Far North Prescribed Wells Area Groundwater Model

Volume 6 –Recharge and discharge processes, hydrochemistry, and springs classification

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Foreword

The Department for Environment and Water (DEW) is responsible for the management of the State's natural resources, ranging from policy leadership to on-ground delivery in consultation with government, industry and communities.

High-quality science and effective monitoring provide the foundation for the successful management of our environment and natural resources. This is achieved through undertaking appropriate research, investigations, assessments, monitoring and evaluation.

DEW's strong partnerships with educational and research institutions, industries, government agencies, Landscape Boards and the community ensures that there is continual capacity building across the sector, and that the best skills and expertise are used to inform decision making.

John Schutz
CHIEF EXECUTIVE
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- project technical lead Mark Keppel, Principal Hydrogeologist, Department for Environment and Water (DEW)
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- project groundwater modelling technical lead Juliette Woods, Principal Groundwater Modeller, DEW.
- project technical geology lead Tony Hill, Deputy Director, Geoscience and Exploration Branch and Principal Geologist, Department for Energy and Mining (DEM)
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External review of the report was provided by:

- Paul Howe Principal Hydrogeologist, CDM Smith Pty Ltd
- Keith Phillipson, Principal Modeller, Australasian Groundwater and Environmental Consultants Pty Ltd.

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Executive summary

The documentation for the Far North Prescribed Wells Area Groundwater Model is presented over several volumes. The purpose of these reports is to provide an overview of the study area, provide scientific evidence for the conceptual hydrogeological model (CHM) used as the basis for the decisions and assumptions used during model construction and history matching. This volume (Volume 6) presents data and previous research concerning the key recharge and discharge processes interpreted to occur within the study area, supplemented by a summary of previous hydrochemistry study conclusions, and a classification of springs for modelling purposes.

The main study area focus is the Far North Prescribed Wells Area in South Australia (SA), which requires an overall study area that extends across the Eromanga Basin in SA and the Northern Territory (NT), with a 'buffer zone' extension into south-western Queensland (Qld) and north-western New South Wales (NSW). This area also covers the Pedirka Basin in SA and the NT, the Arckaringa Basin in SA, and the Cooper Basin in SA, along with part of the Cooper Basin in south-western Qld, which all have potential hydraulic interactions with the Eromanga Basin.

Major ion and isotope hydrochemistry data analysed for this study was mainly sourced from the DEW-managed water well database SA Geodata, supplemented by data obtained from the literature, plus major ion hydrochemistry derived from petroleum exploration and production bores. The water well and petroleum well data sets were quality checked before a basin-wide hydrochemistry assessment was conducted using a range of methods. Recharge and discharge processes were characterised from recent research and published literature, augmented by additional data analysis to expand, or infill previous work. Chloride Mass Balance analysis was conducted using hydrochemistry results from several bores, to supplement older work on recharge. The mapping of potential diffuse discharge signatures near springs used a multispectral imagery data analysis methodology from the literature but expanded to cover all major spring groups in South Australia was also completed.

In broad terms, groundwater emanating from the western margin recharge areas is predominantly Na^{+}+Cl^{-}+SO_4^{-2}, whereas groundwater from the central Eromanga region is predominantly Na^{-}+HCO_3^{-}. Variations and patterns within this broad framework may relate to sub-basinal variations in flow-path, evolution of groundwater hydrochemistry through the dissolution of minerals such as halite or mixing of groundwater from different parts of the basin. The stable isotopes δD and $\delta^{18}O$ show more variance along the western margin than within the eastern portion of the study area. Several radioisotopic tracer studies have been conducted to characterise the age and flow velocity of groundwater. Horizontal flow velocities between 0.05 m/y and 20.9 m/y were identified in the NT portion of the study area using radiocarbon and a flow rate of approximately 0.24 (± 0.03) m/y was found along a transect of wells west of the Peake and Denison Inlier using Chlorine 36.

Although rates of recharge and discharge still have a high degree of uncertainty, the evidence indicates that discharge from the J-K aquifer is greater than recharge. Consequently, groundwater conditions in the J-K aquifer in SA, and particularly the western margin, are transient, and are probably now in a state of natural, long-term, slow decline controlled by paleoclimate.

The largest proportion of inflow into the study area originates from the NT, Qld, and NSW (Figure 1 and Figure 2). Work undertaken during this study to develop potentiometric surfaces representing groundwater flow in the J-K aquifer suggest that this groundwater flow is predominantly from Queensland. Preliminary water balance estimations developed for this study suggest lateral inflow into the SA portion of the study area may be in the order of 457 ML/d, although there is a high degree of uncertainty around this figure due to variations in hydraulic conductivity and interpreted groundwater flow.

An unknown contribution to lateral inflow into the Main Eromanga Aquifer Sequence within the study area is from the Officer Basin along the western margin of the Eromanga Basin, and inflow inferred via the interpreted potentiometric surface (Figure 1). Little is known about such inflows, including whether the potentiometric surface being used to interpret this may be more reflective of a paleo-recharge event dating back to the Cenozoic.

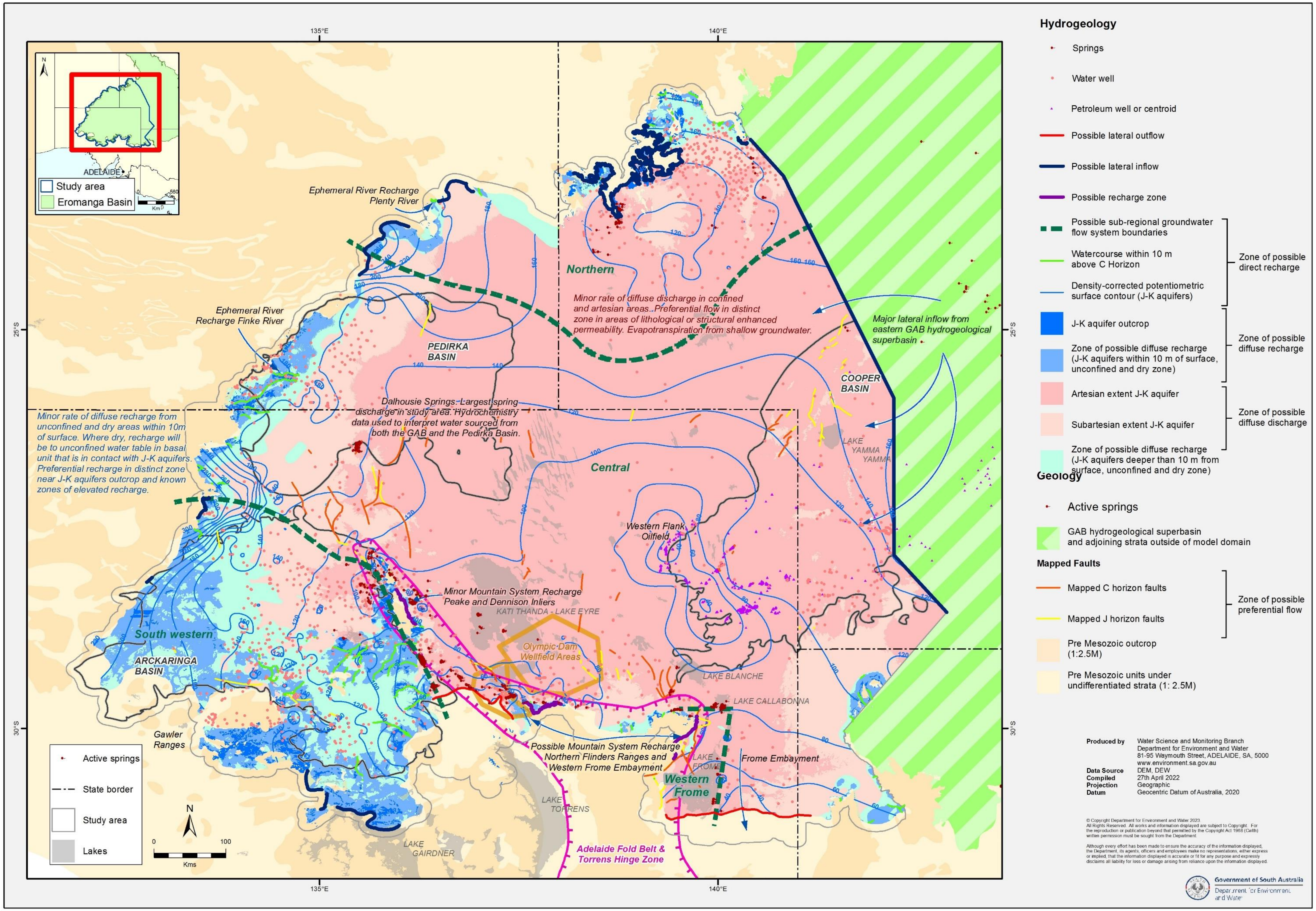
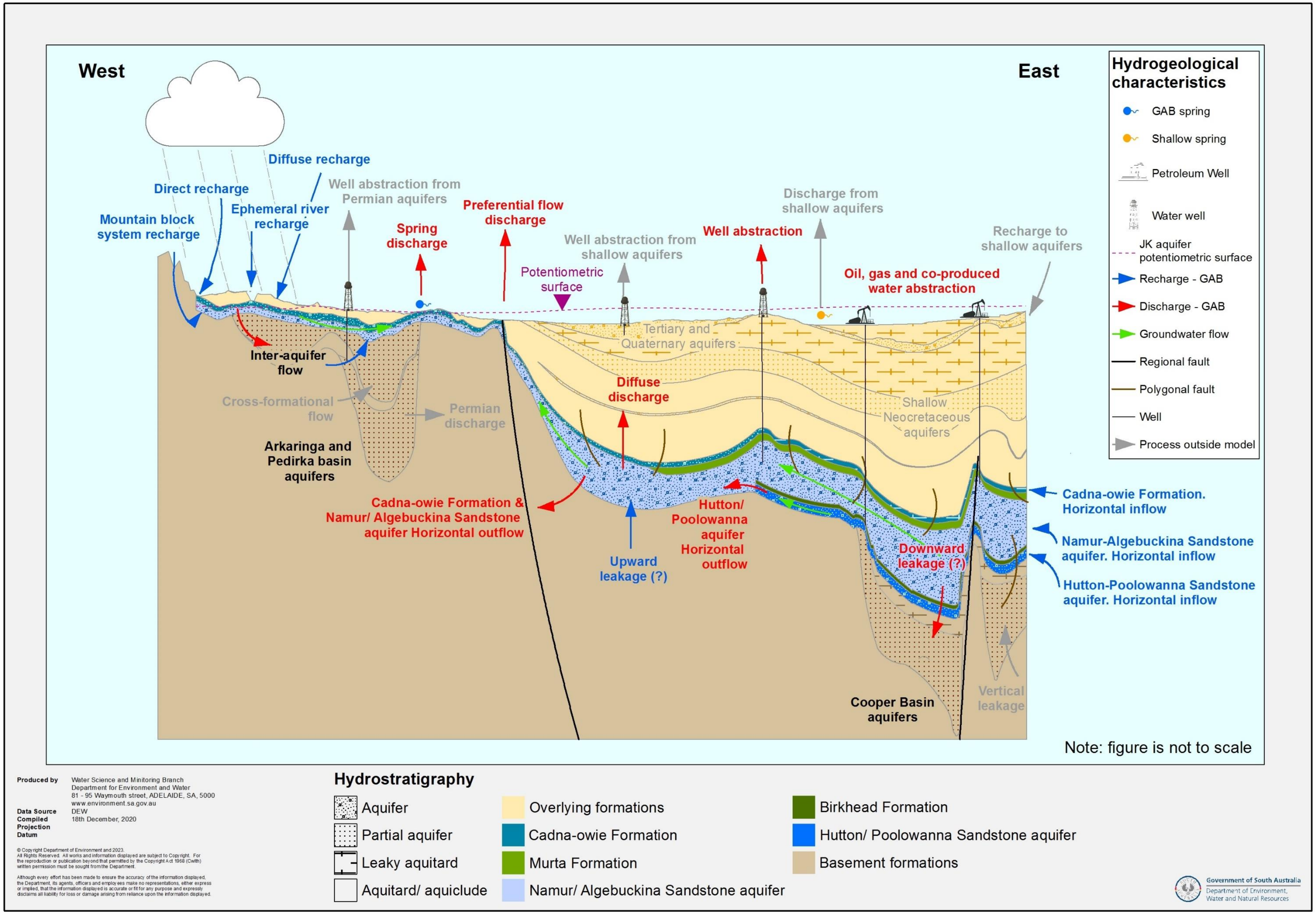


Figure 1: **Schematic conceptual plan of recharge and discharge processes interpreted to occur within the study area**



- **Figure 2:** **Schematic conceptual cross-section of recharge and discharge processes interpreted to occur within the study area**

Based on previous studies, regional-scale, diffuse recharge to the J-K aquifer within the western portion of the study area have been estimated to range between 0.01 to 5 mm/y, with an average estimation of approximately 0.15 mm/y. Estimated figures were corroborated using ^{14}C and coring results in discrete areas but are approximations at best given uncertainties in the applied method.

Ephemeral River Recharge (ERR) to the J-K aquifer has been identified in portions of the Finke and Plenty rivers when rainfall events greater than 100 mm/y occur. The total contribution from ERR along the western margin of the Eromanga Basin has been estimated at between 5,150 and 11,560 ML/y (14 to 32 ML/d). Evidence for ERR in other areas is less conclusive although hydrographs from monitoring wells near Marla and rainfall records suggest ERR may be occurring in this region as well.

Minor recharge occurring via Mountain System Recharge (MSR) has been identified near the Peake and Denison Inliers and potentially other elevated areas near the margins of the Great Artesian Basin (GAB). However, with respect to MSR, the latest research notes that, although such recharge may be occurring, total volumes may be small.

An important form of discharge from both the eastern and western portions of the J-K aquifer within the modelling domain are the 5,000-plus mapped GAB springs (Figure 1). Springs are also an important focus of groundwater modelling because the discharge supports groundwater dependent ecosystems (GDEs) that are of national and international significance and therefore require protection and careful management. Consequently, special attention has been given to describing spring-related discharge during this study so that springs may be properly represented in the final groundwater model.

Published estimates of spring flow based on prior numerical modelling suggest a total flow volume of between 66 to 76 ML/d, with most of this coming from the Dalhousie Springs complex (Figure 1). However, these estimates are likely to have an order of magnitude error due to the inherent difficulties in measuring flows as well as readily accessing springs for measurement. These prior estimates also are likely to not have encapsulated all known spring locations, either by design or by virtue of the number of surveyed spring vents having increased during the interim. Adding to the limitations regarding spring flow estimation is the paucity of gauging data. Most springs in SA are not regularly monitored; consequently, the relationship between spring flow and changes in groundwater pressure over time are not quantified.

Further, any estimation of discharge from spring zones needs to account for both direct and diffuse discharge, as spring wetland environments are potentially also supported by diffuse discharge. As part of this study, diffuse discharge associated with springs was mapped and the area of impact estimated. Depending on the methodology employed, mapped extents using the described methods provided estimates of diffuse discharge areas near springs of between 97 and 412 km^2, constituting a very small proportion of the total study area. Broader scale mapping of diffuse discharge zones using remote sensing and landform mapping identified much larger areas than this, but the contribution of artesian groundwater to evapotranspiration varies significantly across the study area, particularly where there is a notable thickness of younger strata above the J-K aquifer. Further, particularly in the western portion of the study area, it is difficult to discriminate the contribution of different aquifer types using major ions because of a general hydrochemical similarity. Within these broader zones, evaporation rates more than 100 mm/y were estimated. Consequently, there appears on average to be enough evapotranspiration within the study area to account for much of the rainfall within the study area.

A spring classification scheme was developed for the purpose of designing how to represent spring features within the numerical model. Classification was primarily based around interpreted geological controls but was also aided by an assessment of the depth to the source aquifer underneath each spring. The purpose of this analysis was to ascertain the potential hydrogeological significance of any controlling structure and therefore the importance to the numerical model. There were 5 main classifications developed:

1. Confining unit thinning
2. Fracture and minor fault zone,
3. Fault zone
4. Abutment zone
5. Mixed aquifer or non-Main Eromanga Aquifer Sequence springs.

The basis of classification centres on a spring's location with respect to 3 features associated with the structure surfaces developed for the numerical model:

a) thickness of cover above the J-K aquifer

b) proximity of the spring to a fault mappable within the datasets used

c) slope of the structure surface or location of a basement high near a spring location.

While springs are an important discharge mechanism within the study area, other forms of discharge also occur. Diffuse discharge from the J-K aquifer, is thought to be highly dependent on preferential pathway development through the main confining unit, because 'vertical leakage' or diffuse discharge through the undeformed confining unit is either potentially small and/or focussed in areas of preferential flow path development. Vertical leakage of groundwater into undeformed confining units from the J-K aquifer is currently estimated to be very low at between 3×10^{-4} to 5×10^{-4} mm/d. Where preferential pathway development may have occurred, current estimated rates are higher at between 8.64×10^{-5} to 8.64×10^{-4} m/d. Consequently, diffuse discharge through confining units is interpreted as more likely where deformation has improved permeability. Hydraulic-head data may be used to infer lateral outflow in the southern Frome Embayment area; however, there has been little study to confirm this. Previous work regarding groundwater flow near Marree and south of Coward Springs suggests this is more likely to be a groundwater divide between Eromanga Basin aquifer groundwater and aquifer groundwater within the rangelands abutting the basin margin. Conversely, regional potentiometric surface interpretation suggests there may be lateral outflow occurring and so provides an alternative conceptualisation to test with modelling.

The arid climate, low topography, and sparse vegetation coverage results in an elevated evaporation potential. Conceptually, evapotranspiration includes areas where the J-K aquifer strata is found near the surface, as well as where J-K aquifer groundwater discharges to the shallow phreatic water table contained within shallower strata where geological and hydrogeological conditions allow. Within this conceptualisation, areas where the water table is equal to or less than 10 m from surface and contained within J-K aquifer strata are considered the most likely areas for non-spring zone related groundwater evapotranspiration to occur. The 10 m depth is an arbitrary figure that considers natural error within the datasets used to determine land and structure surface elevations.

Average pan evaporation rates for the study area are approximately 3m/y. Further, the actual areal annual evapotranspiration rates for the study area suggest there is sufficient potential evapotranspiration capacity to account for average rainfall. Previous field and remote sensing-based work suggests that a significant proportion of the vertical leakage from the J-K aquifer in the central and western portion of the study area may be accounted for via evapotranspiration; however, in the eastern portion where the J-K aquifer is found at depth, vertical leakage into shallower strata is more likely. Finally, the efficiency of transpiration processes at removing groundwater and infiltrated rainfall before it can enter the water table is likely to vary across the study area. In particular, the effective depth of transpiration across the study area is likely to be highly variable and dependent on the predominant species of plant in a given area.

During the compilation of datasets and information used to develop the conceptual hydrogeological model (CHM), several material data gaps and uncertainties became apparent. In brief, these include:

- ***Hydrochemistry***: Hydrochemistry data require careful interpretation and caution where supplementary information, like multiple analytes and hydraulic information, is lacking. Further, groundwater age and flow determinations from different tracers may provide significantly different results. Results from multiple tracers are required to determine the range of uncertainty when used to determine flux rates.
- ***Regional-scale recharge and lateral inflow***: Head data along the north-western and western margins may still reflect paleo-recharge dating back to the earlier Cenozoic. Consequently, interpretations of lateral inflow in these regions may be overestimated. Further, much contemporaneous recharge appears restricted to localised focused areas, with identification of such area often reliant on circumstantial evidence.
- ***Regional scale discharge:*** Mapping zones of diffuse discharge may constrain the areal extent of where evapotranspiration is most likely to occur; however, the proportion of J-K aquifer groundwater to other aquifer groundwater can vary significantly and can be difficult to quantify if end member chemistries are similar. With respect to lateral outflow, although the potential for this has been identified in the Frome Embayment, this assertion is lacking supporting evidence.

Spring environments. Recent work suggests that springs in certain parts of the study area may have multiple groundwater sources. Further, the large number of springs with a small discharge rate may require a degree of approximate representation in the numerical model. Similarly, there is also uncertainty regarding whether measured discharge from a central vent represents the total discharge from all the spring conduits, as there is the potential for associated diffuse discharge as well as sub-surface discharge. The use of remote sensing techniques to try to address the issue of diffuse discharge may inadvertently include spring water that has re-infiltrated back into the near surface from the spring-fed wetland. Finally, how spring discharge is represented numerically also requires approximation, not only because of these issues but also because of difficulties representing spring structures numerically.

1 Introduction

Groundwater in the Far North Prescribed Wells Area (FNPWA) is vital for the success of the mining, petroleum, pastoral and tourism industries, and the provision of community water supplies in the Landscape SA South Australian Arid Lands (LSA SAAL) Management Region (Figure 1.1). The continued success and expansion of these industries is dependent on balancing the needs of existing users and the environment. Of particular environmental importance are the spring wetland communities in the discharge areas of the Great Artesian Basin (GAB) hydrogeological super-basin which are listed under the Commonwealth Environmental Protection and Biodiversity Conservation Act 1999. Protection of these environments is regulated and managed at a State level through the Far North Water Allocation Plan (FNWAP), through the description and implementation of spring buffer zones, water management zones and drawdown triggers at state borders. Further, the South Australian Government also has regulatory responsibilities over water management under the Roxby Downs (Indenture Ratification) Act 1982.

With demand for groundwater expected to grow in the mining and energy industries, a new numerical groundwater flow model is required to evaluate current knowledge and determine key knowledge gaps. This model will also be a tool to inform management of groundwater resources, both ongoing and for future major developments.

1.1 The Far North Prescribed Wells Area (FNPWA)

Groundwater in the FNPWA is managed under the FNWAP; a key principle being to manage groundwater resources by pressure (head) and to allocate by volume. The FNPWA was prescribed on 27 March 2003, and the first WAP was adopted on 16 February 2009. The 2021 FNWAP was adopted on the 27 February 2021.

Currently, the total groundwater allocation is 176 ML/d (2018-19 data) (Figure 1.2), with the majority (approximately 76% or 134 ML/d) sourced from the GAB hydrogeological super-basin aquifers (Figure 1.3). These allocations are made up of mining, industrial and human requirement supplies, co-produced water (water extracted with oil and gas), stock and domestic use, bore-fed wetlands and other amounts. Demand on the groundwater resources is expected to grow, particularly in response to growth in the mineral and energy industries.

1.2 Previous modelling

Although several groundwater models cover part of the western margin of the GAB hydrogeological super-basin, they are subject to one or more of the following limitations in terms of suitability for cumulative impact assessment to inform management of aquifers within South Australia (SA):

- a small or constrained geographical extent
- an over-simplified or limited aquifer system representation
- proprietary ownership by private companies that prohibits use for regulatory water resource assessments
- being based on outdated hydrogeological conceptualisations that do not reflect the current understanding of basin structure and groundwater processes including recharge and discharge
- not taking into account other interconnected basins that form important water resources in the FNPWA
- not being designed to consider the cumulative impacts of multiple groundwater users.

