saharan Africa: issues and challenges', *Groundwater and Climate in Africa*, p. 104.

Amini, A, Kim, Y, Zhang, J, Boyer, T & Zhang, Q 2015, 'Environmental and economic sustainability of ion exchange drinking water treatment for organics removal', *Journal of Cleaner Production*, vol. 104, p. 413, viewed 12 March 2024, <http://dx.doi.org/10.1016/j.jclepro.2015.05.056>.

Australian Government Bureau of Meteorology 2023, *Australian climate change site networks*, Australian Government Bureau of Meteorology, viewed 2 November 2023, <http://www.bom.gov.au/climate/change/hqsites/>.

Australian Government Bureau of Meteorology 2023, *Climate Data Online*, Australian Government Bureau of Meteorology, viewed 2 November 2023, <http://www.bom.gov.au/climate/data/>.

Australian Government Bureau of Meteorology 2006, *Climate zones based on temperature and humidity*, Australian Government Bureau of Meteorology, viewed 2 November 2023, <http://www.bom.gov.au/climate/maps/averages/climate-classification/>.

Balasooriya, B M J K, Rajapakse, J & Gallage, C 2023, 'A review of drinking water quality in remote and indigenous communities in rich nations with special emphasis on Australia', *Science of the Total Environment*, vol. 903, p. 5-8, viewed 25 October 2023, <https://doi.org/10.1016/j.scitotenv.2023.166559>.

Barnett, S, Harrington, N, Cook, P & Simmons, C T 2021, 'Groundwater in Australia: Occurrence and Management Issues', in Rinaudo, J D (ed) *Sustainable Groundwater Management*, Springer Nature Switzerland, pp. 109-112.

Booth, B & Mitchell, A 2001, 'Exploring ArcCatalog and ArcMap', in *Getting Started with ArcGIS*, ESRI, USA.

California Department of Water Resources 2004, *Ground Water in Fractured Hard Rock*, The Resources Agency, State of California, USA.

Cetrulo, T B, Marques, R C, Malheiros, T F & Cetrulo, N M 2017, 'Monitoring inequality in water access: Challenges for the 2023 Agenda for Sustainable Development', *Science of the Environment*, vol. 727, p. 2, viewed 28 February 2024, <https://doi.org/10.1016/j.scitotenv.2020.138746>.

Cobbing, J & Dochartaigh, B É Ó 2007, 'Hydrofracturing water boreholes in hard rock aquifer in Scotland', *Quaternary Journal of Engineering Geology and Hydrogeology*, vol. 40, pp. 181-186.

Collivignarelli, M C, Abbà, A, Benigna, I, Sorlini, S & Torretta, V 2018, ‘Overview of the Main Disinfection Processes for Wastewater and Drinking Water Treatment Plants’, *Sustainability*, vol. 10, no. 86, p. 2, viewed 11 March 2024, doi:10.3390/su10010086.

Cook, P G 2003, ‘Basic principles’, *A guide to regional groundwater flow in fractured rock aquifers*, Seaview Press, South Australia.

Cromar, N & Willis, E 2022, *Basic Level of Service: Setting for long-term water security in remote South Australia*, Cromar Consulting, Australia.

Curto, D, Franzitta, V & Guercio, A 2021, ‘A Review of the Water Desalination Technologies’, *Applied Sciences*, vol. 11, no. 670, p. 2, viewed 12 March 2024, <https://doi.org/10.3390/app11020670>.

Custodio, E 2007, ‘Groundwater in volcanic hard rocks’, in Krásný, J & Sharp, J M (eds.) *Fractured Rock Hydrogeology: Selected papers from the Groundwater in Fractured Rocks International Conference, Prague, 2003*, Taylor & Francis Group, London, UK, p. 99.

Dar, F A, Perrin, J, Ahmed, S & Narayana, A C 2014, ‘Review: Carbonate aquifers and future perspectives of karst hydrogeology in India’, *Hydrogeology Journal*, viewed 8 May 2024, doi 10.1007/s10040-014-1151-z.

Davies, J & Holcombe, S 2009, ‘Desert knowledge: integrating knowledge and development in arid and semi-arid drylands’, *GeoJournal*, viewed 2 March 2024, doi: 10.1007/s10708-009-9279-4.

Department for Environment and Water 2024, *Stocktake and Water Security Assessment for Self-Supplied Remote Communities: DEW report 2024/3*, Department for Environment and Water, Government of South Australia, Adelaide.