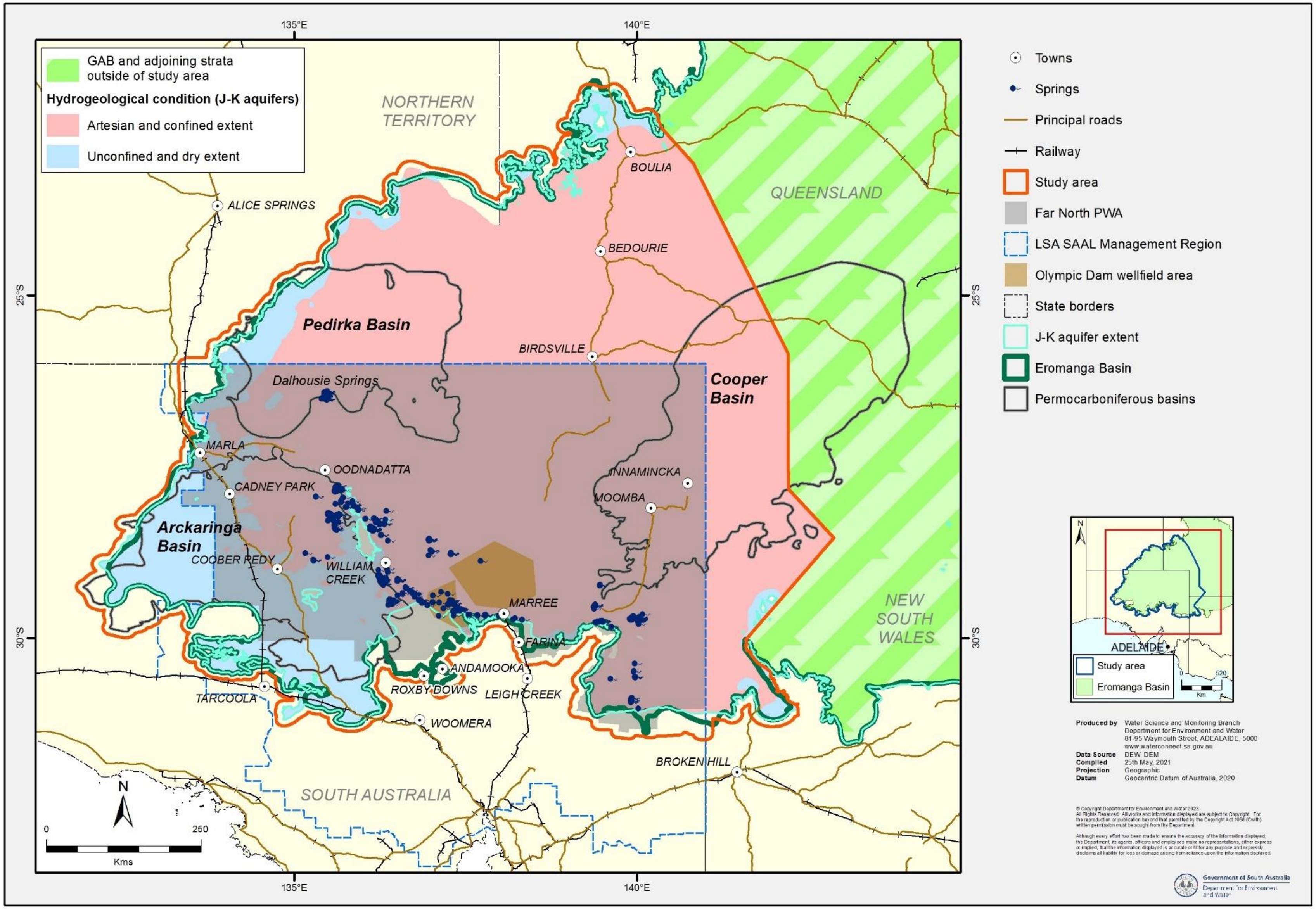


Figure 1.1: Location map of the Far North Prescribed Wells Area and study area

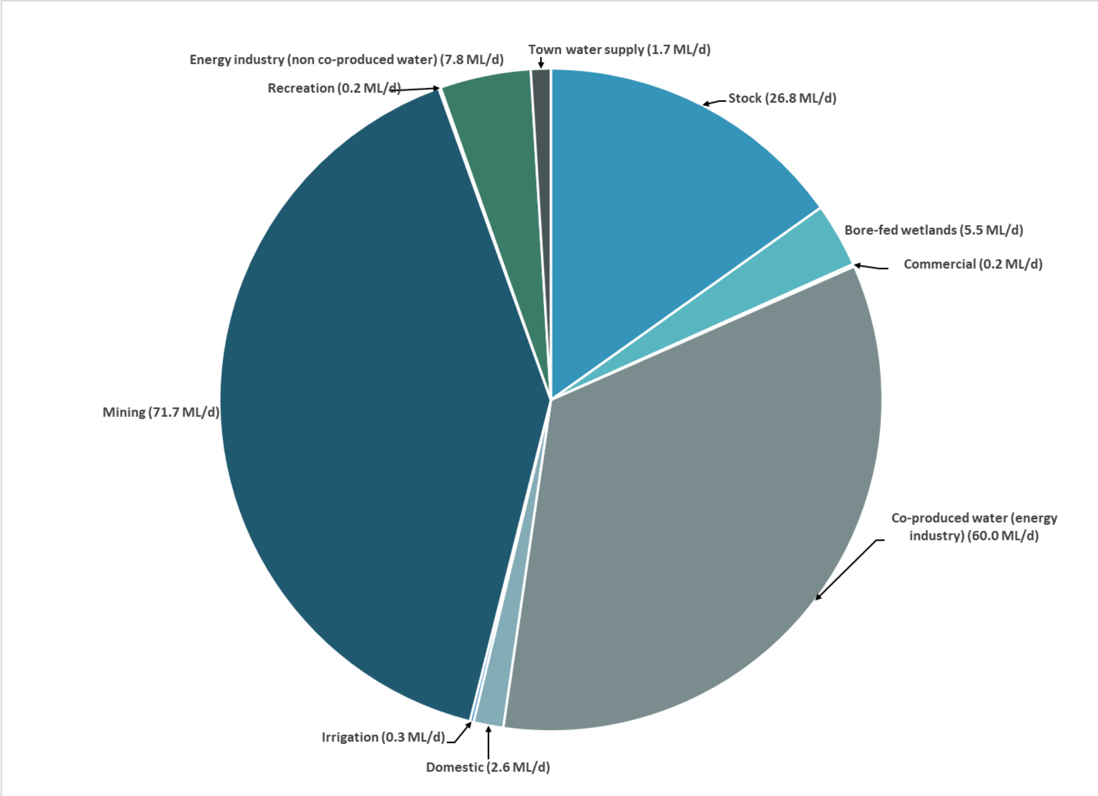


Figure 1.2: Total licensed volume (176 ML/d) presented by licence purpose description, FNPWA

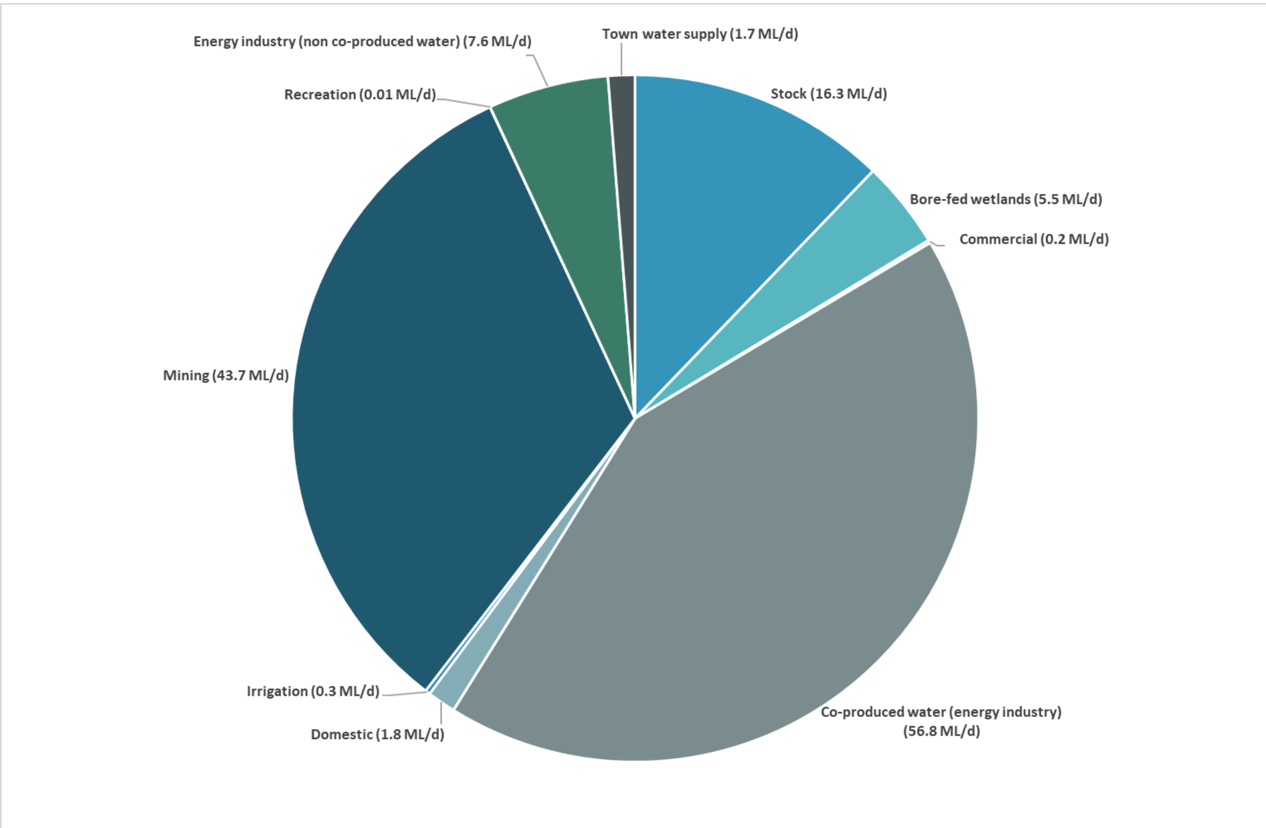


Figure 1.3: Licensed volume sourced from the GAB hydrogeological super-basin (134 ML/d) presented by licence purpose description, FNPWA

DEW has developed a numerical groundwater flow model to address the gaps identified in the existing models and to provide a tool to inform management of groundwater resources in the FNPWA. This model is consistent with the latest science and knowledge and can be updated in the future, providing a quantitative and predictive tool for development assessments and to inform management decisions. Further discussion of previous modelling is provided in Volume 8 of this report.

1.3 The study area

To cover an area of sufficient extent to achieve the model objectives, the study area (Figure 1.1) encompasses portions of the Eromanga Basin in Queensland and NSW, part of the Cooper Basin in Queensland, and the entirety of the following administrative areas and features of hydrogeological significance:

- Eromanga Bain in SA and the Northern Territory (NT)
- Cooper Basin in SA
- Pedirka Basin
- Arckaringa Basin
- the Far North Prescribed Wells Area (PWA).

The initial model design is to simulate groundwater flow within the Main Eromanga Aquifer Sequence, with a focus on the Far North PWA in SA. Future modelling programs may involve extensions to other groundwater flow systems, such as the Cooper, Arckaringa and Pedirka Basins.

The study area (Figure 1.1) covers a total area of about 721,370 km2. A 10 km-wide external buffer encompassing the features described in the above dot points extends beyond the southern, western, and northern perimeters of the study area. The eastern boundary extends between 245 km and 420 km from the NT border into Queensland (Qld), between 125 km and 190 km from the SA border into Qld, and between 60 km and 140 km into New South Wales (NSW) from the SA border. The eastern boundary is designed to allow for lateral inflow of groundwater to the study area in some areas and no flow in others, consistent with the groundwater flow system contours interpreted during this project. The spatial extent of the eastern boundary was selected to provide a sufficient distance away from the areas of interest in SA, so that the hydraulic conditions along the boundary do not materially influence simulation results.

1.4 Reporting structure

Given the size and multi-faceted nature of the investigation supporting model development, reporting occurs over several volumes:

1. Simplified technical summary
2. Hydrogeological framework
3. Hydraulic parametrisation
4. Groundwater flow system dynamics
5. Time series data
6. Recharge and discharge processes
7. Water use and balance estimations
8. Model construction and history matching
9. Model sensitivity and uncertainty analysis.

1.5 Volume Objective

This volume (Volume 6) presents data and previous research concerning the key hydrogeological processes of recharge, discharge and through-flow, supplemented by a summary of the findings from previous hydrochemistry investigations, along with a classification of springs for modelling purposes. Springs are important discharge mechanisms in the study area, and their protection is the primary focus of groundwater management and regulation, which warrants careful modelling treatment. This information supports model development by providing estimates of the spatial and temporal distributions of groundwater recharge, through-flow and discharge that are constrained by quantitative hydrochemistry.

1.6 Relevant hydrostratigraphic background information

Table 1.1 and Figure 1.4, which have been taken from Volume 2 of this study, summarise the key stratigraphic, hydrostratigraphic and model layer nomenclature used during this study. The terms discussed below are used throughout this and other volumes.

As stated previously, the study area covers a sizable portion of the Mesozoic Eromanga Basin, including its entire occurrence in SA and the (NT). The Eromanga Basin is the largest volumetric component of the GAB hydrogeological super-basin (Krieg 1995). The Eromanga Basin can be described as having a bowl shape that is partly defined and modified by faulting (Figure 1.4).

In the SA part of the Eromanga Basin, the most important strata sequence is the Cadna-owie Formation, the Algebuckina Sandstone, and their lateral equivalents (primarily the Namur Sandstone and Adori Sandstone). The collective hydrostratigraphic terminology commonly used in SA for aquifers and partial aquifers within these chronostratigraphically and lithologically connected and extensive units is the 'J-K Aquifer' (Table 1.1). It should be noted that within this general hydrostratigraphic nomenclature there can exist sub-regional scale lithological variation or structural deformation that may promote the development of sub-basinal groundwater flow systems.

The other important aquifer grouping is found in the deeper parts of the Eromanga Basin near the Cooper Basin and is associated predominantly with the Hutton Sandstone and the Poolowanna Formation. In the Cooper Basin region, these aquifer and partial aquifer units and/or groupings are separated by a series of finer grained confining units such as such as the Birkhead, Murta and Westbourne formations (Table 1.1).

The initial design of the model is to primarily simulate groundwater flow within the sequence of strata defined by the top of the Cadna-owie Formation, called the ‘C Horizon’, to the base of Mesozoic sediments (Base of the Poolowanna Formation), or the top of the Pre-Jurassic units, called the ‘J-Horizon’. Collectively, this package of aquifers and confining units is called the ‘Main Eromanga Aquifer Sequence’ (Table 1.1). It is essentially the combination of the extensive J-K aquifer and the sub-basinal Hutton–Poolowanna aquifer, including intervening confining units.

The Main Eromanga Aquifer Sequence is overlain by a confining unit composed of shaly mudstone units of low permeability that are collectively part of the Rolling Downs Group. The main elements of this group are the Bulldog Shale and Oodnadatta Formations which outcrop extensively near the western margin of the GAB hydrogeological super-basin, whereas the Wallumbilla Formation and Allaru Mudstone occur at depth in the central portions of the basin near the borders of SA and Qld.

Of the strata underlying the Main Eromanga Aquifer Sequence, the most important are the sedimentary rocks of the Permo-Carboniferous Arckaringa, Pedirka and Cooper basins. Not only do the sandstones, siltstones, shales, diamictites and coal beds in these basin sediments contain aquifers themselves, but also significant oil, gas and coal resources under varying degrees of development. Outside of the Permo-Carboniferous basins, metasedimentary rocks of the early Paleozoic Warburton Basin, Precambrian rocks of the Adelaide Geosyncline and crystalline Archaean rock may also be found. Future modelling programs may involve extensions to other groundwater flow systems, such as the Cooper, Arckaringa and Pedirka Basins.

For model construction, the Main Eromanga Aquifer Sequence was discretised into 5 model layers based on regional scale hydrostratigraphy (Figure 1.4). These included the Cadna-owie Formation Aquifer/Leaky Aquitard, the Murta Formation confining unit, the Namur–Algebuckina Sandstone Aquifer, The Birkhead Formation confining unit and the Hutton–Poolowanna aquifer. Underlying these is a layer of nominal thickness representative of the Pre-Jurassic basement.

Table 1.1: Summary of hydrostratigraphic unit nomenclature and relationship to model layer design

Collective term	Western study area					Cooper Basin region, study area					Whole of study area	
	Stratigraphic unit	Hydrostratigraphic unit	Model layer name	Hydrogeological characteristic	Qualitative permeability	Stratigraphic unit	Hydrostratigraphic unit	Model layer name	Hydrogeological characteristic	Qualitative permeability	[a]Max. thick. (m)	[a]Ave. thick. (m)
Main confining units	Rolling Downs Group	Main confining unit		Confining unit	Low	Rolling Downs Group	Main confining units		Confining unit	Low	NA	NA
'C' Horizon												
Main Eromanga Aquifer Sequence	Cadna-owie Formation (and lateral equivalents)	J-K aquifer	Cadna-owie Formation (Layer 1)	Partial aquifer/aquifer	Medium	Cadna-owie Formation	Intra-sequence confining unit	Cadna-owie Formation (Layer 1)	Leaky aquitard	Low	689[b]	42
	Algebuckina Sandstone		Namur–Algebuckina Sandstone aquifer, (Layer 3)	Aquifer	High	Murta Formation and McKinlay Member	Intra-sequence confining unit	Murta Formation confining unit (Layer 2)	Low permeability confining unit. McKinlay Member included initially as conservative option; however, an alternative conceptualisation to include within Layer 3 is an option	Low	122	49
						Adori Sandstone, Westbourne Formation*, Namur Sandstone	J-K aquifer	Namur–Algebuckina Sandstone aquifer (Layer 3)	Aquifer	High	1259	211
						Birkhead Formation	Intra-sequence confining unit	Birkhead Formation confining unit (Layer 4)	Low permeability confining unit	Low	225	72
						Hutton Sandstone and Poolowanna Formation	Hutton–Poolowanna aquifer	Hutton–Poolowanna aquifer (Layer 5)	Aquifer	Medium	855	256
'J' Horizon												
Basement	Pre-Jurassic	Basement	Pre-Jurassic Basement (Layer 6)	Partial aquifer. A designated thickness specified below Layer 3 with variable boundary conditions to allow for broad upward or downward leakage. Base of layer 6 is a no flow boundary.	Variable	Pre-Jurassic	Basement	Pre-Jurassic Basement (Layer 6)	A designated thickness specified below Layer 5 with variable boundary conditions to allow for broad upward or downward leakage. Base of layer 6 is a no flow boundary.	Variable	NA	User defined

Note: Table shading reflects hydrogeological properties of model layers. [a] Depths based on isopach interpolation. [b] Maximum thickness was interpolated in close vicinity to a mapped fault but cannot be confirmed. Confirmed thickness of 357 m based on intersection found in Well Unit no. 684200195.

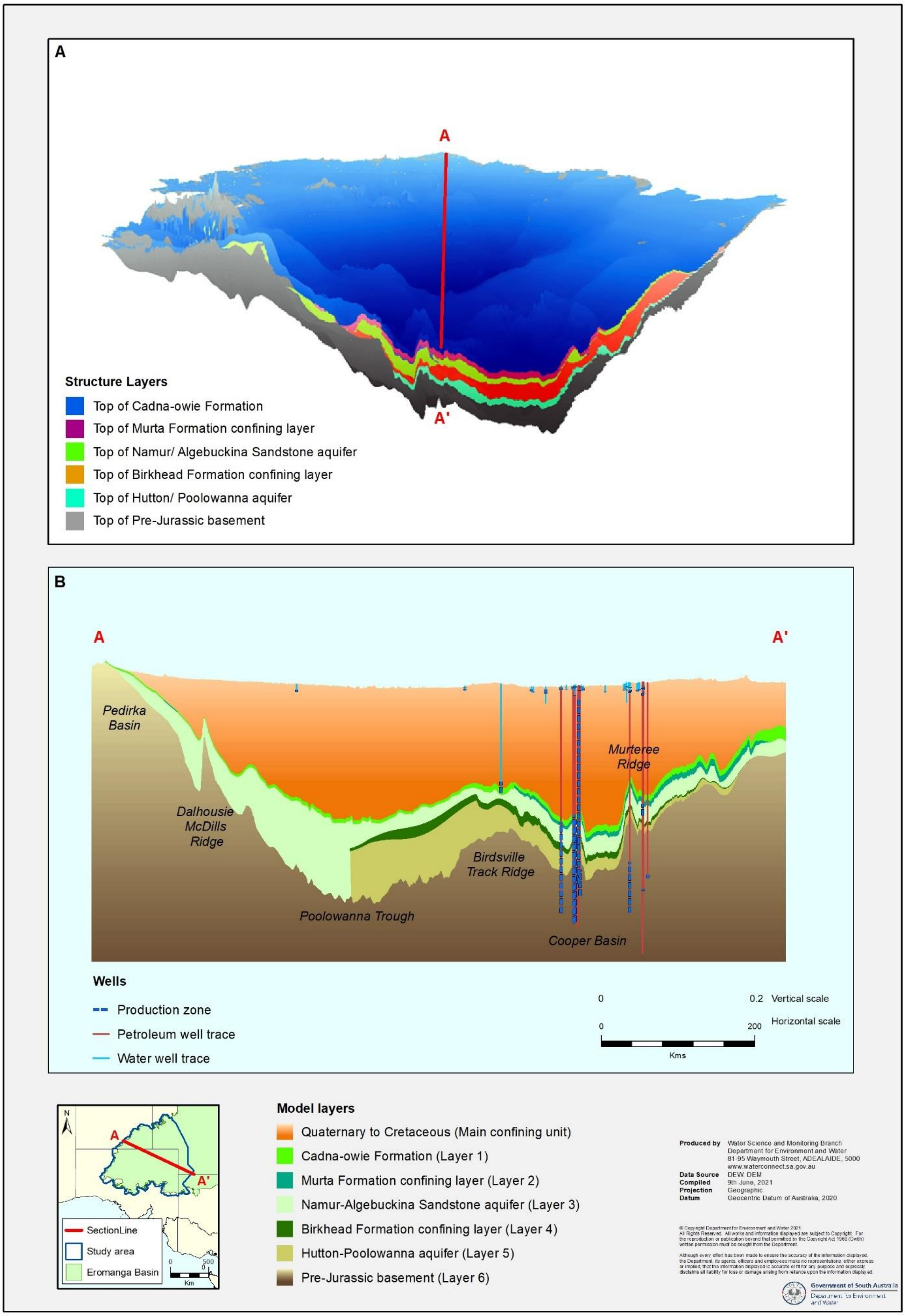


Figure 1.4: A) 3D projection of structure surface used in numerical model B) Cross section through study area showing model layers and key structures

2 Hydrochemistry

Hydrochemistry data can be used as a complementary line of evidence with hydraulics data to evaluate groundwater flow system dynamics and clarify the source of groundwater. Hydrochemistry data can be particularly useful in the absence of hydraulic data derived from pumping tests or in areas where well infrastructure is sparse. The following section summarises key features of the hydrochemistry of the Main Eromanga Aquifer Sequence found within the study area and the limitations of such data with respect to the conceptualisation of groundwater hydrodynamics.

2.1 Data and methods

Major ion and isotope hydrochemistry data analysed for this study was mainly sourced from the DEW-managed water well database SA Geodata, supplemented by data obtained from the literature, primarily from a compilation of Priestley et al. (2020), plus major ion hydrochemistry derived from petroleum exploration and production bores. The water-well and petroleum-well data sets were quality checked before a basin-wide hydrochemistry assessment was conducted using a range of methods.