Department for Environment and Water n.d., *WaterConnect: Groundwater data*, Government of South Australia, viewed 5 October 2023, <https://www.waterconnect.sa.gov.au/Systems/GD/Pages/Default.aspx>.

Department of Mines 1973, *Geological Atlas 1:250,000 Series, COPLEY*, Geological Survey of South Australia, Adelaide.

Department of Primary Industries and Resources 1999, *Geological Atlas 1:250,000 Series, PARACHILNA*, Geological Survey of South Australia, Adelaide.

Doble, R D, London, A, Horner, N, Thiruvenkatachari, R, Priestley, S & O’Brien, G 2023, *Water quality review and treatment technology framework for remote community water supply*, CSIRO, Australia, viewed 25 October 2023, <https://doi.org/10.25919/dwgm-re91>.

Dockery, M & Lovell, J 2016, ‘Far Removed: An Insight into the Labour Markets of Remote Communities in Central Australia’, *Australian Journal of Labour Economics*, vol. 19, no. 3, pp. 147-148.

Dyson, I A 2009, *Geological investigation of potential aquifers in the Nepabunna area: A report for the Department for Water, Land and Biodiversity Conservation*, South Australia.

ESRI 2021, *ArcMap Clip*, ESRI, viewed 26 May 2024, <https://desktop.arcgis.com/en/arcmap/latest/tools/analysis-toolbox/clip.htm>

Etikala, B, Adimalla, N, Madhav, S, Somagouni, S G & Kumar, P L K K 2021, ‘Salinity Problems in Groundwater and Management Strategies in Arid and Semi-arid Regions’, *Groundwater Geochemistry: Pollution and Remediation Methods*, vol. 1, p. 42, viewed 29 February 2024, doi: 10.1002/9781119709732.ch3.

Fenta, M C, Anteneh, Z L, Szanyi, J & Walker, D 2020, ‘Hydrogeological framework of the volcanic aquifers and groundwater quality in Dangila Town and the surrounding area, Northwest Ethiopia’, *Groundwater for Sustainable Development*, vol. 11, p. 1.

Fernandes, A J, Rouleau, A & Vargas Jr, E A 2023, *Structural Geology Applied to Fractured Aquifer Characterization*, The Groundwater Project, Guelph, Ontario, Canada, <https://doi.org/10.21083/978-1-77470-009-9h>

Fildes, S G, Clark, I F, Somaratne, N M & Ashman, G 2020, ‘Mapping groundwater potential zones using remote sensing and geographical information systems in a fractured rock setting, Southern Flinders Ranges, South Australia, *Journal of Earth System Sciences*, vol. 129, no. 160, pp. 1-25, viewed 3 October 2023, <https://doi.org/10.1007/s12040-020-01420-1>.

Fitts, C R 2013, *Groundwater Science*, Elsevier, Waltham, USA.

Fromhold, T A & Wallace, W M 2011, ‘Nature and significance of the Neoproterozoic Sturtian-Marinoan Boundary, Northern Adelaide Geosyncline, South Australia’, *Australian Journal of Earth Sciences*, vol. 58, pp. 605-606.

Gelete, G, Gokcekus, H, Ozsahin, D U, Uzun, B & Gichamo, T 2020, ‘Evaluating disinfection techniques of water treatment’, *Desalination and Water Treatment*, vol. 177, p. 409, viewed 11 March 2024, doi: 10.5004/dwt.2020.25070.

Geological Survey of South Australia 1973, *Copley 1:250,000 Geological Atlas Series Sheet SH 54-9 Zones 5 & 6*, Department of Mines, Adelaide, Australia.

Geological Survey of South Australia 2022, *100K Geology - linear structures*, the Government of South Australia, viewed 19 October 2023, <https://catalog.sarig.sa.gov.au/geonetwork/srv/api/records/50b5a79c-9764-414e-b28d-548dbe006cb3>.

Geological Survey of South Australia 2022, *100K Geology - surface geology*, the Government of South Australia, viewed 24 September 2023, <https://catalog.sarig.sa.gov.au/geonetwork/srv/api/records/e27f9a25-b749-4dba-bfb3-ca90baf04d79>.

Geoscience Australia 2023, *Copley SH5409 1:250,000 AUSTopo - Australian Digital Topographic Map Series*, Geoscience Australia, Canberra, Australia, viewed 18 October 2023, <https://dx.doi.org/10.26186/148133>.