2.1.1 Water well major ion hydrochemistry data set

Before any major ion data was included in analysis, it was vetted for anomalous charge balance errors of >5%. Calculating the charge, or electrical, balance of a suite of major ion results provides an estimation of analysis accuracy (Appelo and Postma 2005). Ideally, the cations or positively charged ions (for example, Na^+, K^+, Mg^{2+}, Ca^{2+}) and the anions or negatively charged ions (for example, HCO_3^-, SO_4^{2-}, Cl^-) should equal, resulting in a water sample that has a near-neutral charge. The charge balance of a water sample can be calculated as follows:

$$Charge\ Balanace\ (C.B.\%) = \frac{\Sigma\ cations - \Sigma\ anions}{\Sigma\ cations + \Sigma\ anions} \times 10 \quad (1)$$

Errors of approximately 2% may be typically expected from laboratory analysis, however Appelo and Postma (2005) recommend that results with a charge balance of >5% be investigated further. As this study uses historical data, re-assessment is not possible and so such results were rejected. After vetting, a database of 821 results for the J-K aquifer was analysed for this study.

Once the major ion database was vetted, major ion hydrochemistry was used to determine Total Dissolved Solids (TDS) trends across the study area, and Piper diagrams were used to determine the broad hydrochemical characteristics of groundwater. To emphasise the interpretation of major proportional major ion groupings, a limited selection of Stiff diagrams was prepared to help visualise the observed differences.

This analysis included the interpretation of trends in the data that are linked to chemical processes such as the dissolution or precipitation of minerals, water quality conditions or the potential origin of analytes in water. Groundwater with comparable proportional major ion concentrations may have similar chemical evolutionary histories and therefore be potentially connected. In contrast, notable variations between proportional major ion concentrations between groundwater types can be interpreted as having different hydrochemical evolutionary histories and that may be used as an argument for limited hydraulic connectivity. Broadly, this analysis was done to investigate the applicability of trends previously identified by Habermehl (1980) and Priestley et al. (2013) relating to data collected from the study area.

2.1.2 Petroleum well major ion hydrochemistry data set

Petroleum companies undertake major ion analysis routinely during production and drill stem test work during the drilling of exploration and production bores. For this study, hydrochemistry results from these tests were compiled and examined, similar to basin-wide datasets for the GAB. The large raw dataset (21,725) compiled for this study was screened for incomplete analyses, vetted for anomalous charge balances >5% and, using the quality control protocols established by Dubsky and McPhail (2001), any results indicating contamination from drilling fluids and filters excluded. Volume 4 of this report provides a description of these protocols, but they are largely designed to screen out any results suspected of contamination during the drilling process. Once this quality control protocol was undertaken, those samples left with a traceable spatial co-ordinate numbered 4,437. Data was primarily analysed using the same methodology as for water wells described previously.

2.1.3 Isotope hydrochemistry

Isotope ratios from groundwater samples may also indicate unique hydrochemical characteristics. As in the case of major ion and trace metal data, similar stable isotope values of water can infer a similar evolutionary history with respect to the source water.

No new analyses of isotope hydrochemistry have been completed for this study. For the majority of work, previously published investigations and reviews have been summarised, with key observations relevant to conceptualisation highlighted.

Comparison of stable isotope values for oxygen 18 ($\delta^{18}O$) and deuterium (δD) found within the SA Geodata database and supplemented with results from Priestley et al. (2020) were examined as a means of replicating interpretation from Priestley et al. (2020). In this instance, these results were compared to a Local Meteoric Water Line (LMWL), which enables interpretation of the effects of evaporation or mixing on groundwater samples. The LMWL describes stable isotope values from precipitation collected from a single site or set of local sites (USGS 2004). Groundwater that has evaporated or has mixed with evaporated water typically plots below the LMWL along lines that intersect the LMWL at the location of the original un-evaporated composition of the water (USGS 2004).

For this investigation, the LMWL for Alice Springs was chosen (Hollins et al. 2018) for comparison during analysis of water stable isotope results. Alice Springs was favoured over Woomera (the closest town to the study area with stable isotopes in precipitation recorded) because of a limited water stable isotope record at Woomera (Liu et al. 2010).

2.2 Water quality

Water quality varies significantly across the SA portion of the study area. Salinity varies from <1,000 mg/L TDS in eastern and central regions to >15,000 mg/L near the south-western margin (Smerdon et al. 2012) (Figure 2.1). In general, Ransley et al. (2015) noted that salinity within the GAB hydrogeological super-basin typically increases down flow paths, with lower salinities generally associated with recharge zones located in eastern and central Queensland. In contrast, Ransley et al. (2015) noted that recharge zones found along the south-western margin have very high salinities that accord with extremely low recharge rates, high evapotranspiration and salt deposits near the surface. Keppel et al. (2015b) also noted that within the south-western margin, groundwater within the underlying Mt Toondina Formation in the Arckaringa Basin can also be hypersaline, particularly in the Phillipson Trough region, which coincides with high salinities in the overlying Eromanga Basin aquifers (Figure 2.1). The interpretation of a potential sub-basinal groundwater flow system in the south-west is partially based on these TDS results (Figure 2.1).

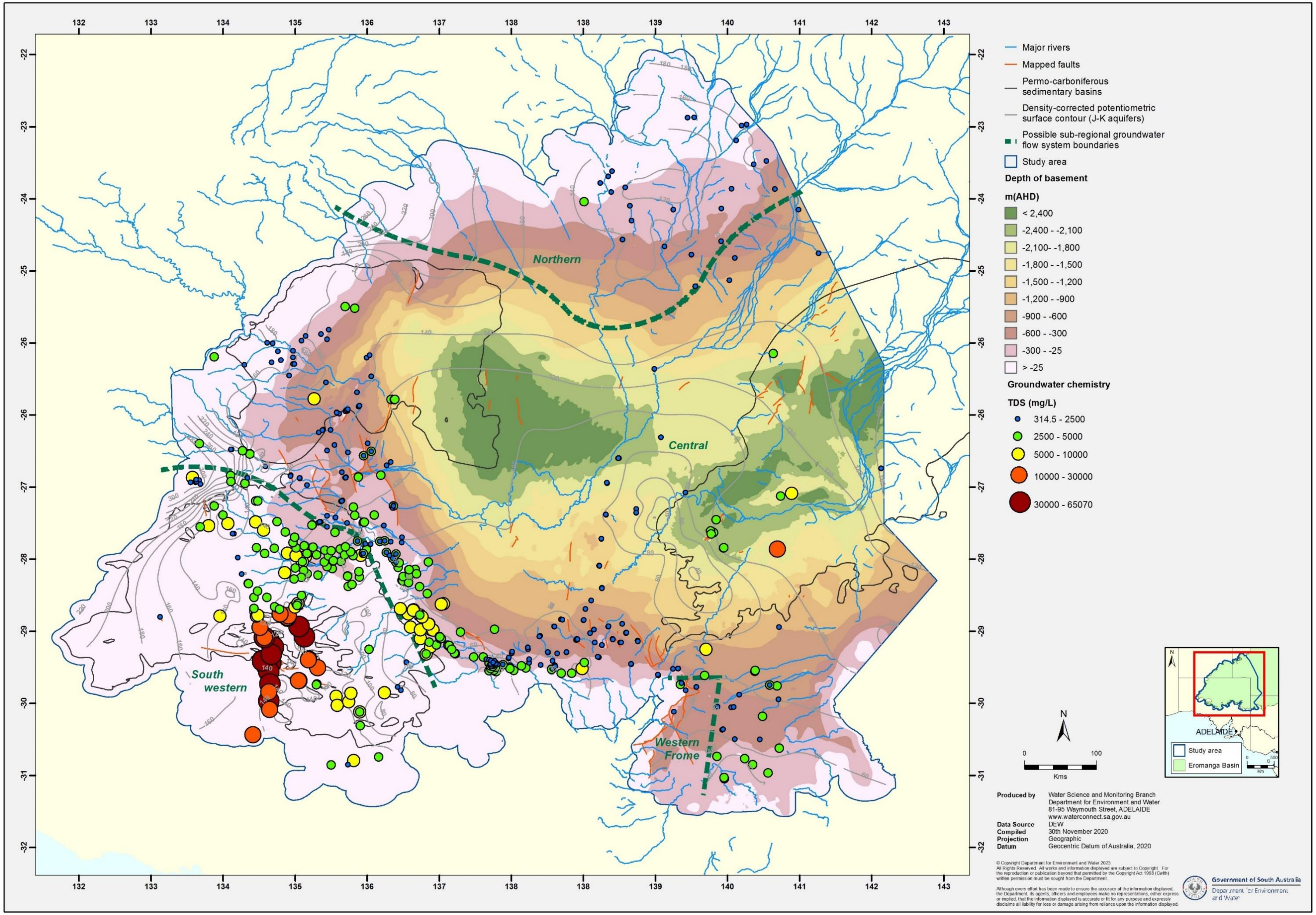


Figure 2.1 Vetted TDS based on major ion hydrochemistry from the Main Eromanga Aquifer Sequence

Ransley et al. (2015) also noted that salinity is higher around central the Eromanga depocentre, located in the Cooper Basin region, and lower in groundwater near the Birdsville Track Ridge that separates the Central Eromanga and Poolowanna depocentres. This latter zone was interpreted to demarcate hydrochemistry between the western Eromanga Basin and regions east of the Birdsville Track Ridge. Finally, in the case of particular analytes such as alkalinity, Ransley et al. (2015) related higher concentrations to the decomposition of organic matter or to indicate of low flow conditions.

Ransley et al. (2015) described groundwater pH as gradually increasing from acidic to alkaline from recharge areas to depocentres near the centre of the basin (that is, down a potentiometric gradient), although they noted that such trends are more accurately observed for groundwater flows emanating from the eastern margin in Qld and NSW. Groundwater from the north-eastern margin of the Eromanga Basin may have a pH in the range of 5.5 to 6.0, increasing to pH 7.5 to 8.5 near the Eromanga Basin depocentre within the confines of the study area. In contrast, generally near neutral pH values are found in the recharge zones of the western and south-western portions of the Eromanga Basin, corresponding with areas with typically low alkalinity. Ransley et al. (2015) noted that near neutral pH values are consistent with the relatively shallow aquifer system in this region that is also lacking evidence for sources of acidic substances such as organic material, methane, clay or volcanic material.

Temperature variation is broadly commensurate with depth, varying from <25˚C along the western margin and within the non-artesian areas of the south-west to >95˚C in the eastern portions of the study area. Temperature and water quality of groundwater across the study area is discussed further in Volume 4 of this report.

2.3 Proportional major ion hydrochemistry

In broad terms, the general proportional major ion chemistry of groundwater emanating from the western margin recharge areas is predominantly Na^{+}+Cl^{-}+ (SO_4^{2-}) whereas groundwater emanating from the central Eromanga region is predominantly Na^{+}+HCO_3^{-} (Habermehl 1980; Jack 1923; Priestley et al. 2013).

With respect to the eastern portion of the study area, J-K aquifer groundwater typically has a proportional major ion chemistry that is Na^{+}+HCO_3^{-} dominant (Figure 2.2). Herczeg et al. (1991) used mass-balance and equilibrium hydrochemistry models to describe the likely water–rock interactions responsible for the predominance of Na^{+}+HCO_3- hydrochemistry in the artesian portion of the J-K aquifer groundwater: (a) dissolution of Na-bearing minerals (e.g. plagioclase and orthoclase), (b) cation exchange that releases Na+ for Ca^{2+} and Mg^{2+} and (c) conversion of Na-smectite to kaolinite. In contrast, the gross Na^{+}+Cl^{-}+ (SO_4^{2-}) groundwater chemistries of the J-K aquifer found in western parts of the study area, as well as shallow aquifers associated with Tertiary and Quaternary alluvial aquifers or outcropping fractured rock aquifers, are more typical of arid zone meteoric recharge (Costelloe et al., 2012).

Priestley et al., (2013) suggested that variations and patterns within this broad framework might relate to sub-basinal variations in flow-path or mixing of groundwater from different parts of the basin. Similarly, the discrimination of groundwaters based on TDS and major ion hydrochemistry can be partly used to interpret discrete groundwater flow systems within the study area. As previously mentioned, Na^{+}+Cl^{-}+ (SO_4^{2-}) groundwater and salinities >14,000 mg/L found in the south-western portion of the study area may be indicative of discrete groundwater flow system involving low volume recharge and high evapotranspiration rates (Figure 2.1). Variations and patterns found within these broader groupings may relate to sub-basinal variations in flow-path or mixing. These may include varying proportional concentrations of SO_4^{2-} (all aquifers), Ca^{2+}, Mg^{2+} and K^{+} (elevated in shallow aquifers located near the south-western margin of the study area (Keppel et al. 2015b)).

These two groundwater types appear to meet and possibly mix along the line of springs that bisect the area, inclusive of the Peake and Denison Inliers (Denison and Davenport Ranges) to form a Na^{+}+Cl^{-} type water (Figure 2.2). Such a mixing interpretation here is simply based on a continuum observed in proportional major ion hydrochemistry toward Na^{+}+Cl^{-} proportional dominance along flow paths interpreted from potentiometric surfaces developed for this study combined with observations concerning increasing TDS.

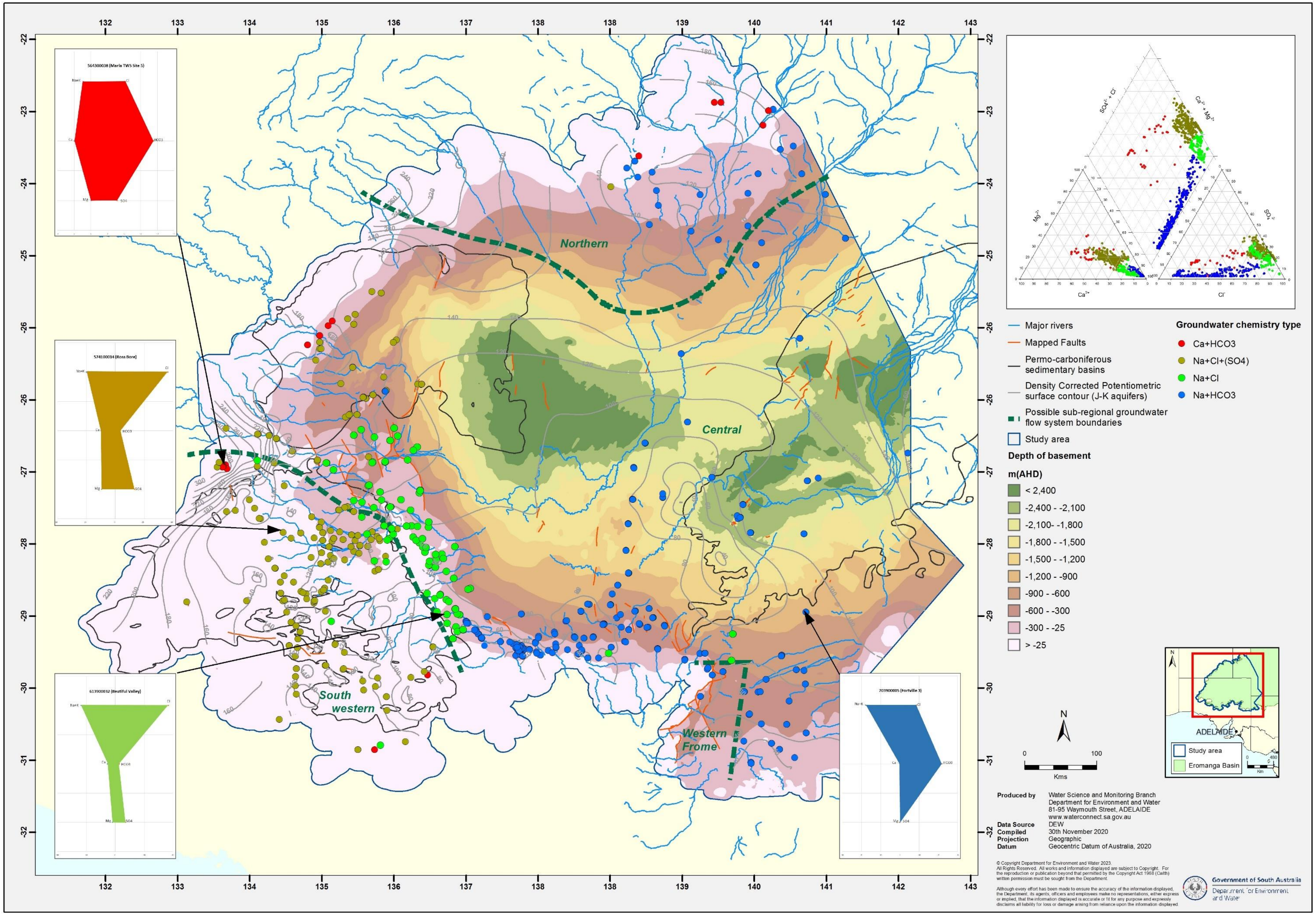


Figure 2.2: Vetted proportional major ion hydrochemistry results from SA Geodata Database and Priestley et al. (2013) from the Main Eromanga Aquifer Sequence and examples of Stiff plots of proportional major ion groups

Alternatively, this trend can be simply interpreted as a common hydrochemical evolutionary endpoint, with the dissolved halite (NaCl) concentration increasing via mineral dissolution in proportion to other ions along flow paths as a consequence of water–rock interactions.

In contrast to these two hypotheses, some occurrences of Na^{+}+Cl^{-} type waters can also accompany TDS results typically less than 2,500 mg/L. Such cases are notable around the northern and eastern margins of the Peake and Denison Inliers (Figure 2.1 and Figure 2.2). In such cases, the primary sources of groundwaters may not be restricted to eastern and/or western groundwaters within the J-K aquifer but may include inflow from another adjacent aquifer. Given the locality of such occurrences, and the generally artesian nature of groundwater, the most likely candidate for this alternate source of groundwater is the fractured rock basement aquifer. The area in question has been identified as one where Mountain System Recharge (MSR) of the J-K aquifer via the underlying fractured rock aquifer in crystalline basement sequences occurs (Wohling et al. 2013a). Further, Keppel et al. (2020) noted that major ion hydrochemistry of fractured rock aquifer groundwater in the crystalline basement from the south-eastern corner of the study area was grossly Na^{+} + Cl^{-} + (SO_4^{2-}) dominant and is therefore like groundwater observed at these locations. Consequently, mixing or evolutionary trends with such groundwater may produce broadly similar results as with western J-K aquifer groundwater but would not exclude the interpretation of discrete groundwater flow systems occurring in the J-K aquifer east and west of the Peake and Denison Inliers.

The notable exception to this is groundwater samples from aquifers near interpreted recharge zones, which are predominantly Ca^{2+} + HCO_3^{-} but also tend to have a very low total salinity, reflecting the input of episodic recharge from rainfall. Such Ca^{2+} + HCO_3^{-} type groundwater is specifically found near Marla, near the Finke River in the NT, parts of the Stuart Ranges and other points around the margins of the western Eromanga Basin (Figure 2.2). Ca^{2+}+HCO_3^{-} type groundwater is also pH neutral and oxidising; as groundwater migrates away from the point of recharge, mineral dissolution and mixing is observed to change the proportional major ion chemistry to a Na^{+}+Cl^{-}+(SO_4^{2-}) type. Chebotarev (1952) and Sheard (1981) first noted a link between Ca^{2+} + HCO_3^{-} type groundwater and potential recharge zones in South Australia.

The various proportional major ion groupings as interpreted using a Piper diagram can also be identified using Stiff diagrams (Figure 2.2). Consequently, such Stiff diagrams may prove useful with respect to identifying mixing or hydrochemistry evolution trends along sub-regional flow paths and therefore could be considered as a way to verify any critical flow patterns revealed by future numerical modelling.

Na^{+}+HCO_3^{-} type groundwater found in shallow aquifers is potentially noteworthy if validated, as such occurrences may be indicative of upward leakage of Main Eromanga Aquifer Sequence groundwater. Of note, Na^{+}+HCO_3^{-} type groundwater was found in one well completed in Paleogene to Neogene (Tertiary) aquifers on the southern margin of the Frome embayment, possibly indicating a zone of discharge supported by calculated flow lines (Figure 2.3). This contrasts with Na^{+}+Cl^{-} type groundwater more broadly found in Tertiary and Neocretaceous aquifers near the south-western Cooper Basin and within the northern portion of the Frome embayment (Figure 2.3) that is more typical of groundwater from these aquifers. In contrast, Costelloe et al. (2012) found little evidence of Na^{+}+HCO_3^{-} type groundwater in mapped discharge zone using forward hydrochemistry modelling and groundwater hydrochemistry types from different aquifers as end members. More success was noted for equivalent regions within the western portion of the study area, although the potential for spring water to infiltrate into the near surface and provide an additional shallow groundwater hydrochemistry endmember was not discussed. This concept is further explored in Chapter 5.

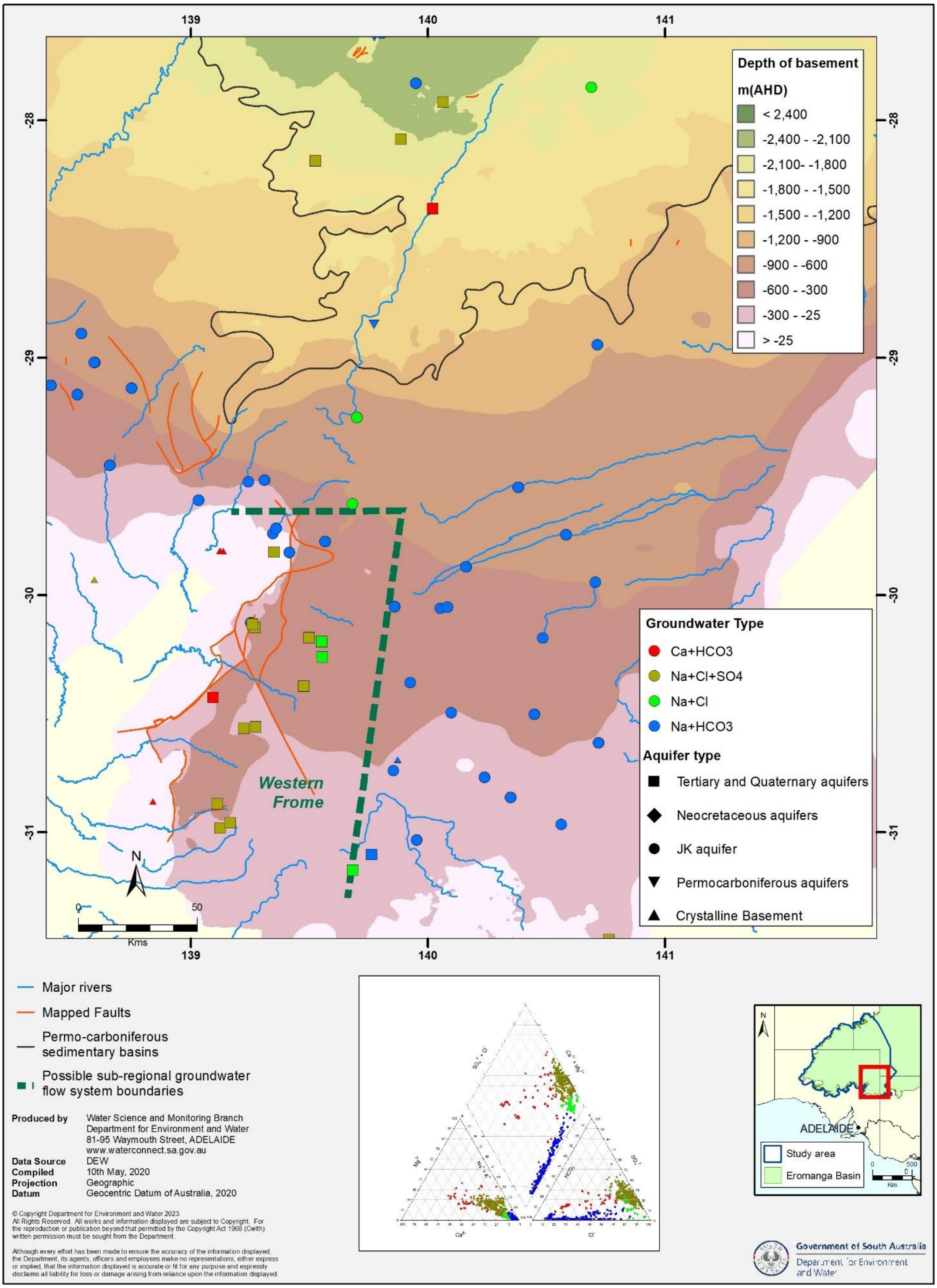


Figure 2.3: Vetted proportional major ion hydrochemistry results from all main aquifers in the Frome Embayment area

2.4 Summary of water quality and proportional major ion hydrochemistry – Petroleum industry

Previous work undertaken by Youngs (1971) found it difficult to distinguish a major ion-based groundwater signature linked to any particular stratigraphy. Groundwater discretisation based on major ions appears restricted to small areas. Of note are descriptions of high SO4 2- found in some artesian groundwater samples from the Main Eromanga Aquifer Sequence, which were otherwise regarded as typical Na^++ $HCO3^-$ type groundwater. Other groundwater samples, particularly from the Gidgealpa Group are notable for concentrations of Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^- and total Fe. Youngs (1971) described such results as being atypical of artesian groundwater; however, as this study attests, notable concentrations of Ca^{2+}, Mg^{2+}, Na^+ and K^+ are not unusual when examined in the totality of proportional major ion hydrochemistry observed from the study area.