Geoscience Australia 2023, *Fractured rocks*, Australian Government Geoscience Australia Canberra, viewed 8 March 2024, <https://www.ga.gov.au/scientific-topics/water/groundwater/groundwater-in-australia/fractured-rocks>.

Geoscience Australia 2023, *Groundwater quality*, Australian Government Geoscience Australia Canberra, viewed 9 March 2024, <https://www.ga.gov.au/scientific-topics/water/groundwater/understanding-groundwater-resources/groundwater-quality>.

Geoscience Australia 2023, *Parachilna SH5413 1:250,000 AUSTopo - Australian Digital Topographic Map Series*, Geoscience Australia, Canberra, Australia, viewed 18 October 2023, <https://dx.doi.org/10.26186/148385>.

Gehling, J G & Droser, M L 2012, 'Ediacaran stratigraphy and the biota of the Adelaide Geosyncline, South Australia', *Episodes*, vol. 35, no. 1, pp. 238-240.

Goldscheider, N, Chen, Z, Auler, A S, Bakalowicz, M, Broda, S, Drew, D, Hartmann, J, Jiang, G, Moosdorf, N, Stevanovic, Z & Veni, G 2020, 'Global distribution of carbonate rocks and karst water resources', *Hydrogeology Journal*, viewed 8 May 2024, https://doi.org/10.1007/s10040-020-02139-5.

Grey-Gardner, R 2008, *Remote Community Water Management*, Desert Knowledge Cooperative Research Centre, Alice Springs, Australia.

Gustafson, G & Krásný, J 1994, 'Crystalline rock aquifers: their occurrence, use and importance', *Applied Hydrogeology*, vol. 2, p. 65.

Han, Z, Ramasamy, J, Lee, Y, He, J, Wang H, Cheng, Y, Dong, H & Ni, Z 2013, 'Asian Transboundary Aquifers Inventory and Mapping', *Journal of Groundwater Science and Engineering*, <https://www.researchgate.net/publication/345717784>.

Hardy, D, Cubillo, F, Han, M & Li, H 2015, *Alternative Water Resources: A Review of Concepts, Solutions and Experiences*, The International Water Association, The Hague, The Netherlands, viewed 12 March 2024.

Harrington, N & Cook, P 2014, *Groundwater in Australia*, National Centre for Groundwater Research and Training, Adelaide, Australia.

Harter, T 2003, 'Groundwater Quality and Groundwater Pollution', *Agriculture and Natural Resources*, viewed 15 March 2024, <https://doi.org/10.3733/ucanr.8084>.

Jayakumar, R, Han, Z, Liu, K & Duan X 2009, 'Transboundary Aquifer of Asia', *UNESCO Chair Workshop on International Strategy for Sustainable Groundwater Management: Transboundary Aquifers and Integrated Watershed Management*, University of Tsukuba, Tsukuba City, Japan, 6 October 2009.

Kernen, R A, Giles, K A, Poe, P L, Gannaway Dalton, C E, Rowan, M G, Fiduk, J C & Hearon, T E 2019, 'Origin of the Neoproterozoic rim dolomite as lateral carbonate caprock, Patawarta salt sheet, Flinders Ranges, South Australia', *Australian Journal of Earth Sciences*, vol. 67, No. 6, p. 820.

Krásný, J & Sharp, J M 2007, '*Groundwater in Fractured Rocks: Selected papers from the Groundwater in Fractured Rocks International Conference, Prague, 2003*, Taylor & Francis Group, London, UK.

Krásný, J, Sharp, J M, Jr & Troeger, U 2014, 'IHA Commission on Hardrock Hydrogeology (HyRoc): Past and present activities, future possibilities', in Sharp J M & Jr (ed.) *Fractured Rock Hydrogeology*, Taylor & Francis Group, London, UK, p. 1.

Lachassagne, P, Dewandel, B & Wyns, R 2014, 'The conceptual model of weathered hard rock aquifers and its practical applications', in Sharp, J M (ed.) *Fractured Rock Hydrogeology*, Taylor & Francis Group, Florida, USA, p. 14.

Langsford, N R & Jago, J B 2023, 'Lower Cambrian volcanism in the Hawker Group and the Billy Creek Formation, Arrowie Basin, Flinders Ranges, South Australia', *Australian Journal of Earth Sciences*, vol. 70, No. 4, p. 479.

Lee, E, Jayakumar, R, Shrestha, S & Han, Z 2018, 'Assessment of transboundary aquifer resources in Asia: Status and progress towards sustainable groundwater management', *Journal of Hydrology: Regional Studies*, vol. 20, p. 104.