Examination of proportional major ion concentrations obtained from petroleum bores for this study has not advanced the overall conclusion of Youngs (1971) much further. The remaining sample distribution of major ion concentrations is like that found for the basin at large. Proportional major ion concentration displays a trend like that displayed in the data set discussed in Section 2.3, in that proportional major ion hydrochemistry encompasses a Na^++HCO_3^--dominant result, through Na^++$Cl^-$and finally to Na^++Cl^-+ (SO_4^{2-}) (Figure 2.4). Like Youngs' (1971) observation, but unlike the previous dataset, parts of this distribution do not appear limited to any particular hydrostratigraphic or spatial region, beyond either small groupings or minor hydrostratigraphic classifications.

Of these minor trends, of note is the general preponderance of Na^++HCO_3^- type groundwater in the Murta and Westbourne Formations, Hutton and Namur sandstone and McKinlay Member, with only minor occurrences of Na++Cl-type groundwater mainly near the southern margin of the Cooper Basin. Similar trends are observed for the Murteree, Merrimellia and Tinchoo Formations in the Cooper Basin (Figure 2.5). In contrast, the groundwater from the Daralinge Formation can be classified as a Na^++Cl^-+ (SO_4^{2-}) type. Most other groundwater samples have a distribution that encompasses both general observed major ion types, although many samples were collected from intercepts encompassing multiple hydrostratigraphic units.

No further remarks regarding hydrochemistry for interpretive purposes in the Cooper Basin region are made, beyond noting that the capacity for interconnectivity between Mesozoic and Permo-Carboniferous aquifers in localised areas has been made previously by Youngs (1971), Altmann and Gordon (2004) and Schulz-Rojahn (1993). Beyond this, targeted sampling using a much wider variety of analytes and a strong understanding of the stratigraphic and structural setting is required to determine the hydrogeological significance of these results. The results of groundwater flow modelling may provide some further insights into the complexities of the groundwater flow systems.

Further, the quality control measures required to remove potentially contaminated samples could compromise the resulting dataset. For example, Dubsky and McPhail (2001) recommended the removal of results with what was considered excessive SO_4^{2-}, K^+, water resistivity and within bounding ranges of Na: Cl, K: Cl and pH, as such results were interpreted as indicative of drilling fluid contamination. Dubsky and McPhail (2001) also devised protocols for recognising 'significant' dilution compared to what Eromanga Formation waters were understood to be. However, as demonstrated using hydrochemistry from the wider basin, proportional major ion hydrochemistry can vary with respect to groundwater source, and also indicate potential for sub-basinal groundwater flow systems, groundwater mixing and inter-aquifer groundwater migration. The use of such a heavily compromised dataset may be limited in highlighting such trends if key analytes are also indicative of potential contamination and dilution with drilling-water.

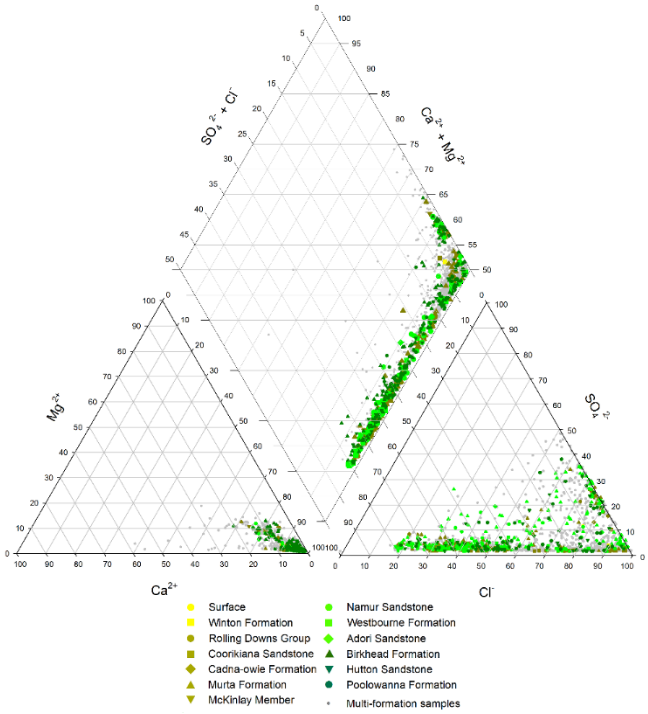


Figure 2.4: Piper plot of proportional major ions results from petroleum well-derived groundwater samples – Eromanga Basin

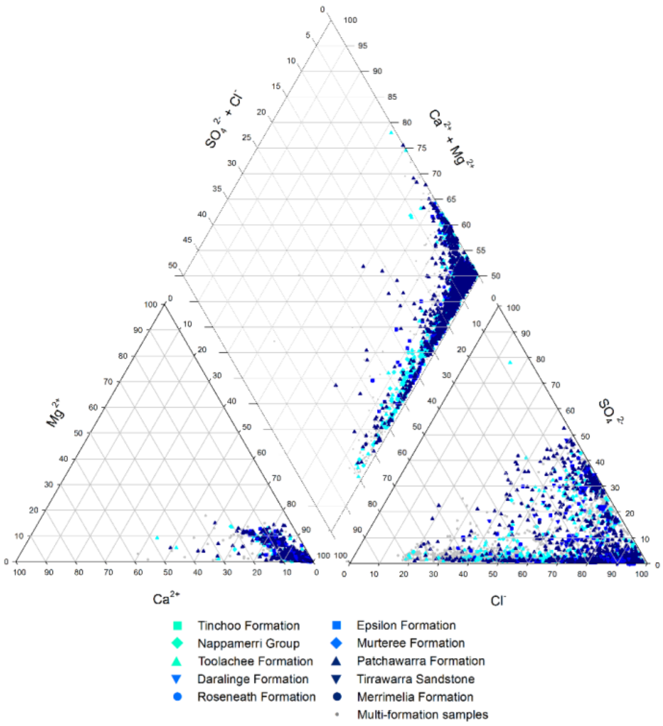


Figure 2.5: Piper plot of proportional major ions results from petroleum well-derived groundwater samples – Cooper Basin

2.5 Summary of environmental isotopes

2.5.1 Oxygen 18 ($\delta^{18}O$) and deuterium (δD)

In a review of historical oxygen 18 ($\delta^{18}O$) and deuterium (δD) results from J-K aquifer groundwater collected in SA, the NT and south-west Qld, Priestley et al. (2020) observed a large difference between the range of results from samples collected west of the Peake and Denison Ranges and Torrens Hinge Zone and those collected to the east. Western samples cover a large range in both $\delta^{18}O$ (−1 and −11‰) and δD (−14 and −77‰), whereas samples from the east have a much narrower range for $\delta^{18}O$ (−6 and −8‰) and δD (−40 and −51‰). An analysis of a selection of results from water wells compiled for this project concurs with the findings of Priestley et al. (2020). The difference in range observed in $\delta^{18}O$ and δD broadly reflects differences in proportional major ion concentrations, and likewise may reflect differences in recharge origin, flow-path and age. The narrow range of results found in the eastern portion of the study area may be reflective of a relatively advanced state of attenuation being reached through mixing during flow through a deep system aquifer (Figure 2.6) (Clark and Fritz 1997). In contrast, the much wider range of $\delta^{18}O$ and δD results found from the western portion of the study area may be more reflective of shorter flow paths or closer proximity to recharge points and thus the wide range may be more reflective of seasonal variation found in local rainfall (Figure 2.6). By way of comparison, Crosbie et al. (2012) presented ranges in $\delta^{18}O$ (~ 5.85 and −13.2‰) and δD (14.8 and −94.8‰) for meteoric samples collected between 2008 and 2010 at Alice Springs that display a wider range than those from J-K aquifer groundwater samples collected from the western portion of the study area.

Priestley et al. (2020) observed that when plotted against the local meteoric water line for Alice Springs, samples collected from the western portion of the study area, and, to a lesser extent, those collected from the eastern side, appear offset towards enrichment, which is consistent with evaporation of rainfall prior to or during recharge.

Ransley et al. (2015) noted that stable isotopes within the western portion of the Cadna-owie–Hooray aquifer (equivalent of the J-K aquifer) display a depleted signature near the Finke River recharge zone, suggesting the lighter isotope signature is indicative of recharge through monsoonal events that are subject to little evaporation. To a lesser degree, relatively depleted stable isotope signatures are also found in regions abutting the Northern Flinders Ranges and the Frome Embayment where recharge may also occur.

2.5.2 Strontium 87/86 ($^{87/86}Sr$)

Priestley et al. (2020) in their review of water chemistry from the western portion of the GAB hydrogeological super-basin found that Dalhousie Springs has a notable distribution of $^{87/86}Sr$ results when compared to results from elsewhere. All $^{87/86}Sr$ samples from Dalhousie Springs have ratios > 0.715, whereas results from elsewhere in the study area have ratios <0.715. This largely concurs with findings during more localised studies in regions north of the Frome Embayment (Keppel et al. 2020), the Peake and Denison Inliers (Keppel et al. 2015a), near the Hamilton Sub-basin (Keppel et al. 2017) and the Margaret Creek region west of Lake Eyre South (Keppel et al. 2015b). In these local studies, it was seen that at least one sample from the J-K aquifer would tend to have a result either comparable to or > 0.715, but more pertinently, such enriched results were not uncommon in groundwater samples from underlying strata, such as Permo-Carboniferous or crystalline fractured rock aquifers in basement rocks. Such ratio distributions were used in these local studies to aid discrimination between aquifer source types, as well as potential sources of water for springs. Most conspicuously, this was done by Wolaver et al. (2020) who used the $^{87/86}Sr$ >0.715 observation in combination with thermal modelling to interpret that groundwater at Dalhousie Springs was being sourced from a combination of the J-K aquifer and the Crown Point Formation found within the underlying Permian Pedirka Basin (Figure 2.6).

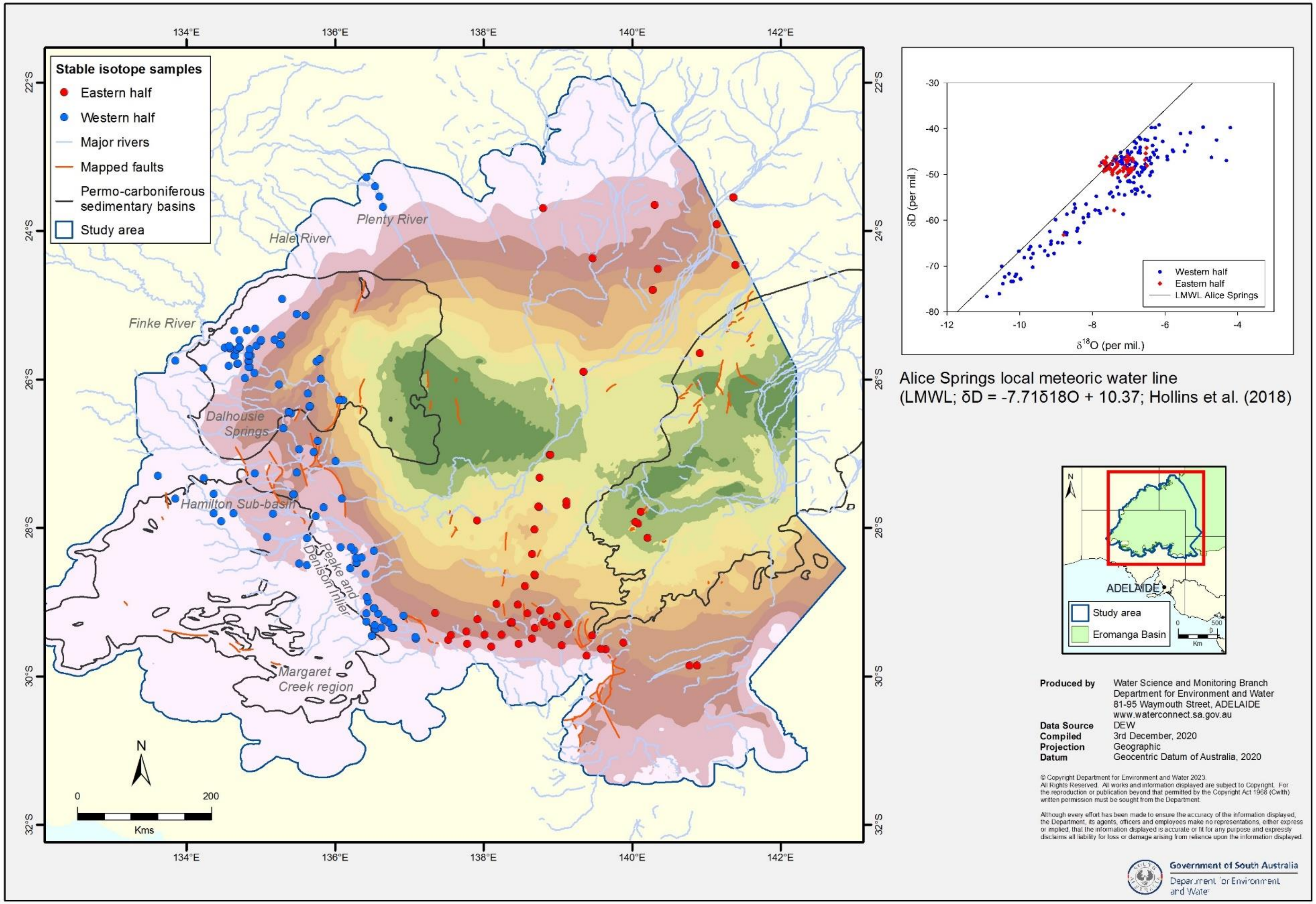


Figure 2.6: $\delta^{18}O$ vs δD, with Alice Springs local meteoric water line

2.5.3 Radioisotopic tracers and groundwater flow

A variety of radioisotopes have been collected from springs and wells within the study area, largely for the purposes of age-dating groundwater. One such purpose for age-dating groundwater is for the calculation of an apparent flow rate, which is the focus of the following discussion.

Radiocarbon (^{14}C) is typically used to date groundwater <30,000 years old, after which point dating becomes more unreliable. Consequently, ^{14}C is best used in areas where recharge zones and apparent flow paths away from such zones are implicitly understood. Priestley et al. (2020) noted that relatively high ^{14}C activity (>9.3 ^{14}C pMC) is recorded in samples from the Finke and Plenty River regions of the NT, as well as more restricted locations near Marla, the Peake and Denison Inliers and along the southern margin of the study area, but in particular the Margaret Creek region. As discussed in Chapter 3, all these areas have been examined with respect to being zones of potential recharge to the Main Eromanga Aquifer Sequence based on these results. Love et al. (2013b) detailed the use of ^{14}C to estimate horizontal flow velocities of 0.05 m/y (east of the Peak and Denison Inliers) between 3.6 and 7.6 m/y (Finke River, NT) and between 6.2 and 20.9 m/y (Hale River, NT). These flow rates are comparable to an earlier study by Matthews (1997), who also used ^{14}C to measure flow rates between 0.8 and 2 m/y in the NT portion of the Eromanga Basin.

As well as ^{14}C, there have been several other radioisotopes used to date groundwater within the study area. One of the more common traces that is applied to groundwater-flow velocity determination, is Chlorine 36 (^{36}Cl), which is used to date groundwater in the range of 100,000 to 1 Ma as well as relatively young water. One of the most pertinent studies to this conceptualisation to have used ^{36}Cl to calculate a flow velocity is Love et al. (2000) who used water well-derived samples collected along two transects west of the Peake and Denison Inliers to determine a flow rate of approximately 0.24 (± 0.03) m/y. Similarly, Phillips (1993) determined a flow rate of 1.3 m/y using ^{36}Cl data from Bentley et al. (1986), considering a study area covering eastern and central Qld and a small portion of north-eastern SA.

However, recent studies have highlighted issues pertaining to the potential for ambiguity when using radioisotopes as age tracers and the importance of undertaking comparative studies. In their study conducted in the Margaret Creek region near the south-western corner of the study area, Priestley et al. (2017) found an ambiguity when comparing the interpreted age provided by several tracers, including ^{36}Cl, ^{14}C and Helium 4 (^{4}He) from the same sample. Priestley et al. (2017) attributed this discrepancy to diffusive transport across flow paths caused by low recharge rates.

More recently, Suckow et al. (2020) presented a study conducted over the Mimosa Syncline in the Surat Basin portion of the GAB hydrogeological super-basin in Queensland. Here, apparent ages for ^{14}C and ^{36}Cl from groundwater samples collected from the Hutton Sandstone aquifer were calculated to try to determine a flow direction and velocity. Based on the calculated apparent ages, flow velocities that differed by one order of magnitude were returned (0.25 m/y for ^{14}C versus 0.025 m/y for ^{36}Cl). Suckow et al. (2020) interpreted that dual porosity was potentially causing the discrepancy in age after discounting for dilution by non-radioactive C and Cl models and reviewing the sedimentology of the Hutton Sandstone. Such dual porosity aquifers may include those with clay lenses, those with developed inter-granular or fracture porosity or thin aquifers surrounded by thick aquitards. Consequently, radioisotopes within the low permeability portions of the aquifer are not only lost through radioactive decay, but also by diffusion into the stagnant matrix of the low permeability portions (Suckow et al. 2020). Further, the rate of diffusion varies between tracers. After applying diffusion-based models for each tracer, a more likely velocity of 0.7 m/y was determined. Suckow et al. (2020) concluded that ^{36}Cl was more likely to be impacted by dual porosity than ^{14}C, but without the analysis of both tracers, the potential for dual porosity impacts would not be recognised.

This study by Suckow et al. (2020), when combined with that from Priestley et al. (2017), Bentley et al. (1986) and others, does highlight the need for caution when using tracer data to determine groundwater velocity for modelling purposes. Several hydrochemical and physical factors that limit the accuracy of calculated velocities may affect the migration of individual tracers. Further, multiple tracer analyses are often required to recognise whether such factors are significant.

3 Recharge and lateral inflow

Recharge and lateral inflow are key components of any hydrogeological system and therefore important elements of a conceptual hydrogeological model (CHM). Consequently, a good understanding of recharge processes is required for numerical modelling, not only because that is a fundamental element of any CHM, but also to ensure correct assumptions are made regarding the recharge distribution and magnitude, both in the past and at the present time.

The transient nature of groundwater recharge identified by Love et al. (2013b) and Ransley and Smerdon (2012) that is concomitant with variations in paleoclimate during the Cenozoic adds an extra complexity to the CHM, in that it is unlikely that the system encapsulated within the study area was ever in steady state. Further, although rates of recharge and discharge still have a high degree of uncertainty, modelling work by Rousseau-Gueutin et al. (2013) and Welsh et al. (2012) suggest contemporaneous recharge is much lower than discharge and therefore the GAB hydrogeological super-basin is likely to be in a natural state of long term, slow decline controlled by paleoclimate.

Recharge mechanisms identified within the study area by Love et al. (2013b) include direct recharge through outcropping or sub-cropping aquifer units, via contact with the modern-day drainage system (Ephemeral River Recharge or ERR), via cross formational flow in the form of Mountain System Recharge (MSR) or via diffuse recharge. The relative importance of each mechanism is dependent on the extent of outcrop or sub-crop, the presence, absence, and hydrogeological properties, and/or the degree of porosity-forming deformation. With respect to confining units, hydrogeological properties of importance include the thickness of the unit, the prevailing vertical hydraulic conductivity, and the prevailing head gradient.

The potential for inter-aquifer connectivity between the Main Eromanga Aquifer Sequence with overlying or underlying aquifers within the study area as a source of recharge to the former, while recognised as important, is discussed in Volume 2 of this report.

3.1 Data and methods

Relevant recharge data has been predominantly sourced from a literature review of previous studies (for example, Love et al. 2013a; Wohling et al. 2013b; Figure 3.1). Recharge extent and rates were collated for both diffuse and focused (for example, ephemeral river and mountain system) recharge mechanisms.

To augment this previous research, Chloride Mass Balance (CMB) analysis was conducted using hydrochemistry results from several bores, to supplement older work on recharge. Further, sufficient monitoring data has been found co-incident with a known area of interpreted recharge near Marla to undertake an assessment with respect to recharge. These two investigations are discussed further in the following sections.

3.1.1 Comparison of well hydrographs to rainfall

Comparing rainfall totals to water levels in wells screening water table aquifers within a given area is a useful way of analysing the link between rainfall and groundwater recharge. One of the few places in SA where a monitoring network exists in the J-K aquifer that may receive rainfall-derived recharge is near Marla (Figure 3.1). The monitoring network is located near the town water supply bores. Sheard (1981) reported that recharge to shallow unconfined aquifers inclusive of the J-K aquifer was likely to be occurring within an ephemeral wetland area. To assess this further and to begin quantifying the likely impact of rainfall on the local water table, the cumulative deviation from the monthly average rainfall was calculated and compared to water levels from observation bores within the region.