MacDonald, A M & Davies, J 2000, '*A brief review of groundwater for rural water supply in sub-Saharan Africa: BGS Technical Report WC/00/33*', British Geological Survey.

MacDonald, A M, Davies, J & Dochartaigh, B È Ò 2002, '*Simple methods for assessing groundwater resources in low permeability areas of Africa: Commissioned Report CR/01/168N*', British Geological Survey.

Martínez-Santos, P 2017, 'Does 91% of the world's population really have "sustainable access to safe drinking water?"', *International Journal of Water Resources Development*, p. 1, viewed 27 February 2024, doi: 10.1080/07900627.2017.1298517.

Masiyandima, M & Giordano, M F 2007, 'Sub-Saharan Africa: Opportunistic Exploitation', *The Agricultural Groundwater Revolution: Opportunities and Threats to Development*, <https://cabidigitallibrary.org by 2001:8003:a0aa:e001:2499:5ff0:702f:18bc>.

NHMRC & NRMMC 2011, *Australian Drinking Water Guidelines Paper 6 National Water Quality Management Strategy: Version 3.8 Updated September 2022*, National Health and Medical Research Council, National Resource Management Ministerial Council, Commonwealth of Australia, Canberra.

NUDLC 2020, *Minimum Construction Requirements for Water Bores in Australia: Fourth Edition*, National Uniform Drillers Licensing Committee, Australia.

Odling, N E & Roden, J E 1997, 'Contaminant transport in fractured rocks with significant matrix permeability, using natural fracture geometries', *Journal of Contaminant Hydrology*, vol. 27, no. 3, pp. 147-148.

Ofterdinger, U, Macdonald, A M, Comte, J -C & Young, M E 2024, *Groundwater in fractured bedrock environments: managing catchment and subsurface resources - an introduction*, The Geological Society of London, https://doi.org/10.1144/SP479-2018-170.

O'Connell, B, Wallace, M W, Hood, A v S, Lechte, M A & Planavsky, N J 2019, 'Iron-rich carbonate tidal deposits, Angepena Formation, South Australia: A redox-stratified Cryogenian Basin', *Precambrian Research*, vol. 342, p. 10, viewed 25 March 2024, <https://doi.org/10.1016/j.precamres.2020.105668>

Parashar, R & Reeves, D M 2017, 'Groundwater Sustainability in Fractured Rock Aquifers', *Sustainable Water Resources Management*, <https://www.researchgate.net/publication/320644891>.

Pearce, M, Willis, E, McCarty, C, Ryan, F & Wadham, B 2008, *A response to the National Water initiative from Nepabunna, Yarilena, Scotdesco and Davenport Aboriginal settlements*, Desert Knowledge Cooperative Research Centre, Alice Springs, Australia.

Preiss, W V & Forbes, B G 1981, 'Stratigraphy, correlation and sedimentary history of Adelaidean (Late Proterozoic) basins in Australia', *Precambrian Research*, vol. 15, p. 258.

Preiss, W V, Dyson, A I, Reid, P W & Cowley W M 1998, ‘Revision of lithostratigraphic classification of the Umberatana Group’, *MESA Journal*, vol. 9, p. 41.

Priyan, K 2021, ‘Issues and Challenges of Groundwater and Surface Water Management in Semi-Arid Regions’, in CB Pande & KN Moharir (eds.) *Groundwater Resources Development and Planning in the Semi-Arid Region*, Springer Nature Switzerland, Cham, Switzerland, p. 4.

Ramesh, K & Elango, L 2012, ‘Groundwater quality and its suitability for domestic and agricultural use in Tondiar river basin, Tamil Nadu, India’, *Environmental monitoring and assessment*, p. 3888, viewed 9 March 2024, doi 10.1007/s10661-011-2231-3.

Samper, J, Naves, A, Pisani, B, Dafonte, J, Montenegro, L & García-Tomillo, A 2022, ‘Sustainability of groundwater resources of weathered and fractured schists in the rural areas of Galicia (Spain)’, *Environmental Earth Sciences*, vol. 81, no. 141, pp. 1-5.

Sapari, N, Azie, R J R, & Jusoh, H 2010, ‘Groundwater in fractured granite for water supply to remote areas in Malaysia’, *Water Practice & Technology*, vol. 5, no. 2, pp. 1-7.