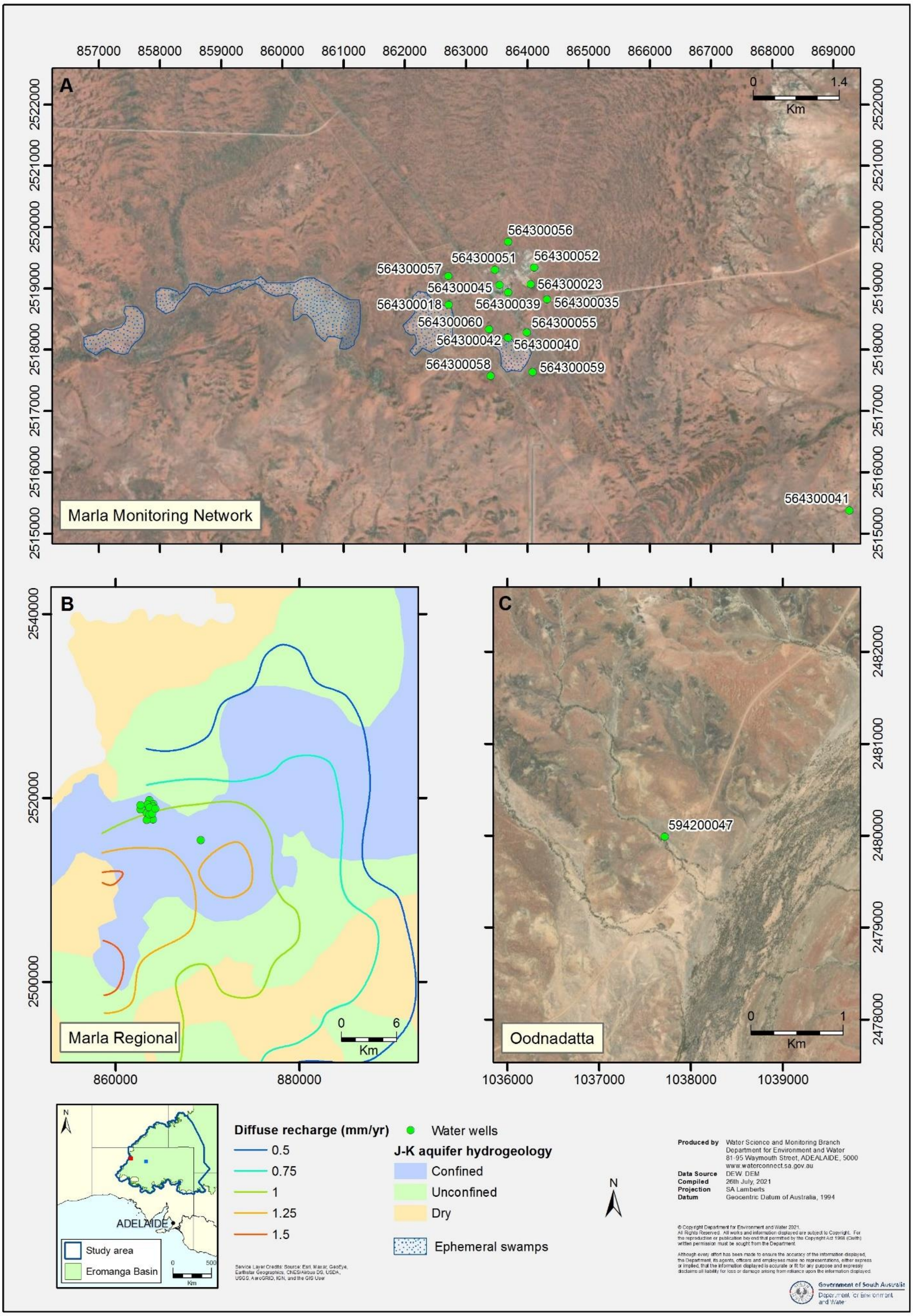


Figure 3.1: A) Marla monitoring well network, B) diffuse recharge estimates from Wohling et al. (2013b) and C) Oodnadatta water well used in D analysis

To calculate the cumulative rainfall deviation from the average (CRD) for rainfall, firstly an average of rainfall for each month over the recorded period is calculated. This number for each given month is then subtracted from the equivalent monthly record to determine the monthly deviation from the average. Finally, the deviation from each month is sequentially added to the previous month to obtain a cumulative deviation from the monthly average. The resultant graph can be used to highlight trends in rainfall and therefore any likely impacts on water table level.

Where the graph is in decline, it means that sequential months over the period in question are all reported as having below average rainfall. Conversely, where the graph rises, the reverse is true, indicating a wetter period. Finally, where the graph is neither rising nor falling significantly, sequential months for the given period have reports of rainfall at or near the long-term averages for each of the months.

Consequently, if rainfall were the primary input affecting the water table in the region surrounding Marla, the trend of water table levels might be expected to respond similarly to the CRD. Rainfall for the region is being represented here by data from two weather stations, namely Marla Police Station (16085) and Mintabie (16064), so the full period of groundwater monitoring can be compared. The close similarity in rainfall totals and CRD between the two stations where they overlap indicates that this treatment is reasonable.

Further, one well (594200047) near the township of Oodnadatta was also compared to CRD data obtained from the Oodnadatta Airport (17045) weather station due to an apparent correlation between the two (Figure 3.1).

3.1.2 Direct recharge estimate

A preliminary estimate of the recharge rate and volume was calculated for the Marla region. Recharge rates for times corresponding to increases in water table height were estimated using the formula (Leaney et al. (2011):

$$R = S_y \left(\frac{dh}{dt}\right) \qquad (2)$$

Where *R* is recharge (m/y), S_y is the specific yield (estimated at 5% based on effective porosity from Kellett et al. (1999)) *dh* is the change in groundwater height and *dt* is the time over which the change in height occurred. Sixteen (16) hydrographs from the Marla network were examined. In most cases, a recharge event from the mid-1980s and/or the early 1990s was examined. Other minor recharge events from the mid-2000s and mid 2010s also occurred but in general the data was not as clear (Appendix A).

3.1.3 Chloride mass balance (CMB) recharge estimates

A saturated CMB approach by Gee et al. (2004) was used to derive an estimate of diffuse recharge to aquifers where possible in the Mt Willoughby region of the study area (Figure 3.2). This area overlaps with a study area used for a similar focus presented by Wohling et al (2013b); however, results from the two studies have not been combined and are discussed separately.

The CMB method assumes that all chloride in the target aquifer is derived from atmospheric inputs and that chloride has conservative characteristics in the vadose zone. The CMB method also assumes that the chloride deposition rate has not varied over time and that steady state conditions exist in the aquifer. If the loss of chloride to overland flow and evapotranspiration is negligible and the addition of chloride from rock weathering is immaterial, then estimates of recharge using the following relationship can be derived:

$$R = \frac{p \times Cl_p}{Cl_{gw}} \qquad (2)$$

Where *R* is recharge (mm/y), *p* is precipitation (mm/y), Cl_p is the chloride concentration in precipitation (mg/L), and Cl_{gw} is the chloride concentration in groundwater (mg/L).

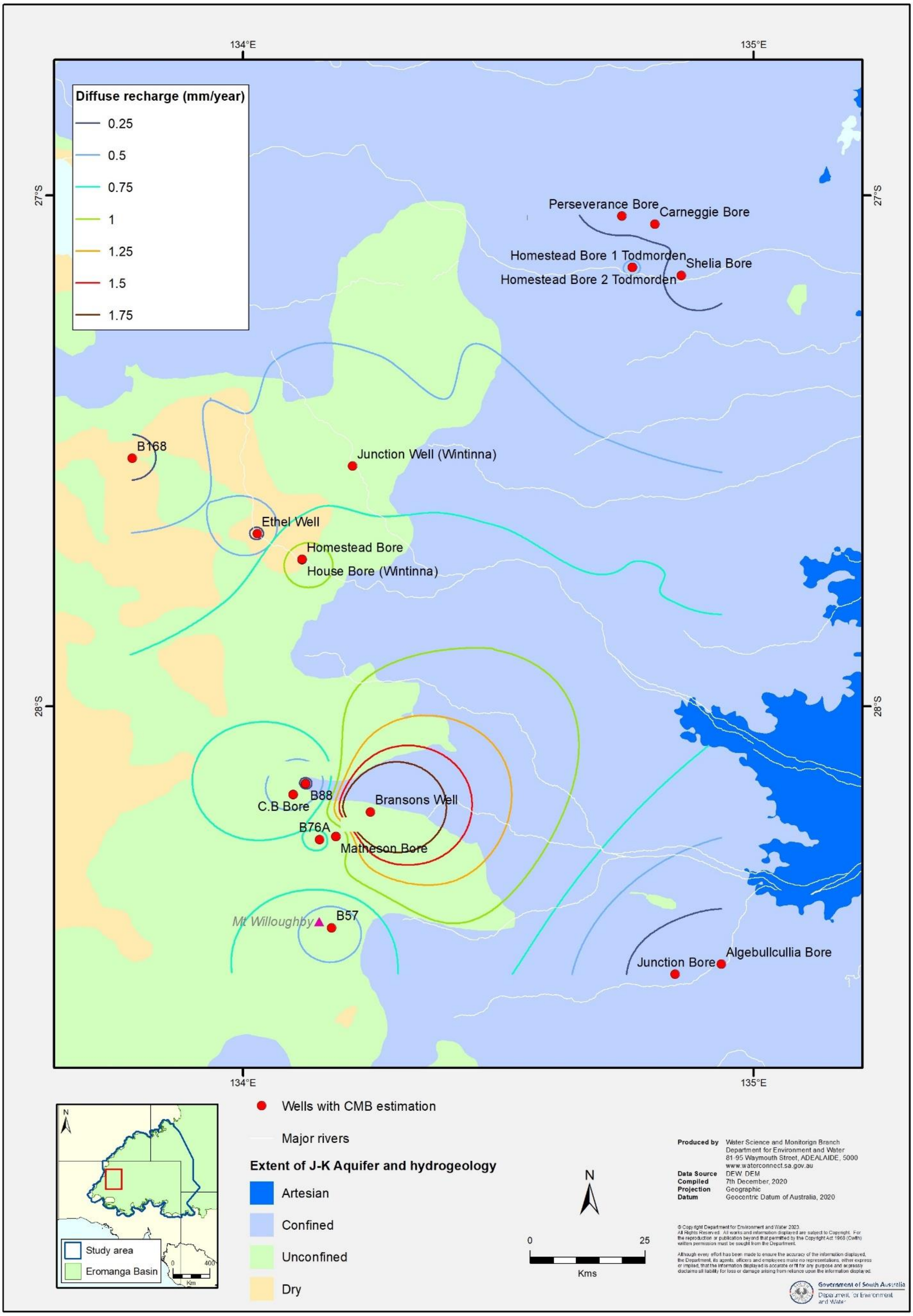


Figure 3.2: Location map of wells used to estimate recharge via CMB and CMB results

Chloride deposition can take the form of wet (rainfall) or dry (aerosols) deposition, where the mass of wet and dry chloride deposition is known the recharge relationship can be further simplified to:

$$R = \frac{Cl_{dwdf}}{Cl_{gw}} \times 100 \quad (3)$$

Where Cl_{dwdf} is the chloride deposition from wet and dry fallout (kg/ha/y).

Point estimates of chloride deposition at each of the well sites were estimated using the Australian 0.05° gridded chloride deposition spatial coverage (Davies and Crosbie 2014). There is uncertainty associated with the chloride deposition rate as these values were obtained from a national interpolated surface with only one data point near the study area and very limited data coverage in Central Australia. Given the generalisations and uncertainties characteristic of the data used to undertake this CMB-based assessment of diffuse recharge, it must be emphasised that the rates obtained are order of magnitude estimates only.

Well details and estimated chloride deposition at each site included in this study as extracted from Davies and Crosbie (2014) is provided in (Table 3.1). The following wells were analysed using CMB after reports by Smith (1976) found that groundwater within a fractured rock aquifer within the Bulldog Shale appeared to be transient, with the interpretation being groundwater in the shallow aquifers was recharging the underlying J-K aquifer.

3.2 Lateral inflow

The largest proportion of inflow into the study area originates from the NT, Qld, and NSW (Figure 3.3). Work by Love et al. (2013b) suggests that the proportion of inflow from Qld and NSW is less than previously thought, whereas estimates of inflow from the NT are greater. However, the work conducted to develop a potentiometric surface detailed in Volume 4 suggests that inflows from Queensland are still of primary importance. Volume 7 of this report presents groundwater inflow estimates. This volume contains an estimated total of 457 ML/d of lateral inflow within the J-K aquifer into the study area.

An unknown contribution to lateral inflow into the Main Eromanga Aquifer Sequence within the study area is from the Officer Basin along the western margin of the Eromanga Basin, and inflow inferred via the interpreted potentiometric surface (Figure 3.3). Little is known concerning the hydrogeology of the Officer Basin with respect to connectivity with the GAB. Alexander and Dodds (1997) interpreted recharge to occur via several Cenozoic paleo-drainages that extend from the Musgrave Ranges, as well as localised recharge, whereas Lau et al. (1995a and b) described the general hydrogeology in simplistic terms as an unconfined system underlain by Precambrian basement rocks.

3.3 Diffuse recharge

Diffuse recharge for this study is groundwater that recharges the J-K Aquifer in a manner that is not focused but is dispersed over a relatively large area. Recent work has suggested that diffuse recharge to the J-K aquifer along the western margin of the Eromanga Basin is relatively small compared to other sources of water such as lateral inflow. Similarly, Wohling et al. (2013b) estimated diffuse recharge within the western Eromanga Basin to be approximately 0.15 mm/y, within a range of between <0.1 mm/y to 1.8 mm/y reported near Marla (Figure 3.1B). Estimated figures were corroborated using 14C and coring results in discrete areas but are approximations at best given uncertainties in the applied method. Similarly, Kellett et al. (1999) used CMB to estimate recharge rates of between 0.1 to 5 mm/y in the southern portion of the study area and Love et al. (2000) estimated 0.16 ± 0.08 mm/y west of the Peake and Denison Inliers (Figure 3.3).

Table 3.1: Input drill-hole data used and calculated CMB-based recharge for drill-hole data in Mt Willoughby area

Name	Cl mg/L	East	North	Aquifer	Cl dwdf	Recharge rate mm/y
Shelia Bore	1247.97	486024	6996243	QT	1.368363	0.110
Carneggie Bore	1127.9	480853	7007381	QT	1.330359	0.118
Perseverance Bore	1066.9	474440	7009092	QT	1.329437	0.125
House Bore (Wintinna)	111.13	412854	6934311	QT	1.600634	1.440
Homestead bore	223.84	412853	6934388	QT	1.600634	0.715
Homestead Bore 2 Todmorden	241.3	476512	6997977	QT	1.366812	0.566
Junction Well (Wintinna)	278.23	422466.8	6954682	QT	1.525723	0.548
Homestead Bore 1 Todmorden	295.89	476482	6997977	QT	1.366812	0.462
Ethel Well	717.56	404154.8	6939877	QT	1.575095	0.220
Bransons well	49	426393	6879692	T	1.9176	3.954
Algebullcullia	1443.35	493835.4	6846917	JK1	2.081945	0.144
Junction Bore	1362.23	485001.7	6844734	JK1	2.088972	0.153
B88	978	413908	6885742	Kmb	1.884463	0.193
B88	969	413908	6885742	Kmb	1.884463	0.194
B88	955	413908	6885742	Kmb	1.884463	0.197
B88	953	413908	6885742	Kmb	1.884463	0.198
B168	737	379882	6956011	Kmb	1.521353	0.206
B57	681	419094	6854553	Kmb	2.125942	0.312
C.B bore	542.6	411528	6883420	Kmb	1.884463	0.347
C.B bore	530	411528	6883420	Kmb	1.884463	0.356
B76A	294	416686	6873679	Kmb	1.956798	0.666
Matheson Bore	244	419752	6874367	Kmb	1.95542	0.801
Matheson Bore	219	419752	6874367	Kmb	1.95542	0.893

Note: QT: Quaternary/Tertiary alluvial aquifer; T: Tertiary aquifer; JK1: J-K aquifer; Kmb: Bulldog Shale; Cldwdf: chloride deposition from wet and dry fallout (from Davies and Crosbie 2014)

To complement works undertaken by Wohling et al. (2013b), results of the CMB analysis to calculate possible recharge in the Mt Willoughby region of the study area are presented in Table 3.1. Recharge rates to the J-K aquifer and overlying Bulldog Shale vary between 0.2 and 0.9 mm/y. Calculated recharge to shallower aquifers was comparable, although notably there were two greater than 1 mm/y. Figure 3.2 provides well locations and results. These results are like previous estimates described above.

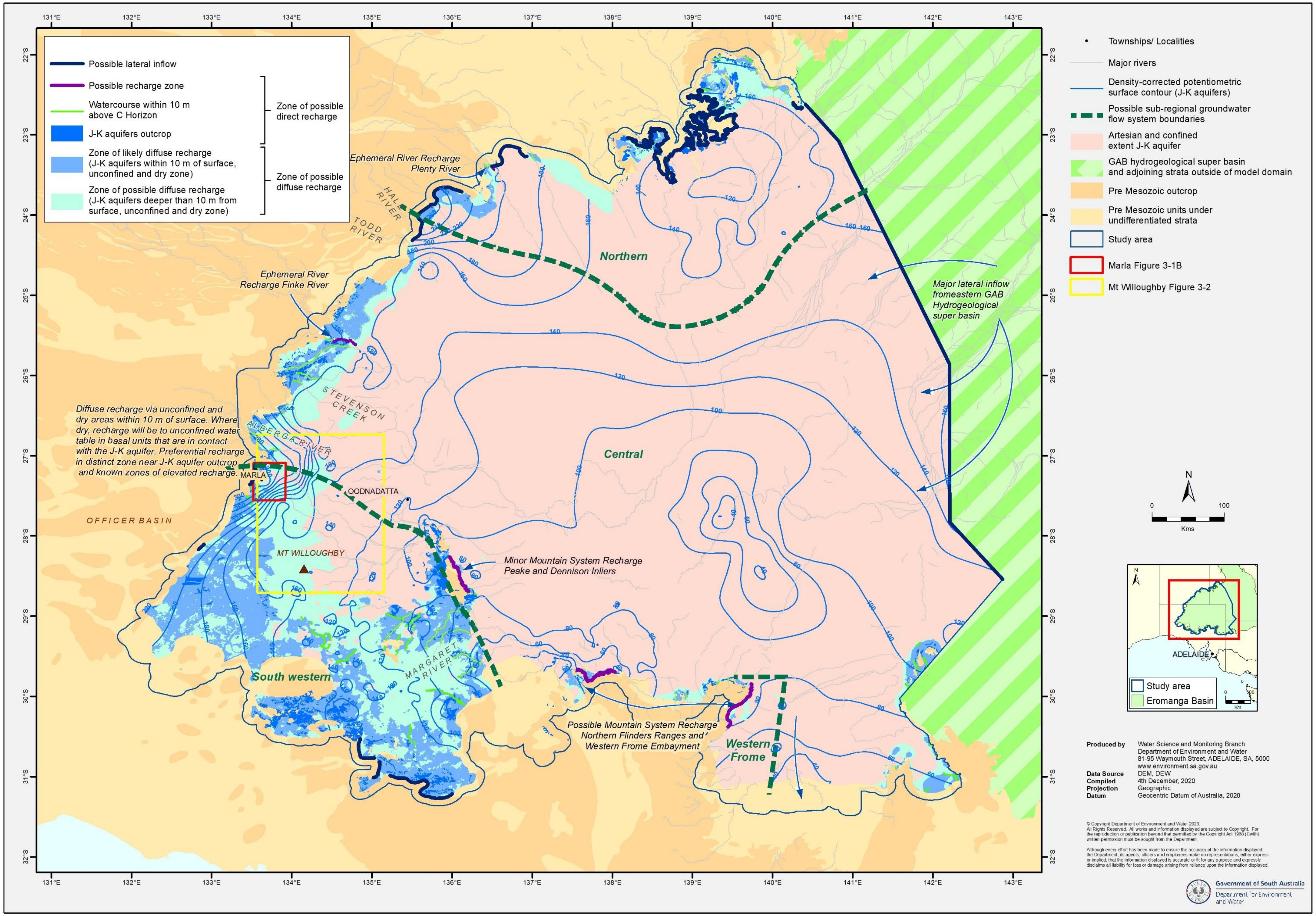


Figure 3.3: Conceptualisation of recharge and lateral inflow

Diffuse recharge from rainfall is conceptualised as most likely in areas where the depth to the J-K aquifer is less than 10 m. The 10 m depth is an arbitrary figure that considers natural error within the datasets used to determine land and structure surface elevations. Such areas occur along the western and south-western margin as well as limited areas along the margin of the Northern Flinders Ranges (Figure 3.3). This area is approximately 60,450 km2 or approximately 8% of the study area. Using the rate developed by Wohling et al. (2013b) and Love et al. (2000) provides a total volumetric rate if diffuse recharge of approximately 25 ML/d. Using the error range developed by Love et al. (2000), this recharge volume may vary between 13 and 40 ML/d.

Finally, Suckow et al. (2020) determined a recharge rate to the Hutton Sandstone in the Mimosa Syncline region of the Surat Basin, Queensland of 452 ML/y using tracer data, which contrasts with previous studies suggesting a recharge rate of 17 GL/y using CMB. Suckow et al (2020) considered both estimations valid for different conceptualisations, with the latter related to recharge into outcrop that includes a component of 'rejected recharge', whereas the former number is representative of flux into the confined aquifer system. Although the Hutton Sandstone is an important component of the Main Eromanga Aquifer Sequence in SA, recharge rates as determined by Suckow et al. (2020) are not directly applicable to the model for this study, given its spatial domain. That being said, data from Suckow et al. (2020) could be used as qualitative targets for the modelling work or used as a weighting to limit their influence on the calibration.

3.4 Direct and episodic recharge

Cenozoic alluvial aquifers or Neocretaceous aquifers in outcrop may receive episodic recharge via rainfall and resultant streamflow/runoff. Underlying aquifers in contact with these units also receive groundwater recharge if a relative downward pressure gradient and a feasible lithological or structural connectivity pathway exists. Areas where this may occur include the north-western and south-western margin of the Eromanga Basin, where several streams and associated alluvium deposits occur. Ransley and Smerdon (2012) suggested total recharge in the western portion of the GAB to be approximately 6,600 ML/y. However, areas of potential recharge near Mount Willoughby, Margaret River, and the Northern Flinders Ranges may not be counted in this, although such areas may not markedly increase this recharge estimate.

Direct recharge via aquifer outcrop may also occur near the Peake and Denison Inliers, along the margins of the Northern Finders Ranges and the far west near Marla (Figure 3.3) (Sheard 1981; Sheard 1982), as well as via fractured Bulldog Shale in the unconfined portions of the basin (Smith 1976). Smith (1976) suggested that groundwater in fractured Bulldog Shale near Mt Willoughby (Figure 3.3) was leaking downward into the J-K aquifer beneath based on observations taken over two field campaigns. In contrast, Fulton et al. (2013) did not find evidence for recharge through an interpreted fracture zone within the Bulldog Shale within the Finke River, NT.

3.4.1 Comparison of well hydrographs to rainfall – Marla monitoring network and Oodnadatta.

With respect to direct recharge near Marla, such an interpretation can be examined because Marla is one of the few places in SA where a monitoring network exists in a part of the GAB hydrogeological super-basin that may receive rainfall-derived recharge. Sheard (1981) reported that recharge to shallow unconfined aquifers inclusive of the J-K aquifer was likely to be occurring within an ephemeral wetland area. To assess this further and to begin quantifying the likely impact of rainfall on the local water table, the CRD rainfall was calculated and compared to water levels from observation bores within the region. Appendix A presents hydrographs and CRD rainfall.

Where the monitoring record is sufficiently long, hydrograph data from many of the wells reflect gross trends observed in CRD. This correlation suggests that local rainfall is recharging the water table in this western region, and, by extension, indicates that the region is a zone of recharge to the J-K aquifer. Such a correlation indicates a link between recharge to the J-K aquifer in this area and seasonal rainfall.

A preliminary average recharge rate of approximately 0.2 m/y was estimated using hydrograph data, with individual rates ranging from 0.03 to 0.5 m/y. The average time over which these rates occurred was 1.1 years. Further, an ephemeral wetland area of approximately 2.3 km2 estimated from satellite imagery (Figure 3.1) was used to obtain a recharge volume of approximately 465,600 m3/y (1.3 ML/d).

However, such recharge events are relatively rare and episodic. Consequently, the annualised rate and volume are much smaller; using an assumption that such events occur over roughly decadal intervals, a recharge volume of 0.1 ML/d can be determined. Whilst this figure might be extrapolated to describe direct recharge rates across the study area, the rate and the area over which it could be applied (approximately 1% of the model area) is sufficiently small to be regarded as negligible.