Shammas, N K 2015, *Water Engineering: Hydraulics, Distribution and Treatment*, John Wiley & Sons, New Jersey, USA. <https://ebookcentral.proquest.com/lib/flinders/detail.action?docID=7104368&pq-origsite=primo>.

Shapiro, A M 2002, *Fractured-rock aquifers: understanding an increasingly important source of water*, U. S. Geological Survey, doi: 10.3133/fs11202.

Shen, Y & Chen, Y 2010, ‘Global perspective on hydrology, water balance, and water resources management in arid basins’, *Hydrological Processes*, vol. 24, p. 129, viewed 29 February 2024, doi: 10.1002/hyp.7428.

Shube, H, Kebede, S, Azagegn, T, Nedaw, D, Haji, M & Karuppannan, S 2023, ‘Estimating Groundwater Flow Velocity in Shallow Volcanic Aquifers of the Ethiopian Highlands Using a Geospatial Technique’, *Sustainability*, vol. 15, no. 14,490, p. 2.

Singhal, B B S & Gupta, R P 2011, *Applied Hydrogeology of Fractured Rocks: Second Edition*, Springer, the Netherlands, https://doi.org/10.1007/978-90-481-8799-7.

State of New South Wales NSW Ministry of Health, n.d., *Groundwater Treatment Fact Sheet*, State of New South Wales NSW Ministry of Health, Australia, viewed 11 March 2024, <https://www.health.nsw.gov.au/environment/water/Documents/groundwater-treatment-fact-sheet.pdf>.

Tahir, M S, Sagir, M & Tahir, M B 2023, ‘Wastewater Treatment Methods’, *Advances in Water and Wastewater Treatment Technology*, Springer Nature Singapore, Singapore, <https://doi.org/10.1007/978-981-99-1187-5>.

Tzoupanos, N D & Zouboulis, A I 2008, ‘Coagulation-Flocculation Processes in Water/Wastewater Treatment: The Application of New Generation of Chemical Reagents’, *6th IASME/WSEAS International Conference on Heat Transfer, Thermal Engineering and Environment (THE’08)*, 20-22 August 2008.

Verma, S 2024, ‘Miscellaneous Methods II’, *Water and Wastewater Engineering Technology*, Taylor & Francis Group, Florida, USA, doi: 10.120119781003347941.

Water Services Association of Australia 2022, *Closing the water for people and community gap: improving water services to first nations remote communities*, Water Services Association of Australia, Australia.

Watt, EL, Berens, V & Magarey, PD 2012, *Non-prescribed groundwater resources assessment-South Australian Arid Lands Natural Resources Management Region: DFW Technical Report 2012/01*, Government of South Australia through Department for Water, Adelaide.

Williams, W D 1999, ‘Salinisation: A major threat to water resources in the arid and semi-arid regions of the world’, *Lake & Reservoir: Research and Management*, vol. 4, p. 85.

Willis, E, Pearce, M, Jorgensen, B & Martin, J 2015, *Water Supply and Governance Options for Outback Towns in South Australia*, Goyder Institute for Water Research, Adelaide, South Australia.

World Health Organization 2023, *Drinking-water*, World Health Organization, Geneva, viewed 28 February 2024, <https://www.who.int/news-room/fact-sheets/detail/drinking-water>.

Wyrwoll, P R, Manero, A, Taylor, K S, Rose, E & Grafton, R Q 2022, ‘Measuring the gaps in drinking water quality and policy across regional and remote Australia’, *Clean water*, vol. 32, p. 9.

APPENDICES

Appendix A Groundwater well data in Iga Warta (Department for Environment and Water, n.d.).

No.	Unit no	Aquifer	Well depth (m)	Production zone (m)	Water level (m)	Yield (L/s)	TDS (mg/L)	EC (uS/cm)	pH	Ca (mg/L)	Cl (mg/L)	CO_3 (mg/L)	Hardness (mg/L)	Mg (mg/L)	Na (mg/L)	SO_4 (mg/L)
1	6636-223	Ehw	165.0	80.0-165.0	-	-	-	-	-	-	-	-	-	-	-	-
2	6636-224	Ehw	160.0	-	-	-	-	-	-	-	-	-	-	-	-	-
3	6636-225 (active well)	Ehw	146.0	112.0-146.0	-	1.00	1,083	1,960	7.0	-	-	-	-	-	-	-
4	6636-226	Ehw	162.0	-	-	-	-	-	-	-	-	-	-	-	-	-
5	6636-322	Ehw	169.0	169.0	96.0	1.40	944	1,710	-	-	-	-	-	-	-	-
6	6636-354	-	196.0	-	-	0.60	2,150	3,865	-	-	-	-	-	-	-	-
7	6636-355	-	123.0	-	-	-	-	-	-	-	-	-	-	-	-	-

Appendix B Groundwater well data for the Leigh Creek Station area (Department for Environment and Water, n.d.).

No.	Unit no	Aquifer	Well depth (m)	Production zone (m)	Water level (m)	Yield (L/s)	TDS (mg/L)	EC (uS/cm)	pH	Ca (mg/L)	Cl (mg/L)	CO_3 (mg/L)	Hardness (mg/L)	Mg (mg/L)	Na (mg/L)	SO_4 (mg/L)
1	6536-2	-	-	-	-	-	2,299	4,127	-	134	855	244	656	77	618	367
2	6536-3 (active well)	-	-	-	-	-	4,055	7,196	-	196	1,618	286	1,042	136	1,124	701
3	6536-5	Nib	-	-	-	-	2,313	4,152	-	143	898	234	685	80	630	386
4	6536-6	Nib	-	-	-	-	528	960	-	56	80	226	271	37	109	34
5	6536-7	-	-	-	-	-	2,955	5,282	-	130	1,134	277	713	101	837	476
6	6536-8	-	29.0	11.6-29.0	5.2	0.08	4,826	8,518	-	181	2,046	307	1,113	160	1,404	734
7	6536-204	Nia	-	-	-	-	4,698	8,302	-	114	1,946	208	671	93	1,511	827
8	6536-422 (active well)	-	64.0	22.0-64.0	5.0	14.00	-	-	-	-	-	-	-	-	-	-
9	6536-3209	Nia	133.0	121.5-133.0	38.5	1.00	-	-	-	-	-	-	-	-	-	-
10	6536-3210	-	153.0	2.5-153.0	40.0	0.50	1,061	1,920	-	-	-	-	-	-	-	-

Appendix C Information regarding groundwater well data in Kakalpurannha (Department for Environment and Water, n.d.).

No.	Unit no	Aquifer	Well depth (m)	Production zone (m)	Water level (m)	Yield (L/s)	TDS (mg/L)	EC (uS/cm)	pH	Ca (mg/L)	Cl (mg/L)	CO_3 (mg/L)	Hardness (mg/L)	Mg (mg/L)	Na (mg/L)	SO_4 (mg/L)
1	6536-83	Nww	24.4	-	-	-	3,170	5,659	6.7	-	-	-	-	-	-	-
2	6536-130	Nww	38.1	2.4-38.1	13.7	1.30	5,343	9,399	7.0	-	-	-	-	-	-	-
3	6536-205	-	9.2	-	9.1	-	-	-	-	-	-	-	-	-	-	-
4	6536-206	-	9.6	-	5.0	-	-	-	-	-	-	-	-	-	-	-
5	6536-207	-	7.0	-	6.3	-	2,295	4,120	-	-	-	-	-	-	-	-
6	6536-208	-	5.5	-	4.9	-	2,109	3,791	-	-	-	-	-	-	-	-
7	6536-209	-	5.8	-	4.5	-	2,991	5,343	-	-	-	-	-	-	-	-
8	6536-210	-	19.4	-	13.1	-	2,386	4,280	-	-	-	-	-	-	-	-
9	6536-211	-	10.0	-	9.5	-	11,765	19,900	-	-	-	-	-	-	-	-
10	6536-212	-	10.0	-	9.0	-	2,295	4,120	-	-	-	-	-	-	-	-
11	6536-213	-	8.7	-	7.7	-	1,788	3,220	-	-	-	-	-	-	-	-
12	6536-214	-	10.5	-	9.3	-	1,832	3,300	-	-	-	-	-	-	-	-
13	6536-215	-	7.4	-	6.2	-	2,109	3,791	-	-	-	-	-	-	-	-
14	6536-240	-	31.4	2.0-31.4	6.7	0.40	-	-	-	-	-	-	-	-	-	-
15	6536-274	-	5.8	-	3.2	0.38	2,155	3,874	-	29	870	308	85	4	775	29
16	6536-323	-	21.6	2.4-21.6	1.2	0.75	2,966	5,300	7.2	-	-	-	-	-	-	-
17	6536-334	-	32.0	6.0-32.0	9.0	-	7,292	12,655	6.9	-	-	-	-	-	-	-
18	6536-357	-	17.9	6.0-17.9	6.4	0.05	1,901	3,420	-	-	-	-	-	-	-	-
19	6536-3202	Nww	14.0	7.0-14.0	-	0.50	1,770	3,190	8.2	-	-	-	-	-	-	-
20	6536-3203	Nww	18.2	6.0-18.0	-	0.20	1,776	3,200	7.7	-	-	-	-	-	-	-
21	6536-3207	Nww	24.0	-	-	-	-	-	-	-	-	-	-	-	-	-
22	6536-3208	Nww	30.0	24.0-30.0	6.0	1.20	2,727	4,880	-	-	-	-	-	-	-	-
23	6536-3218	Nww	30.0	24.0-30.0	6.0	1.20	-	-	-	-	-	-	-	-	-	-
24	6536-3229	Nww	74.0	62.0-74.0	11.0	0.13	1,861	3,350	-	-	-	-	-	-	-	-
25	6536-3271	Nww	18.2	6.0-18.0	5.7	1.00	3,030	5,410	-	-	-	-	-	-	-	-
26	6536-3371	Nww	129.0	17.5-129.0	6.0	0.25	2,499	4,480	-	-	-	-	-	-	-	-
27	6536-3372	Nww	60.0	17.5-60.0	-	-	-	-	-	-	-	-	-	-	-	-
28	6536-4427 (active well)	Nww	12.5	6.5-12.5	-	0.65	1,945	3,500	-	-	-	-	-	-	-	-
29	6536-4452	Nww	12.00	8.0-12.0	-	8.00	1,910	3,438	-	-	-	-	-	-	-	-