A similar trend, although captured over a shorter time-period, was observed within an artesian well located near Oodnadatta (Figure 3.1C). Well unit number 594200047 displays a <1 m fluctuation that appears to mimic CRD for rainfall as recorded at Oodnadatta Airport. The well has a total depth of 365 m bgs with the top of the screened interval (or casing point) at 341 m bgs and an artesian water level approximately 18 m above ground surface. The well is located within a small tributary to the Neales River, which is about 800 m away. Given this well is artesian, the correlation between head measurement and CRD is highly unlikely to reflect recharge processes. More likely, pressure within this well is reflecting changes in abstraction related to the availability of water for stock or is reflecting loading pressure of groundwater recharging overlying shallow aquifers.

Interestingly, in these areas where localised recharge has been found to, or is suspected to occur, groundwater with a major ion signature type of Ca^{2+}+HCO_3^- and predominantly low salinity was found in nearby wells (see Chapter 2 and Figure 2.2). Chebotarev (1952) first noted that such water chemistry was suggestive of recharge in a groundwater study of the Torrens Basin to the south of the study area. By extension, Sheard (1981) and Sheard (1982) also noted the potential for recharge-via-ephemeral-swamps near Marla, partly because of similar Ca^{2+}+HCO_3^- chemistries in groundwater. The low salinity and major ion hydrochemistry is suggestive of pedogenic calcrete dissolution in recently infiltrated rainwater. This signature then becomes overwhelmed via concentration of Na^+, Cl^- and other ions via evaporation or via mineral dissolution as groundwater migrates down gradient.

3.4.2 Ephemeral River Recharge

Ephemeral River Recharge (ERR) is recharge that occurs where aquifer strata are in contact with the base of ephemeral river channels, that lose water into the aquifer during times of inundation. Evidence for recharge via ERR from the Finke and Plenty Rivers in the NT was found by Matthews (1997) and Fulton et al. (2013) (Figure 3.3). Matthews (1997) considered elevated radiocarbon in groundwater near the Finke River and suggested that indirect recharge in the region could account for a bulk recharge of approximately 107 m3/y (27 ML/d) in the NT portion of the GAB. Fulton et al. (2013) determined that recharge near the Finke and Plenty rivers was linked to rainfall events greater than 100 mm/y and were annualised to rates of between 380 to 850 mm/y for the Finke River and 17 to 92 mm/y for the Plenty River. In the Plenty River case, recharge occurs within 2 branches; the recharge zone along the eastern branch is 1.88 km2 while the recharge zone for the west branch covers 0.96 km2. Fulton et al. (2013) described the reach of the Finke River where recharge occurs as approximately 35 km long and covering an area of approximately 13 km2. Therefore, volumes of recharge may reach the order of between 0.1 to 0.7 ML/d for the Plenty River and 13.5 to 30 ML/d for the Finke River.

Fulton et al. (2013) stated that the estimated total contribution from ERR ranges from 5,150 to 11,560 ML/y (14 to 32 ML/d). Further, Fulton et al. (2013) suggested there might be limited potential for recharge to the J-K aquifer via the Hale, Todd and Alberga Rivers, and Stevenson Creek, although this potential is largely based on a lack of data and in any case would require inter-aquifer connectivity with overlying strata (Figure 3.3).

Other areas where recharge may occur as indicated through the potentiometric surface and hydrochemistry (where available) includes near the south-western margin near Margaret Creek, particularly where the depth to the top of the J-K aquifer is less than 10 m (Figure 3.3). In the case of Margaret Creek, Keppel et al. (2015b) and Priestley et al. (2017) found some hydrochemical evidence for modern groundwater (Figure 3.3). and considered that recharge here was notably viable when heads in well couples completed in different aquifers were found to be comparable.

3.4.3 Mountain system recharge

MSR is the general term developed by Wohling et al. (2013a) to describe recharge to sedimentary basin strata via connectivity to fractured rock aquifers associated with mountain blocks and fronts on the margins of the basin. Rainfall in mountainous areas enters the fractured rock aquifer, which eventually migrates via gravity into the adjoining basinal aquifer. Minor recharge occurs via MSR near the Peake and Denison Inliers and potentially other elevated areas near the margins of the western Eromanga Basin (Figure 3.3). However, with respect to MSR and diffuse recharge, the latest research notes that, although such recharge may be occurring, total volumes may be very small. Love et al. (2013b) estimated MSR to be similar in magnitude to diffuse recharge rates calculated by Wohling et al. (2013b) using CMB.

4 Spring-related discharge

An important form of discharge from both the eastern and western portions of the J-K aquifer within the modelling domain are the 5,000-plus mapped GAB springs (Figure 1.1and Figure 5.1A). Springs occur from Lake Frome and the northern edge of the Flinders Ranges near the south-eastern corner of the study area, near the Torrens Hinge Zone and the Peake and Denison Inlier to the Dalhousie Anticline (Figure 5.1A). Groundwater flows to springs preferentially via lithological pathways, fractures and faults developed within the confining unit shales and/or thinning of the confining unit via uplift and erosion.

Springs are also an important focus of groundwater modelling because the discharge supports groundwater dependent ecosystems (GDE's) that are of national and international significance and therefore require protection and careful management.

Consequently, special attention has been made to describing spring-related discharge during this study so that springs may be properly represented in the final groundwater model. Further information discussed here is also designed to contribute to any future iterations of the groundwater model that may incorporate more detail concerning shallower strata.

As well as describing what is known about spring discharge pertinent to numerical model construction from the literature, a spring classification system was developed to guide spring representation in current and future groundwater modelling. Further, to ensure that all discharge attributable to spring environments is accounted for, mapping of diffuse discharge zone associated with spring environments was reviewed and expanded.

Relevant discharge data has been predominantly sourced from a literature review of previous studies. When considering discharge from springs, discussions concerning both direct (flowing) discharge and diffuse discharge have been considered. With respect to monitoring data from springs, periodic flow measurement data taken at Dalhousie Springs and near Lake Eyre South (time series data) is presented and discussed separately in Volume 5 of this report.

4.1 Spring discharge

Published estimates of spring discharge vary; however, most suggest spring flow in SA equates to more than 60 ML/d of discharge from the GAB. Using measured and estimated gauging data collected by Williams (1974), Boucaut et al (1986) reported a total spring discharge of approximately 23,500 ML/y (≈64 ML/d) for SA, with approximately 20,500 ML/y (≈ 56 ML/d) attributable to Dalhousie Springs, in the far north of the state (Figure 1.1). In their water balance, South Australian Arid Lands Natural Resources Management Board (SAAL NRM) (2009) attributed 24.1 GL/y (≈ 66 ML/d) to spring discharge, based off modelling work undertaken by Welsh (2000). Calibration targets used for model construction by Golder (2015) for Olympic Dam wellfield operations suggested a total spring discharge of approximately 76 ML/d, with the biggest spring group by discharge again being Dalhousie Springs. Not all spring groups appear to have been represented in the Golder (2015) figure. Further, since these estimates, the number of mapped and catalogued spring points has increased (Gotch, 2013; Keppel et al. 2016) and so these figures may under-represent total spring discharge; a current audit of the State Government managed online database SA_Geodata puts the number of spring points at over 5,100. It should be noted that these estimates are like to be highly uncertain due to the inherent difficulties in measuring flows as well as readily accessing springs for measurement.

In contrast, Habermehl (1980) stated that spring discharge for the entire GAB equated to 1,500 L/s (≈130 ML/d), suggesting the SA springs contribute approximately half of all spring discharge.

Additionally, spring flow has been estimated to fluctuate over time, predominantly because of groundwater extraction. For instance, Boucaut et al (1986) noted that total flow at Dalhousie Springs appeared to have declined from 20,500 ML/y to 19,300 ML/y (≈ 53 ML/d) between gauging events conducted between 1974 and 1985, whilst BHP (2018) and Volume 5 describe historical fluctuations in spring flow associated with variations in groundwater extraction from the Olympic Dam wellfields.

Adding to the limitations regarding spring flow estimation is the paucity of gauging data. Current spring flow monitoring is not considered sufficient to quantify spring discharge volumes for water balance purposes. Most springs in SA are not regularly monitored; consequently, the relationship between spring flow and changes in groundwater pressure over time are not quantified. Spring flow monitoring programs are largely designed to provide an indication of change, which is then used to represent impacts on larger spring systems. The regular spring flow data that is currently available is presented and discussed in Volume 5 of this report.

With respect to other forms of discharge, spring discharge of between 64 to 76 ML/d represents a comparable, although smaller, volume to other outflow types estimated during water balance calculations for this study. In comparison, vertical leakage and diffuse discharge is 274 ML/d, lateral outflow 73 ML/d and water use via wells 134 ML/d. Discussion on how these estimates were calculated is provided in Volume 7 of this report.

Further, any estimation of discharge from spring zones needs to account for both direct and diffuse discharge, as areas of spring discharge are also likely to support diffuse discharge. Diffuse discharge mechanism estimates, and complicating factors are discussed in Chapter 7.

4.2 Spring Classification

A spring classification system was developed for this conceptual model with the aim of aiding spring representation within the numerical model. Springs in this classification system are categorised according to their primary structural controlling feature as well as with respect to interpreted structure surfaces. Conceptualisation was partly based on work undertaken by Keppel et al. (2015a) and Keppel et al. (2016) for springs within the Neales River, Lake Cadibarrawirracanna, Lake Blanche and Lake Callabonna regions, but expanded to include springs across the entire study area. In these previous works, each unique spring conceptual model was assigned a coding. For this work, classification is divided into 2 parts that are related to the depth to the source aquifer and the primary interpreted geological control giving rise to spring formation. Figure 4.1 presents a schematic depiction of each classification type.

In developing this classification system, we recognise that strata above the Main Eromanga Aquifer Sequence are not being explicitly represented in this phase of work, although this may change later. Consequently, the classification system is designed to highlight the key features of springs with respect to what evidence they may provide about either structural deformation specifically within the Main Eromanga Aquifer Sequence, or the likely source of groundwater. However, enough detail has been provided that if shallower strata are explicitly represented later, sufficient information about spring configuration is captured such that it may be considered during model construction.

Springs were first ordered with respect to the depth to the top of the Cadna-owie Formation (C Horizon, Table 1.1) as developed for this project. Ordering was based upon a normal distribution of depths to the C Horizon found underneath springs. Four populations were interpreted that generally correlated to depths of 10, 20, 100 and 380 m bgs (Figure 4.2). The demarcation depth between populations represents a rounded figure to the nearest simple integer interpreted from the normal distribution and as such it is recognised that there may be some overlap in the distributions of each group. This analysis does not imply any direct correlation between spring formation and depth to the C Horizon (Table 1.1); rather, these populations are likely to represent a general relationship pertaining to geological controls and where these controls occur with respect to confining unit thickness. These populations are used here to direct conceptualisation and ultimately the degree of complexity required to depict them numerically, particularly with respect to the impact such geology has on regional hydrogeology.

For example, a spring that occurs where there is a very thin confining unit may be represented simply; however, where the confining unit is thick and faulting has been interpreted, springs may be used as evidence for the impact of faulting on hydrogeology and therefore a more complex depiction is required.

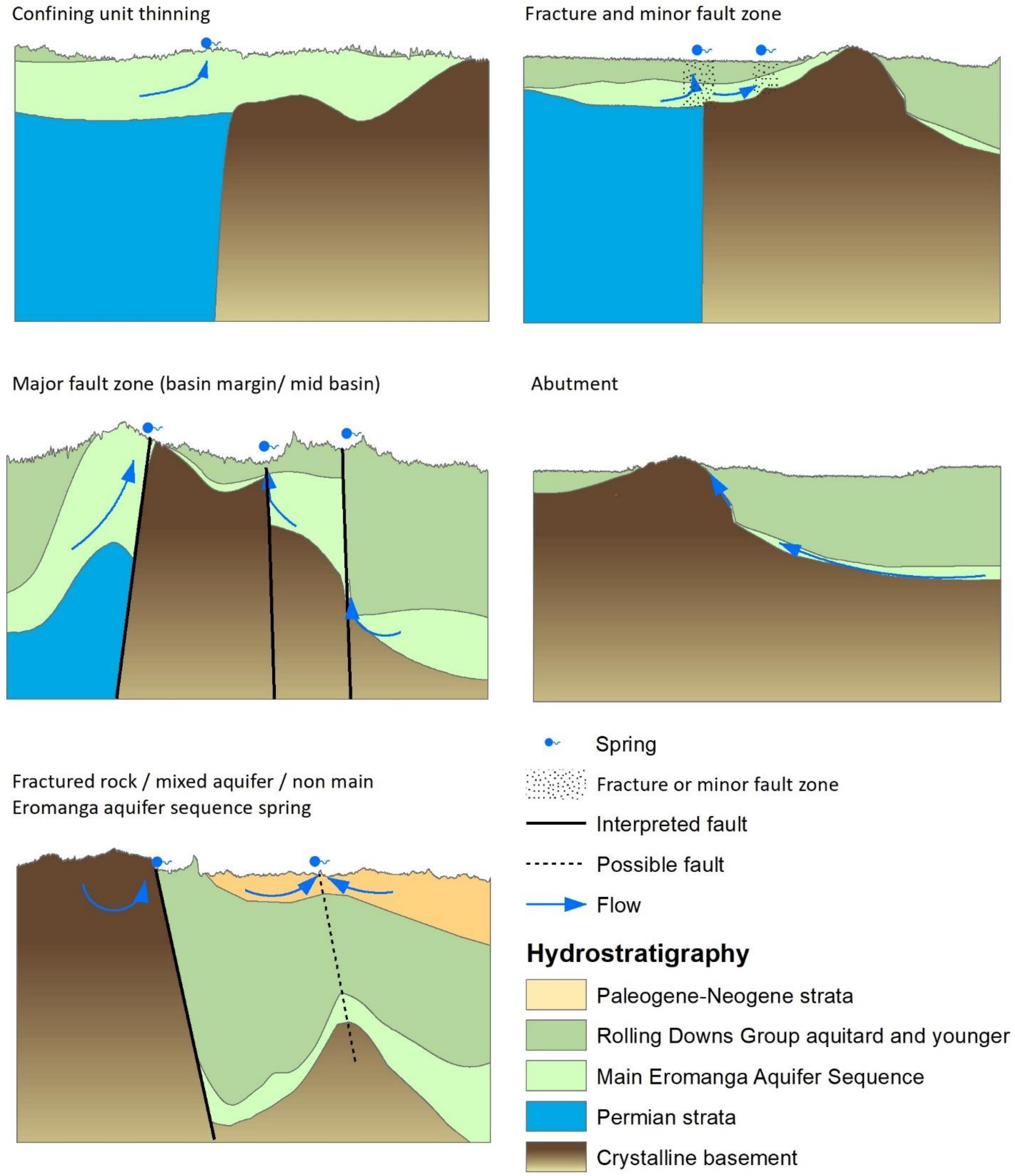


Figure 4.1: Schematic diagrams of various geological classifications

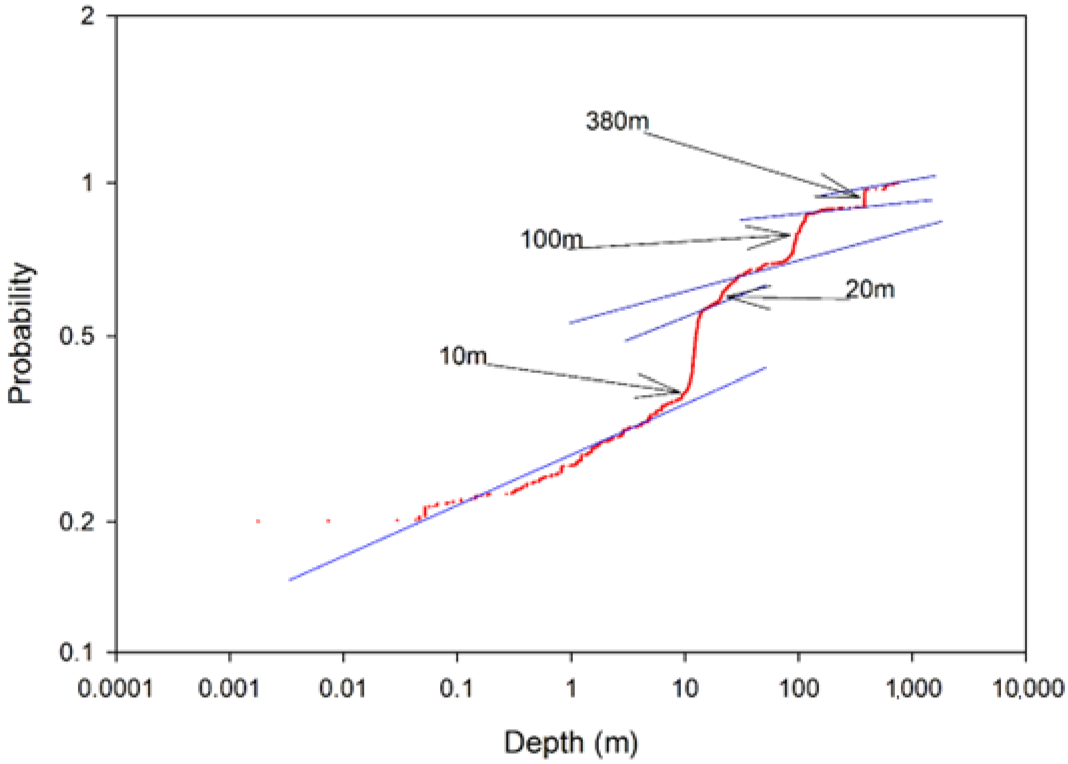


Figure 4.2: Normal probability plot of spring depth

Mapped springs were then grouped into one of 5 possible classification types based on the depth analysis as well as a comparison to the structural and outcrop geology found near springs. In general, there were 5 classifications developed:

- Confining unit thinning
- Fracture and minor fault zone (including monoclines)
- Major fault zone, either at the basin margin or mid-basin
- Abutment zone
- Mixed aquifer or non-Main Eromanga Aquifer Sequence springs.

Figure 4.1 provides a schematic representation of these geological classification types.

The basis of classification centres on the spring location with respect to 3 features associated with the structure surfaces developed for the numerical model:

a) The thickness of cover above the J-K aquifer (C Horizon)

b) the proximity of the spring to a fault mappable within the datasets

c) the slope of the structure surface or location of basement high near a spring location.

Further, it may be possible to categorise a given spring in a few geological classification types as there may be multiple lines of evidence pointing to more than one influence or there may be similarities between classification types. Classification in such instances favours an interpretation of the most significant factor to spring formation in combination with consideration of numerical model scale and construction limitations.

The various spring classifications as well as presenting spring locations with respect to this system are described in detail below:

4.2.1 Confining unit thinning type

Where springs occur in regions with less than 20 m of confining unit cover, an important reason for spring formation is interpreted to be a thinning and possible breaching of the Mesozoic confining unit by erosion (Figure 4.1). Prominent examples of such springs occur west of the Peake and Dennison Inlier (Figure 4.3). In such cases, weathering and associated regolith processes such as secondary cementation and subsequent hardpan development have combined with gradual removal of confining unit materials and concomitant lowering of topographic elevation to allow the windowing of the water table and the formation of the spring environment observed.

In some cases, minor fracture development within outcropping aquifer material or local variations in weathering and regolith process may form discrete spring vents; however, rock failures responsible for conduit formation may be very small in scale. Small-scale structures may be associated with deeper-seated structures, but these may not be resolvable using regional-scale geophysical data sets. In such cases, the employment of local-scale geophysics may be helpful to clarify controls on spring formation.

In the same way, springs may also form within discernible fault zones or major structural discontinuities that are also associated with confining unit thinning. Such examples include faulting at Dalhousie Springs as well as springs associated with the astrobleme at Mount Toondina, or within water courses that appear to have preferentially developed along zones of structural deformation.

4.2.2 Fracture and minor fault zone type

Fracture and minor fault zone types relate to springs that occur in regions where the depth to the J-K aquifer is greater than 20 m; however, there is no fault structure discernible via displaced or juxtaposed aquifer units using the datasets employed to develop structure surfaces. Consequently, conduit formation allowing groundwater to migrate through the confining unit is interpreted to be related to a fracture zone (Figure 4.1).

The cause of fracture development may vary. One possibility is that faults prominent in crystalline basement that may have had some influence in determining basinal configuration have only recently extended into overlying strata via a fault ‘tip’ (Curewitz and Karson 1997). This contemporaneous development has not had sufficient time to cause deformation to the same extent as observed in the crystalline basement. Therefore conceptually, spring propagation is associated with networks of smaller fractures that are concentrated in zones where basement structures are reactivated to form monoclinal flexures and fault propagation folds (Karlstrom et al. 2013) and possibly dilate in response to the inherent tectonic stress regime and hydraulic pressure. This may be particularly relevant in parts of the study area underlain by rocks associated with the Adelaide Fold Belt, which has been highlighted as a zone of enhanced seismicity and preferential pressure release of continental stress (Leonard 2008; Louden 1995; Sandiford and Quigley 2009) (Figure 4.1 and Figure 4.3). Another possibility where faulting within the crystalline basement cannot be determined is that the associated differences in tensile strength and compressibility may lead to deformation of overlying sedimentary rocks in ways responsive to variations in the crystalline basement configuration. One of these potential responses is gentle slumping of overlying sediments with associated joints, fracture zones and minor fault development.

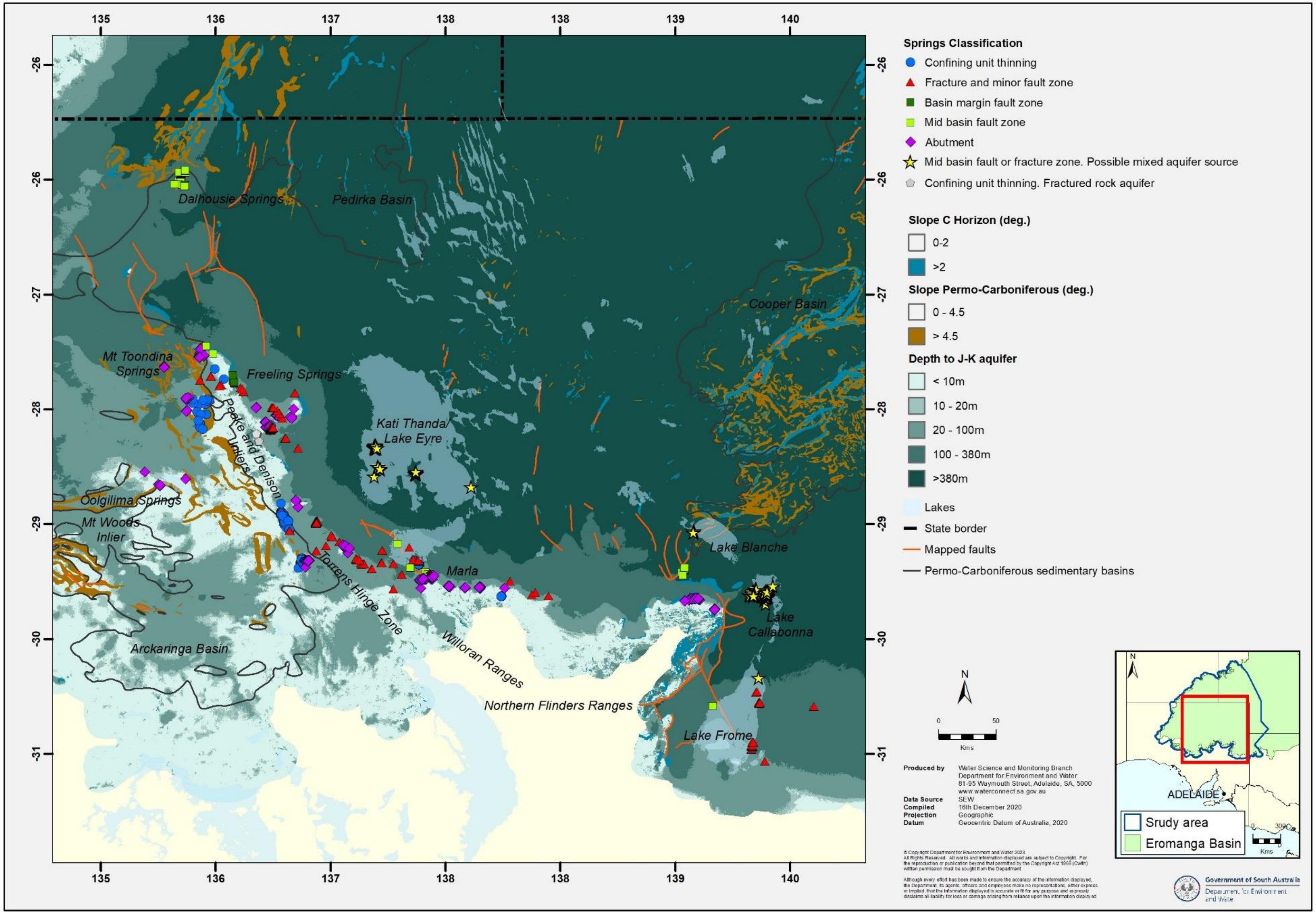


Figure 4.3: Springs grouped according to classification

Springs that can be classified using this model predominantly occur near the Peake and Denison Inlier, the Northern Flinders Ranges as well as springs located near the Torrens Hinge Zone. Here, spring localities are closely correlated to either the north-eastern margin of the Arckaringa Basin near the Boorthanna Trough or near the margin of a major trench or sub-surface inlier structure such as Oolgilima Springs located near the Mount Woods Inlier (Figure 4.3). Such margins represent zones where large changes in thickness of unconsolidated to consolidated younger sedimentary rocks overlying crystalline basement rocks occur. In Figure 4.3, these basin and trench margin areas have been highlighted where the slope of base Permo-Carboniferous sediment is steep compared to the rest of the basin. The proximity of springs at these locations suggests that, despite the lack of fault structures with discernible displacement and juxtaposition of aquifer units being resolvable, structural deformation associated with this margin and the coincident Torrens Hinge Zone may be responsible for spring formation (Figure 4.3). Given overlying sedimentary rocks in this instance are inclusive of Permo-Carboniferous strata, there appears to be at least a structural relationship between springs and the north-eastern margins of the Arckaringa Basin and the coincident Torrens Hinge Zone.

Classification between a minor or major fracture zone types is largely based on analysis of normal probability distribution of springs according to the depth to the J-K aquifer. Undertaking this analysis suggests that springs may be grouped into two populations that are in part correlated with spatial distribution (Figure 4.2). Springs that may be classified as minor are largely found around the margins of the Peake and Dennison Inliers and the margin of the GAB south of Maree (Figure 4.3). In contrast, springs that may be classified as major are predominantly located near the Torrens Hinge Zone between the Willoran Ranges and the Peake and Dennison Inliers as well as the Frome Embayment (Figure 4.3). This spatial clustering around regional geological features may point to an underlying structural causation for springs within each sub-type that happens to correlate with a common depth-range to the J-K aquifer.

4.2.3 Fault and abutment zone types

In these model types, springs occur near a fault or abutment zone where displacement and juxtaposition of aquifer units is discernible using the data sets employed to develop structure surface horizons for the numerical model (Figure 4.1). These faults or abutments may be located near a basin margin or mid-basin. Many basin-margin, fault-related springs occur along the eastern and northern margins of the Peake and Dennison Inlier (Figure 4.3 and Figure 4.4), whereas the most prominent springs associated with mid-basin fault structures are located south of Lake Blanche (Figure 4.3). To classify as fault-related for this exercise, a spring is located within 5 km of a mapped fault or area known to have faulting from surface geology or geophysics mapping. The 5 km buffer is arbitrary and considers that secondary fault structures that splay off a primary fault are often related to spring conduit formation.

The faults associated with these springs may have caused major displacement of basinal aquifer and confining units, potentially leading to a complex hydrogeology, including the development of low-permeable barriers to lateral groundwater flow and the potential for multiple sources of groundwater for springs, including from fractured crystalline basement. The potential for groundwater from multiple aquifers supplying springs in such a setting is discussed in Aldam and Kuang (1989), Wohling et al. (2013a) and Halihan et al. (2020) and is compatible with geophysical modelling (Aldam and Kuang, 1989; Inverarity 2014). Such complexity is more likely to be found where a fault occurs away from the margins of a basin, potentially altering groundwater flow along the flow path. Near the margins of the basin, a fault may simply determine the configuration of the margin including stratigraphic relationships or may influence groundwater flow with respect to lateral outflow versus vertical flow to the surface.

Abutment zone springs occur when the aquifer encounters a low-permeable rock outcrop or sub-crop and the pressurised water is forced along the edge of the sub-crop and outcrop to the surface. In many cases, abutment-type springs are considered to be a subcategory of the fault zone type if the abutment was formed from up-thrown impermeable basement rocks along a fault plane. In Keppel et al. (2015a) this would make the abutment type the equivalent of the 'Fault zone - basin margin' type and consequently, the Freeling Springs example (Figure 4.4, from Keppel, 2013) may also qualify as an abutment type.

However, an abutment type classification and no other would be warranted where no fault is discernible, but a basement high occurs near springs. This may occur near a sub-cropping or outcropping intrusive.

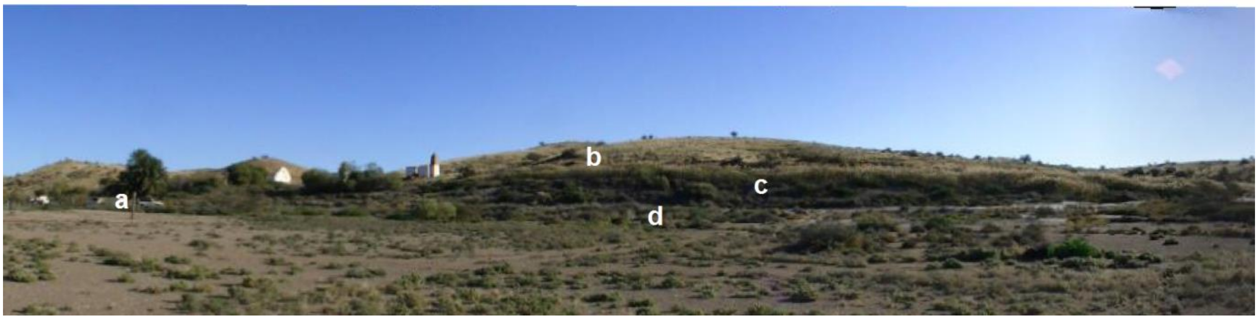


Figure 4.4: Panorama of the Freeling Springs south site, looking west The largest spring (EFS001) (a) is located at the far south of the complex. The Peake and Denison Inliers (b) are composed of up-thrown Adelaidean basement rocks. A large stand of Phragmites australis supported by discharging groundwater marks the Kingston Fault (c). Calcareous spring deposits (d) are present in the foreground.

Abutment zone springs occur on the eastern side of the Peake and Denison inlier where several sub-cropping basement highs have been mapped near springs, along the Northern Flinders Ranges and on the eastern margin of Lake Frome, where springs coincide with the Benagerie Ridge.

4.2.4 Mixed or non-Main Eromanga Aquifer Sequence type

The final model types relate to non-Main Eromanga Aquifer Sequence springs, or springs that may have a mixed aquifer source. These springs predominantly represent those supplied by Cenozoic- or Neocretaceous-aged aquifers, or fractured rock aquifers found within basement outcrop or sub-crop near the margins of the western Eromanga Basin (Figure 4.3). In many instances, such springs may form where breaks in topographic slope intersect the phreatic groundwater surface. In others, particularly in areas near the depocentres, spring formation may be structurally controlled, but the hydrogeological characteristics of the structures may limit the spring water source to shallow aquifers only. These latter springs typically occur in regions where the thickness of cover sequences to the J-K aquifer is greater than 380 m. However, in some cases, structure may be sufficiently significant to permit multiple aquifer sources to contribute to spring flow; for instance, Wolaver et al. (2020) used observations of 87/86Sr >0.715 that are atypical of J-K aquifer groundwaters and thermal modelling to interpret that spring water at Dalhousie Springs is sourced from the Cron Point Formation in the Permian Pedirka Basin as well as the overlying Eromanga Basin/JK aquifer. Similarly, Keppel et al. (2015b) used several environmental and radiogenic tracers to determine that the source of groundwater at one spring in the south-east of the Eromanga basin was supplied by the Permian Boorthanna Formation in the Arckaringa Basin, rather than the Eromanga Basin aquifer that supplies the vast majority of springs in that region.

Springs located within depocentres such as Kati Thanda-Lake Eyre or Lake Frome are classified here despite little supporting evidence to classify these springs one way or the other (Figure 4.3). The inaccessibility of these springs means that the required geophysical evidence to map structure or obtain hydrochemical evidence to identify a groundwater source is not available. The location in depocentres and the thick (>380 m) accumulation of sedimentary rocks above the J-K aquifer is a common feature of these springs. This thick accumulation of sedimentary rocks also affords the possibility that a shallow aquifer source may at least be partially contributing source water to the springs, as well as confining burial pressure limiting the supply of deeper groundwater. Indeed, if it could be established that the only source of groundwater to these springs is from shallow aquifers, their location within a depressed position in the landscape may suggest a confining unit thinning type model. Consequently, the decision to classify these springs as such stems from gross similarities with respect to environmental location and depth to the J-K aquifer as springs located near Lake Blanche and Lake Callabonna, where more evidence exists.

4.3 Multispectral mapping of diffuse discharge around springs

To supplement our understanding concerning the significance of spring wetlands as zones of discharge, a multispectral imagery data analysis was used to map potential diffuse discharge signatures near springs. Methodology applied for this investigation was sourced from the literature but expanded to cover all major spring groups in South Australia.

Prior to this study, there have been several studies that have examined diffuse discharge estimation from shallow groundwater inclusive of spring environments (for example, Woods 1990; Costelloe et al. 2015a). Two recent notable studies mapped diffuse discharge near selected GAB SA springs using remote sensing data (Turner et al. 2015 and Matic et al. 2020), and that methodology was selected for extension to a regional scale for this study.

Turner et al. (2015) used albedo and temperature estimations to constrain areas of diffuse discharge. Albedo thresholds were selected using principal component analysis of Landsat 8 visible bands, with the first component identifying bright evaporite crusts relating to salt deposition from surface water. Turner et al. (2015) used thermal infrared bands from Landsat 8 data to map areas which remain cooler due to the flux of groundwater via diffuse discharge). The study covered a small proportion of GAB spring areas and relied on detailed field mapping for training and evaluation of the threshold classifications.

In contrast, Matic (2018) and Matic et al. (2020) used a soil moisture index (Landsat 8 normalised difference moisture index, or NDMI) and a variety of salt indices (Landsat 8 visible and near infrared band combinations) to map areas with varying degrees of confidence. Training data developed from fieldwork observations and detailed regolith mapping was used to find the best band combinations for salt index mapping, from which diffuse discharge estimates were derived. The theory behind Matic et al. (2020) is that diffuse discharge results in areas of high soil moisture that can vary seasonally with temperature, and can also be affected by continuous evaporation, the combination of which often leading to the development of salt scalding surrounding spring vents.

The Turner et al. (2015) methodology resulted in smaller area estimates for those spring groups common to both studies. Classification thresholds to apply to the remote sensing data were determined by training classification models obtained during fieldwork mapping regolith for each scene. Matic et al. (2020) datasets covered a large proportion of springs in SA, except for those within the large playa lakes of Lake Frome, Kati Thanda-Lake Eyre and Lake Cadibarrawirracanna (Figure 4.5).

It should be noted that for all past and present analyses, there has been no prior judgement concerning the source of diffusely discharging groundwater associated from spring environments; only the gross area subject to diffuse discharge processes has been mapped. As detailed in Costelloe et al. (2012) and Keppel et al. (2020) spring water and associated diffuse discharge surrounding spring environments may have multiple sources including:

- the J-K aquifer
- a shallower aquifer found in the Neocretaceous or younger strata
- a component sourced from local recharge rainfall, particularly if the spring environment is located within a hydrological terminus, such as Kati Thanda-Lake Eyre or Lake Frome.

Such limitations are discussed further in Chapter 7. In summary, however, although this approach risks over representing diffuse discharge from the J-K aquifer, discriminating between groundwater sources in multispectral data is not possible without extensive additional data, such as hydrochemistry data and associated modelling analysis (for example, Costelloe et al. 2015b). Further, the approach taken here is considered conservative and ensures that all possible points of discharge have been captured.

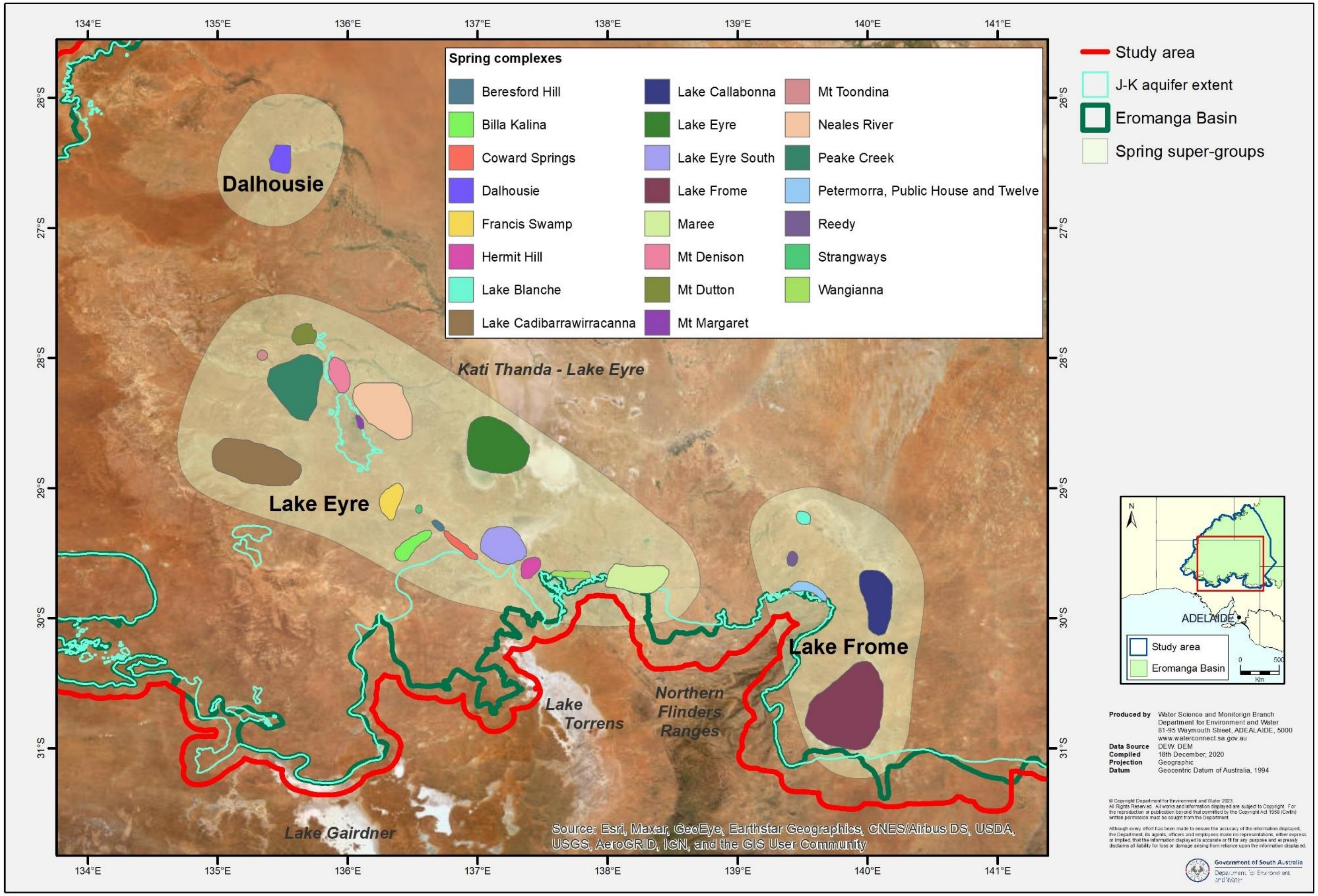


Figure 4.5: Spring complexes included in this study and from Matic et al. (2020)

4.3.1 Data and methods

The approach used for this study was to extend the work of Matic et al. (2020) by applying comparable thresholds to Landsat 8 scenes covering the playa spring groups within the study area (Figure 4.5). An estimate of the area interpreted to represent diffuse discharge was identified by using a standard multispectral product which correlates to soil moisture (Normalised Difference Moisture Index, or NDMI) and the presence of evaporite deposits (a variety of 'salt indices' based on Matic et al. 2020). Specifically, the following general workflow was adopted:

- Matic et al. (2020) estimates were extended to the playa spring groups
- As per Matic et al. (2020), a 4 km buffer around springs was used for most springs, with spring vent locations obtained from SA Geodata. The exception to this was Lake Frome, where a larger buffer was employed due to incomplete mapping of spring vents.
- The surface moisture on playas was mapped using the soil moisture indices to find the driest period. The same indices as Matic et al. (2020) employed were used: USGS NDMI for soil moisture and the Matic SI8 and SI14 salt indices.
- Infrared brightness temperature from atmospherically corrected (Level 2) USGS Landsat 8 scenes was used, as per the methodology described in Turner et al. (2015), to compare areal extents to NDMI estimations.
- Raster images of areas mapped as potentially being representative of diffuse discharge at varying levels of confidence and compiled area estimates were produced. High confidence (conservative) estimates are based on the soil moisture indices only. More inclusive (less confident) estimates are based on both soil moisture and salt indices.

In developing this workflow, a number or alternative data sources and indices were explored to ensure the optimal approach was employed. These include:

- The use of Sentinel-2 imagery instead of Landsat 8 was investigated. Sentinel-2 is a similar earth observation system to Landsat-8, although it offers higher resolution data. However, the slight improvement in resolution was outweighed by the increase in processing time.
- All available visible and near infrared salinity indices were investigated; however, the indices employed by Matic et al. (2020) were found to be optimal.

4.3.2 Results of diffuse discharge mapping around springs

Areas of diffuse discharge near springs were mapped using multispectral remote sensing data. Table 4.1 and Figure 5.1B detail the locations of spring complexes mapped during this exercise. Mapped discharge areas varied between 0 (Lake Eyre South islands) and 61.82 km2 (Francis Swamp, Figure 4.5) (Table 4.1). Total mapped extents using the described methods provided estimates of diffuse discharge areas near springs of between 97 and 412 km2 (Table 4.2 and Figure 5.1B). The lower of the two numbers uses the methodology from Matic et al. (2020) but also considers albedo and temperature estimations developed by Turner et al. (2015) to constrain areas of diffuse discharge. Turner et al. (2015) used thermal infrared bands to map areas which remain cooler due to the presence of a flux of groundwater via diffuse discharge. The upper number uses both soil moisture and the less uncertain salt indices without any temperature constraints. Although the difference between these bounding estimations appears large, when compared to the extent of the study area both can be considered small, constituting less than 0.06% of the total study area.

The largest additional area added during this study to that calculated by Matic et al. (2020) occurs along the eastern margin of Lake Frome, where persistent areas of moisture were found between mapped spring vents (Figure 4.6). This new area increased the total area of diffuse discharge mapped by Matic et al. (2020) by between 2% and 6% based on the level of conservatism employed. In a similar way, depending on the level of conservatism with respect to the methodology used to determine diffuse discharge area, this region also provided the area with the greatest uncertainty with respect to study area total, ranging between 4% and 25%.

Whilst the area of spring-related diffuse discharge is small compared to the overall study area (<0.06%) and notwithstanding the difficulty assigning a definitive total discharge rate to this area range, the volumetric rate of discharge may still be reasonably significant. Assigning the areal evaporation rate range of 100 to 350 mm/y yields a discharge volume estimate of between 27 to 395 ML/d. In summary, total spring discharge, when both direct and diffuse components are considered together, are a very important component of the overall water balance for the study area.

Table 4.1: Results of multispectral diffuse discharge mapping

Spring group	Discharge area (km^2)	Reference
Beresford, Elizabeth, Coward Springs	19.11	Matic 2018
Billa Kalina	22.37	Matic 2018
Dalhousie	36.56	Matic 2018
Francis Swamp	61.82	Matic 2018
Hermit Hill	15.73	Matic 2018
Lake Blanche	0.00	This study
Lake Cadibarrawirracanna	1.08	This study
Lake Callabonna	8.38	This study
Lake Eyre North	3.07	This study
Lake Eyre South group	58.21	Matic et al. 2020
Lake Eyre South islands	0.00	This study
Lake Frome	25.43	This study
Marree	8.69	Matic et al. 2020
Mt Denison	10.55	Matic et al. 2020
Mt Dutton	2.01	Matic et al. 2020
Mt Toondina	0.34	Matic et al. 2020
Neales River	9.63	Matic et al. 2020
Peake Creek	61.43	Matic et al. 2020
Petermorra and Public House	5.53	Matic et al. 2020
Reedy Springs	0.31	Matic et al. 2020
Strangways	4.87	Matic et al. 2020
The Bubbler and nearby	40.74	Matic et al. 2020
Twelve Springs	0.06	Matic et al. 2020
Wangianna	3.69	Matic et al. 2020

Table 4.2: Results from diffuse discharge mapping around springs.