Appendix D Yappala groundwater well data (Department for Environment and Water, n.d.).

No.	Unit no	Aquifer	Well depth (m)	Production zone (m)	Water level (m)	Yield (L/s)	TDS (mg/L)	EC (uS/cm)	pH	Ca (mg/L)	Cl (mg/L)	CO_3 (mg/L)	Hardness (mg/L)	Mg (mg/L)	Na (mg/L)	SO_4 (mg/L)
1	6534-179	Npr	-	-	-	-	2,484	4,454	-	149	930	203	1,128	183	494	528
2	6534-180	-	10.7	-	6.3	-	4,175	7,400	-	-	-	-	-	-	-	-
3	6534-181	-	12.0	-	7.0	-	3,319	5,914	-	-	-	-	-	-	-	-
4	6534-204 (active well)	Npb	70.0	-	63.0	-	2,251	4,040	-	-	-	-	-	-	-	-
5	6534-205	-	9.4	-	8.4	-	13,099	22,000	6.5	-	-	-	-	-	-	-
6	6534-206	-	7.2	-	6.0	-	4,997	8,807	-	-	-	-	-	-	-	-
7	6534-320	-	70.0	-	-	-	-	-	-	-	-	-	-	-	-	-

Appendix E Water chemistry of the wells in the Wilkawillina Limestone aquifer. (Department for Environment and Water, n.d.).

No.	Unit no	Well depth (m)	TDS (mg/L)	EC (uS/cm)	pH	Ca (mg/L)	Cl (mg/L)	CO_3 (mg/L)	Hardness (mg/L)	Mg (mg/L)	Na (mg/L)	SO_4 (mg/L)	Alkalinity (mg/L)	HCO_3 (mg/L)	K (mg/L)	NO_3 (N) (mg/L)
1	6536-191	88.00	3,252	5,800	7	118	592	-	706	100	408	267	-	577	4	11
2	6636-139	178.00	-	-	-	104	394	-	-	53	274	250	-	177	-	-
3	6636-149	120.00	1,289	1,950	8	210	193	-	878	86	125	365	557	613	3	0
4	6636-16	48.77	1,228	2,222	-	141	479	282	753	98	277	200	-	-	-	-
5	6636-18	100.89	1,270	2,274	-	100	381	241	542	71	274	197	-	-	-	-
6	6636-209	101.60	1,057	1,736	7	152	179	-	665	69	130	310	406	423	5	0
7	6636-7	31.39	1,299	2,349	-	123	390	241	656	83	243	218	-	-	-	-
8	6636-8	48.46	2,313	4,127	-	134	731	346	828	119	558	418	-	-	-	-
9	6736-32	-	2,627	-	-	176	865	277	899	111	630	561	-	-	-	-

Appendix F The data on water chemistry of wells drilled in the Angepena Formation aquifer (Department for Environment and Water, n.d.).

No.	Unit no	Well depth (m)	TDS (mg/L)	EC (uS/cm)	pH	Ca (mg/L)	Cl (mg/L)	CO_3 (mg/L)	Hardness (mg/L)	Mg (mg/L)	Na (mg/L)	SO_4 (mg/L)	Alkalinity (mg/L)	HCO_3 (mg/L)	K (mg/L)	NO_3 (N) (mg/L)
1	6433-154	66.75	1,583	2,856	-	228	568	338	841	66	287	96	-	-	-	0
2	6433-175	-	2,170	3,900	-	139	945	260	885	130	507	193	-	-	-	-

No.	Unit no	Well depth (m)	TDS (mg/L)	EC (uS/cm)	pH	Ca (mg/L)	Cl (mg/L)	CO_3 (mg/L)	Hardness (mg/L)	Mg (mg/L)	Na (mg/L)	SO_4 (mg/L)	Alkalinity (mg/L)	HCO_3 (mg/L)	K (mg/L)	NO_3 (N) (mg/L)
3	6433-79	60.35	1,242	2,247	-	94	430	234	234	135	180	157	-	-	-	0
4	6532-776	23.16	7,925	13,727	-	174	3,844	555	1,613	286	2,465	600	-	-	-	-
5	6532-782	12.19	1,499	2,705	-	84	545	304	556	83	380	99	-	-	-	-
6	6532-795	53.34	599	-	8	73	140	170	342	40	93	14	-	-	-	63
7	6532-832	46.63	1,070	-	-	164	457	167	642	57	159	63	-	-	-	-
8	6532-856	45.72	10,081	17,238	-	338	5,278	497	2,927	506	2,783	675	-	-	-	-
9	6532-888	50.90	4,683	8,276	-	188	2,349	386	1,399	211	1,292	234	-	-	-	-
10	6532-891	32.61	4,755	8,399	-	176	2,339	406	1,427	238	1,311	283	-	-	-	-
11	6533-253	51.21	1,313	2,372	-	94	478	281	528	71	316	70	-	-	-	-
12	6536-204	-	4,698	8,302	-	114	1,946	208	671	93	1,511	827	-	-	-	-
13	6536-3*	-	4,055	7,196	-	196	1,618	286	1,042	136	1,124	701	-	-	-	-

Remark: 6536-3* refers to a well located in the Leigh Creek Station.

Appendix G The water chemistry data of groundwater wells in the Wonoka Formation aquifer (Department for Environment and Water, n.d.).

No.	Unit no	Well depth (m)	TDS (mg/L)	EC (uS/cm)	pH	Ca (mg/L)	Cl (mg/L)	CO_3 (mg/L)	Hardness (mg/L)	Mg (mg/L)	Na (mg/L)	SO_4 (mg/L)	Alkalinity (mg/L)	HCO_3 (mg/L)	K (mg/L)	NO_3 (N) (mg/L)
1	6633-85	8.22	1,370	-	-	16	530	281	856	113	206	84	-	-	-	-
2	6636-2	-	2,955	5,259	-	174	1,160	211	1,070	156	687	558	-	-	-	-
3	6636-29	9.14	1,042	1,887	-	83	260	240	442	57	228	166	-	-	-	-
4	6637-37	9.14	1,170	2,094	-	89	264	250	528	71	244	248	-	-	-	-
5	6637-40	9.14	3,370	-	-	107	1,157	214	842	139	927	831	-	-	-	-
6	6637-41	-	1,399	2,274	-	54	520	119	442	73	353	281	-	-	-	-
7	6738-22	-	5,783	-	-	336	1,184	228	1,256	101	1,511	2,323	-	-	-	90

Appendix H The chemical and physical quality of groundwater from the Bonney Sandstone aquifer (Department for Environment and Water, n.d.).

No.	Unit no	Well depth (m)	TDS (mg/L)	EC (uS/cm)	pH	Ca (mg/L)	Cl (mg/L)	CO_3 (mg/L)	Hardness (mg/L)	Mg (mg/L)	Na (mg/L)	SO_4 (mg/L)	Alkalinity (mg/L)	HCO_3 (mg/L)	K (mg/L)	NO_3 (N) (mg/L)
1	6636-56		3,055	5,457	-	107	1,244	214	699	104	887	497	-	-	-	-
2	6738-17	2.30	9,324	16,002	-	368	2,800	287	2,855	463	2,232	3,152	-	-	-	-