Author	Area (km^2) More conservative	Less conservative	Comments
Turner et al. 2015	42		Not all spring groups
Matic et al. 2018	175 (Soil moisture)	373 (Soil moisture + Salt crusts)	All spring groups except Lake Frome and Lake Eyre
Matic et al. 2020 This study	97 to 189 (Soil moisture, Low end prioritises Turner's albedo & temp. estimates; high end uses only Matic soil moisture)	412 (Soil moisture + Salt crusts)	All spring groups

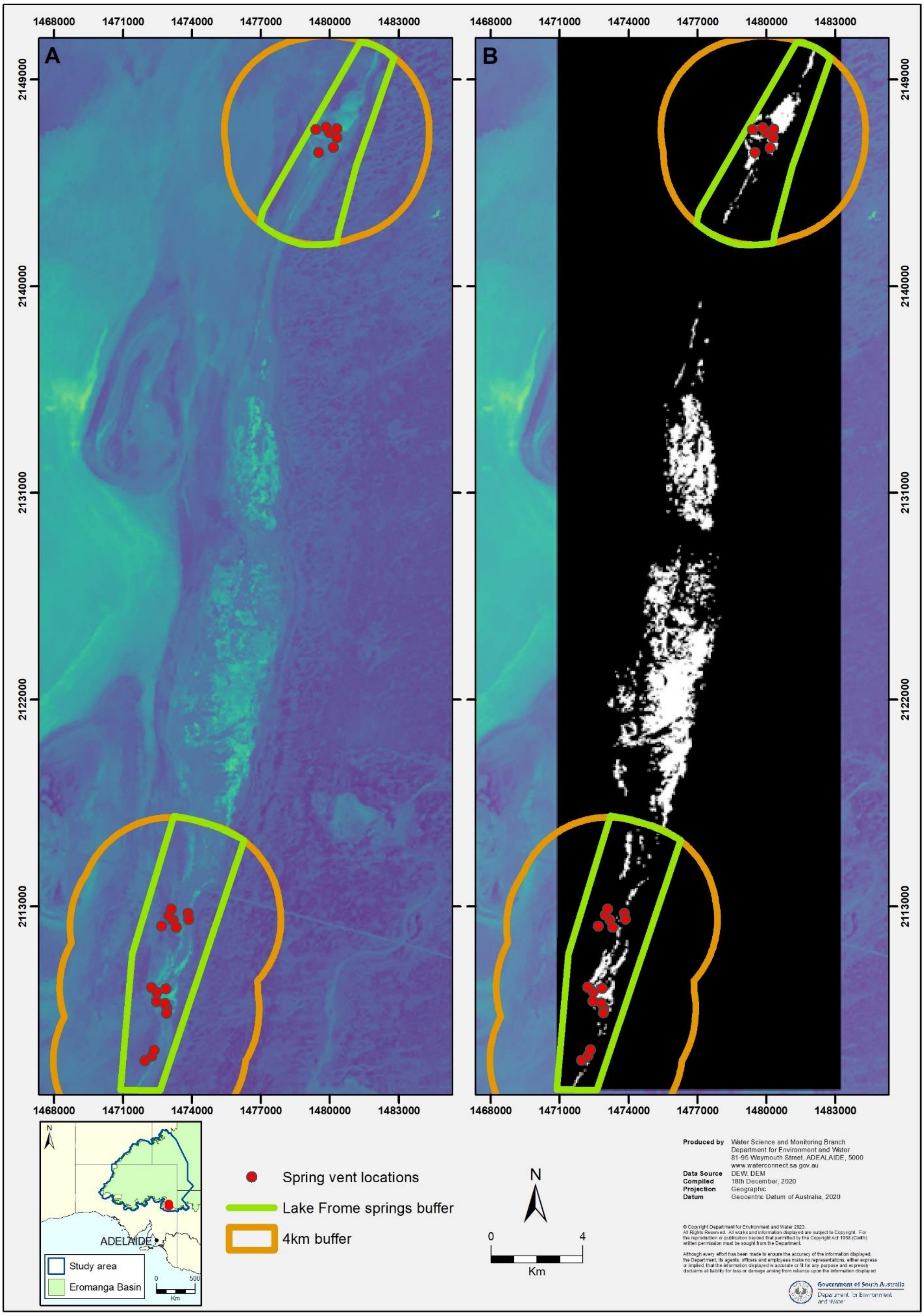


Figure 4.6: A) NDMI mapping from Lake Frome East B) Zones representative of diffuse discharge highlighted

5 Diffuse discharge and lateral outflow

As well as discharge from springs, diffuse discharge into adjacent strata, either vertically or as later outflow are also key components of any CHM. Consequently, a good understanding of these discharge processes is required for numerical modelling.

Diffuse discharge may occur extensively across the study area, although its significance greatly depends on the hydrogeological characteristics of strata overlying and underlying the Main Eromanga Aquifer Sequence.

The potential for inter-aquifer connectivity between the Main Eromanga Aquifer Sequence with overlying or underlying aquifers within the study area, while recognised as important, is discussed in Volume 2 of this report.

Relevant discharge data has been predominantly sourced from a literature review of previous studies. In particular, the extent of discharge (leakage) through the overlying confining unit away from spring groups is estimated based on the results of previous studies (for example, Harrington et al. 2013; Costelloe et al. 2012; Costelloe et al. 2015b).

5.1 Lateral outflow

Hydraulic heads as described by the potentiometric surface developed for the J-K aquifer suggest outflow might occur along the southern margin of the Frome Embayment into the Precambrian and early Phanerozoic rocks of the Northern Flinders Ranges (Figure 5.1). With respect to outflow from the Frome Embayment, there has been little study concerning outflow and the role of Lake Frome as an evaporative discharge feature for the J-K aquifer (Figure 5.1A).

Groundwater flow as described by the potentiometric surface also suggests lateral outflow might occur along parts of the southern margin of the GAB aquifer near Maree and south of Coward Springs. However, any interpretation of lateral outflow needs to consider the topography encountered along the basin margin and the potential for gravity-driven hydraulic head from outside of the basin and what constraint, if any, these may impose. The southern and south-eastern margins of the Eromanga Basin in South Australia are bordered by the Northern Flinders Ranges and the Stuart Shelf, which largely have higher elevations than the basin to the north and therefore may contain a hydraulic system that could constrain any outflow. Further, the areas near Maree and Coward Springs also have a high proportion of springs. BHP Billiton (2011) used informed conceptualisation and numerical modelling to argue that an evaporative discharge zone concomitant with springs acts as a groundwater divide between the largely artesian groundwater of the J-K aquifer to the east and the aquifers and unconfined groundwater systems to the south and south-west such as the Tent Hill Formation aquifer within the Stuart Shelf. Additionally, Howe et al. (2008) suggested the main discharge mechanism for groundwater within the underlying Boorthanna Formation aquifer within the Arckaringa Basin was outflow into hard rock aquifers within the Tent Hill Formation (Figure 5.1A).

Therefore, while the primary conceptualisation respects the previous work above and suggests discharge is primarily through springs, an alternative conceptualisation that can be tested during modelling is that some form of lateral outflow is occurring in the Stuart Shelf region (Figure 5.1).

5.2 Diffuse Discharge

Diffuse discharge for the purposes of this study, is groundwater that discharges from the Main Eromanga Aquifer Sequence in a manner that is not focused but dispersed over a relatively large area. In a practical sense, such discharge cannot be directly observed or measured as a flow, but rather manifests in surficial environments as large areas of observed seepage or scalding, and in subsurface environments as a mass transfer of water through pore spaces. Diffuse discharge in this section is discussed in two parts: firstly, subsurface diffuse discharge and secondly, diffuse discharge to surface in the form of evapotranspiration.

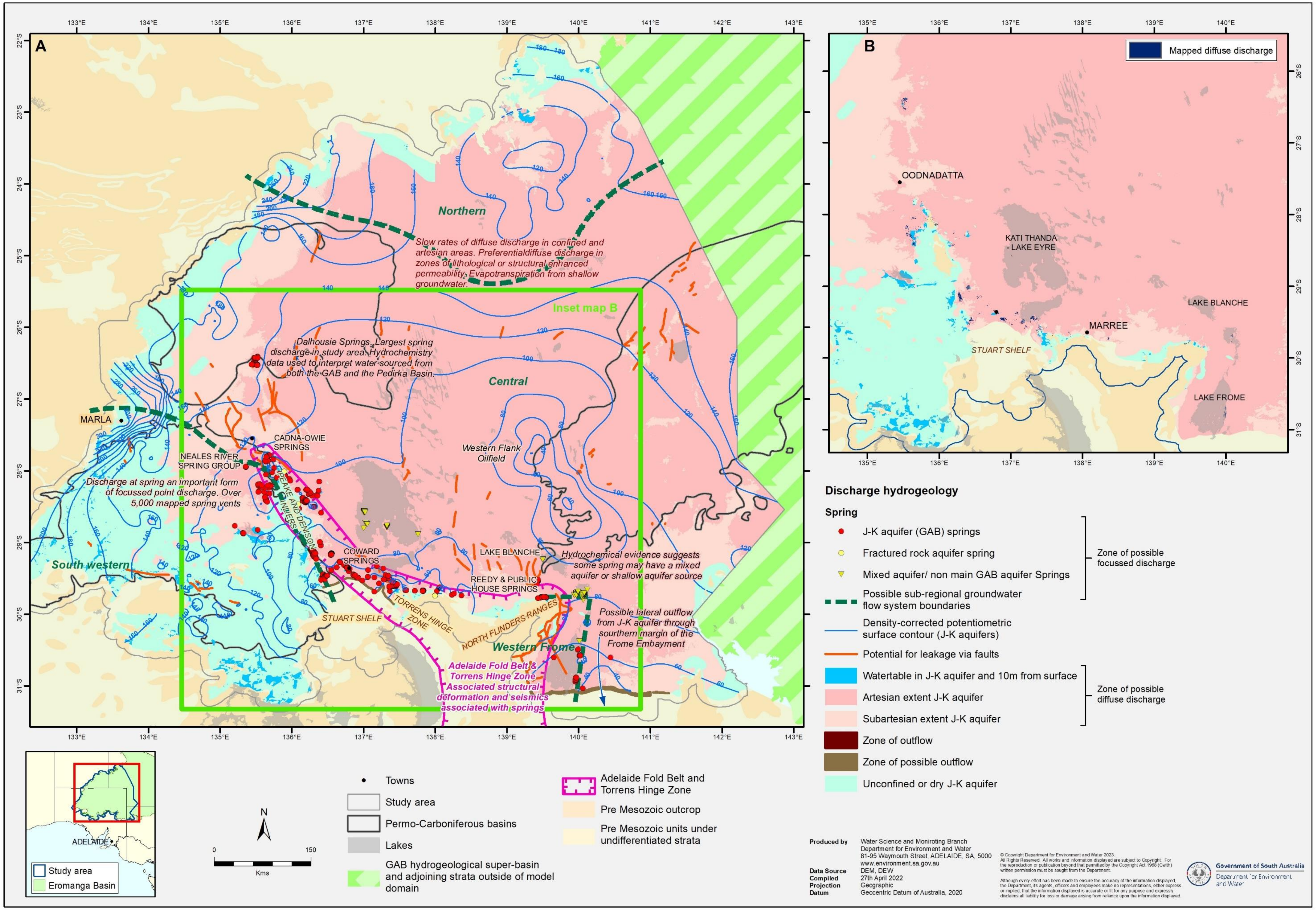


Figure 5.1: A) Conceptualisation of discharge B) Mapped areas of diffuse discharge

5.2.1 Subsurface diffuse discharge

Diffuse discharge through competent aquitard rocks such as the Bulldog Shale and the Oodnadatta Formation of the Rolling Downs Group overlying the J-K aquifer may be small. The most recent estimates of vertical hydraulic conductivity for the main confining unit (Rolling Downs Group) above the J-K aquifer are between 3.46 x 10^{-8} to 1.04 x 10^{-8} m/d (0.4 x 10^{-13} to 1.2 x 10^{-13} m/s) using physical techniques (Harrington et al. 2013). This equates to a slow diffuse discharge rate through the confining unit of between 3 x 10^{-4} to 5 x 10^{-4} mm/y, (average of 4 x 10^{-4} mm/y) or a volume of approximately 0.2 ML/d over the South Australian and Northern Territory portions of the GAB.

Conversely, Harrington et al. (2013) measured vertical hydraulic conductivity rates of between 8.64 x 10^{-5} to 8.64 x 10^{-4} m/d (1 x 10^{-9} to 1 x 10^{-8} m/sec) using environmental tracers from shallow groundwater wells. Harrington et al. (2013) inferred that this represented diffuse discharge rates in areas of preferential pathway development through the confining unit and into shallow aquifers. Using these new hydraulic conductivity estimates, Harrington et al. (2013) determined that 14% of the GAB within SA and the NT would require the preferential flow conductivity of 8.64 x 10^{-5} m/d to accommodate the vertical discharge estimate of 274 ML/d presented in the 2009 FNWAP. With respect to preferential flow-path development, this is most likely where large regional fault zones have developed or where underlying regional structures may have influenced the development of preferential pathways via deformation of overlying sedimentary strata. Additionally, Ransley and Smerdon (2012) noted that polygonal faulting has deformed the confining unit of the GAB and could provide a means for vertical upward leakage from the GAB into shallower strata.

5.2.2 Evapotranspiration

Conceptually, evapotranspiration includes areas where the J-K aquifer strata is found near the surface, as well as where J-K aquifer groundwater discharges to the shallow phreatic water table contained within shallower strata where geological and hydrogeological conditions allow (Figure 5.2A). Broadly, such occurrences are interpreted where a pathway between pressurised groundwater in the J-K aquifer and the water table is established and where head data suggests there is sufficient pressure to allow for vertical leakage. Pathways between the water table and the J-K aquifer include where there is lithological connectivity or deformation of strata between the two to allow structural connectivity. Within this conceptualisation, areas where the water table is equal to or less than 10 m from the surface and contained within J-K aquifer strata are considered the most likely areas for non-spring zone related groundwater evapotranspiration to occur (Figure 5.1). The 10 m depth is an arbitrary figure that considers natural error within the datasets used to determine land and structure surface elevations.

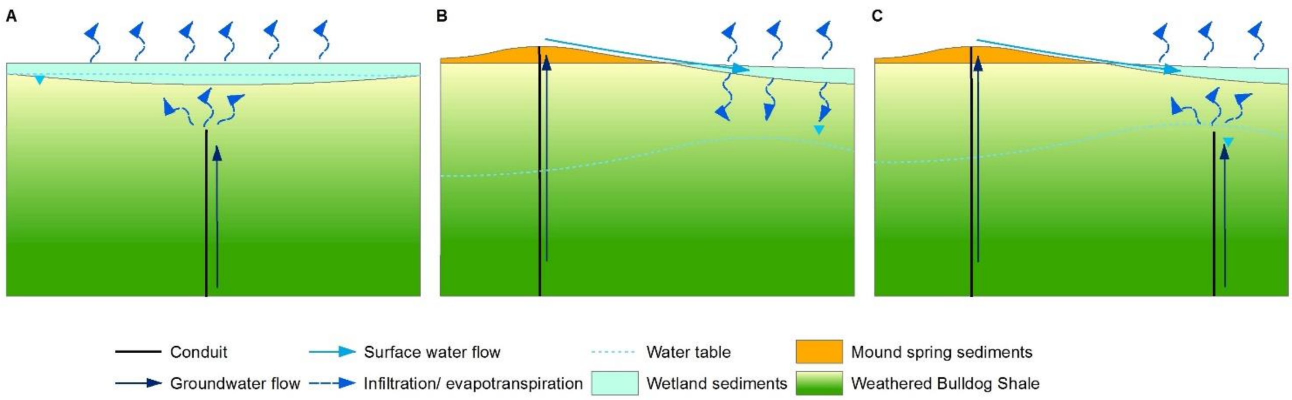


Figure 5.2: Schematic depiction of diffuse discharge A) Diffuse discharge into a basin margin/ephemeral wetland environment B) Water loss from a spring wetland via evapotranspiration and infiltration C) Combined water outputs from direct spring discharge and subsurface diffuse discharge into a combined spring and diffuse discharge wetland environment

The arid climate, low topography and sparse vegetation coverage results in an elevated evaporation potential. Areas where evapotranspiration is enhanced are generally mapped as areas of either wetness or high salt accumulation. In the study area, such areas are commonly found in basins or depressions in the landscape associated with ephemeral lakes, drainage development or in the wider area around springs (Figure 5.2A).

Hamilton et al. (2005) measured average pan evaporation rates in the Cooper Creek region of Central Australia of 2.5 m/y, while Tetzlaff and Bye (1978) reported an evaporation rate of approximately 3 m/y in the Lake Eyre region. These latter figures match data obtained from the Bureau of Meteorology (BoM. (BoM, 2016)). Further, mapping by BoM (2016) suggests that most of the study area is subject to actual areal annual evapotranspiration rates of between 100 and 350 mm/y, which is the equivalent to or in excess of average annual rainfall (BoM, 2019) (Figure 5.3). Woods (1990) estimated evapotranspiration in similar environments between 0.5 to 7 mm/y, using Cl^- and δD in soil profiles, whereas Costelloe et al. (2015a) estimated evaporative discharge rates in zones mapped as high discharge zone could reach more than 100 mm/y. Consequently, based on such gross, regional scale assessments, there appears to be sufficient potential evapotranspiration capacity to account for average rainfall within the study area.

This was further explored by Costelloe et al. (2011) and Costelloe et al. (2015a and 2015b), who attempted to estimate evaporative discharge from near the basin margins using both field measurements and remote sensing techniques targeting regions mapped as likely areas of discharge. Costelloe et al. (2015a) calculated total rates of evapotranspiration-related discharge to vary between 22.8 ML/d and 77.2 ML/d using quantitative classification of remote sensing imagery to map landform types and between 199.5 ML/d and 687.4 ML/d using a variety of remotely sensed and field data to map landforms semi-quantitatively. Costelloe et al. (2015b) described 3 zones from which variable rates of evapotranspiration were estimated, including the Liquid Transport Zone (LTZ), the Mixed Transport Zone (MTZ) and the Carbonate Zone around springs. LTZ was interpreted to provide the highest rates of phreatic evapotranspiration, being characterised through wet soils, salt precipitation and low surface temperatures. MTZ zones are areas surrounding LTZ where the evapotranspiration front is sub-surface and therefore occurs as a combination of vapor and liquid phases. MTZ is characterised by drier soils, warmer temperatures and less salt precipitation than LTZ. Finally, carbonate platforms represent flat lying zones of predominately carbonate precipitate around springs.

Using the steady state model results of Welsh (2000) as a benchmark to determine the J-K aquifer groundwater component of evapotranspiration, Costelloe et al. (2015a) suggested that the higher phreatic evapotranspiration zones estimated by landform mapping account for 73 to 251% of the total vertical leakage component modelled by Welsh (2000), the eastern, predominantly artesian zone being 4 to 13% and the mixing zone between these two being 5 to 22%, respectively. Costelloe et al. (2015a) indicated that there is sufficient evaporative capacity within the high discharge zone mapped within the western portion of the study area to account for most annual recharge. This finding is similar to that derived from a gross comparison of average annual rainfall and potential evapotranspiration.

Further, the evaporation estimations of Costelloe et al (2015a) appear to support results of hydrochemistry modelling by Costelloe et al. (2012). Costelloe et al. (2012) used forward evapotranspiration modelling of major ion concentrations and stable isotope results obtained from unconfined shallow fluvial aquifer groundwater samples to suggest a variable, locality-specific degree of input of artesian groundwater to shallow aquifers. This study examined several sites around springs, extending from Reedy and Public House springs near Lake Blanche to Cadna-owie Springs and the Neales River spring group to the north and east of the Peake and Denison Inliers (Figure 5.1). Costelloe et al. (2012) found that phreatic evaporation in the eastern, largely artesian zone was predominantly from shallow alluvial aquifer sources, with very little, if any, discernible contribution from J-K aquifer groundwater. Consequently, Costelloe et al. (2015a) described the vertical leakage pathways of artesian water in the eastern portion of the study area as complex.

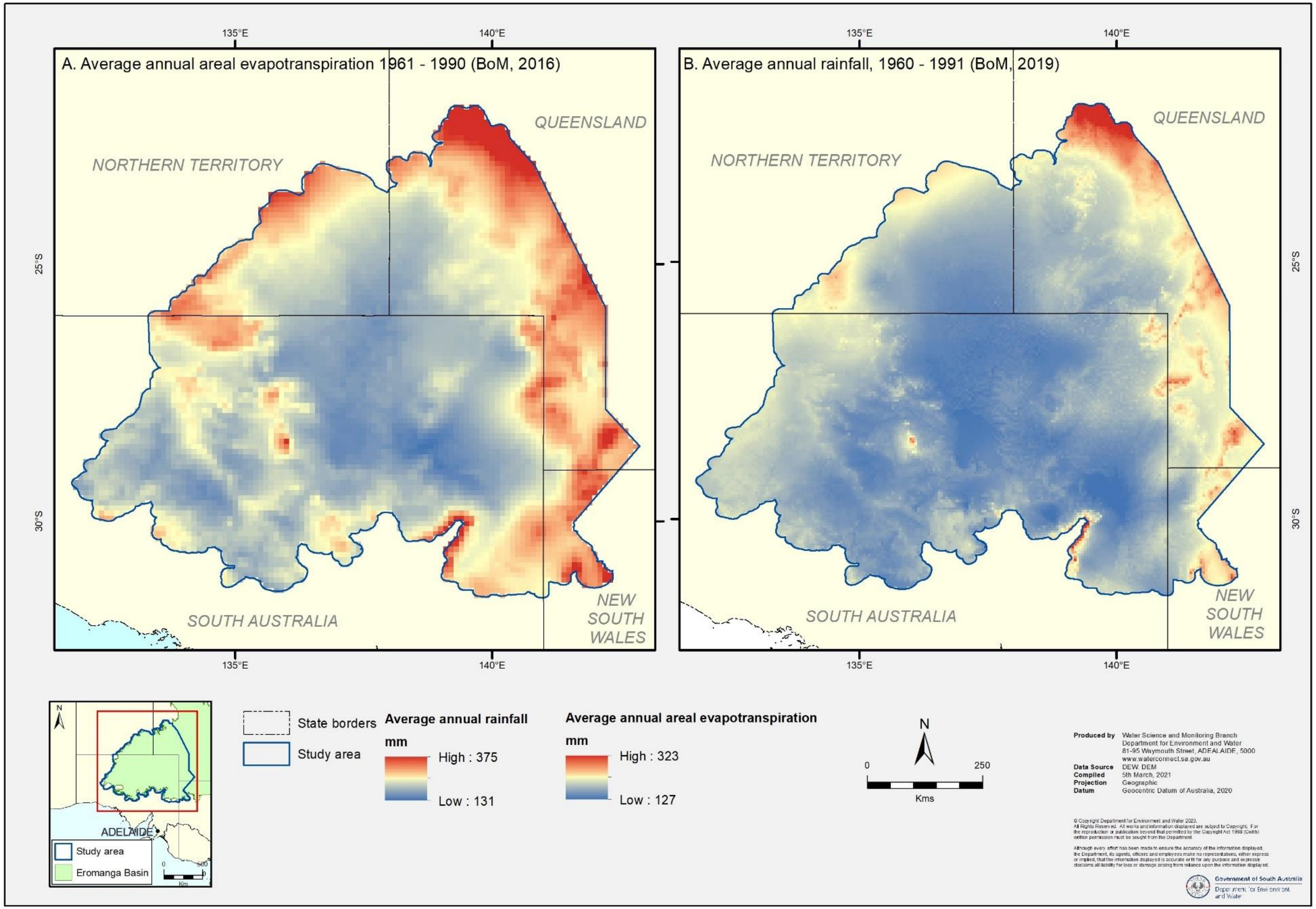


Figure 5.3: A) Average annual areal evapotranspiration. B) Average annual rainfall

In contrast, Costelloe et al. (2012) suggested that artesian water was at least partially, and in some cases significantly, contributing to phreatic evapotranspiration in the Eromanga Basin largely west of the Peake and Denison Inliers and the Torrens Hinge Zone, despite difficulty distinguishing between groundwater types using proportional major ion hydrochemistry. The J-K aquifer within this portion of the study area tends to occur at shallower depths compared to regions further east, and includes substantial areas of outcrop and sub-crop. However, in their assessment, Costelloe et al (2012) did not elaborate upon the exact migration pathway artesian water takes into the near surface.

The migratory pathway of artesian groundwater into the shallow aquifer near springs is a complicating factor, particularly with respect to determining the proportion of direct spring discharge versus groundwater that is only discharging diffusely. Holmes et al. (1981) demonstrated that recharge to a shallow water table beneath spring tail wetlands was occurring with the use of water level data from temporary piezometers, while Keppel et al. (2012) required a proportion of infiltration from the spring wetland to account for water loss not attributable using hydrochemistry mass balance analysis (Figure 5.2B). For average annual infiltration rates from the spring wetlands examined, Keppel et al. (2018) applied infiltration rates of between 60 and 70% of total surficial spring discharge, with no allowance for any subsurface or secondary vent contribution to flow. From here, water can discharge via evapotranspiration within the wider spring wetland or become part of the phreatic groundwater system. Additionally, the wider spring wetland may also represent areas where diffuse discharge from the J-K aquifer is directly occurring via preferential pathway development that is contained within the subsurface (Figure 5.2C).

Finally, the efficiency of transpiration processes at removing groundwater and infiltrated rainfall before it can enter the water table was explored by Costelloe et al. (2008) and Keppel et al. (2017). In both studies, a variety of riparian vegetation species, including Eucalyptus coolabah (Coolabah), E. camaldulensis ssp. obtusa (River Red Gum), and Acacia spp. (Mulga) were examined for groundwater dependence and in no case was there evidence beyond a partial dependence. In the case of Acacia spp and E. coolabah in downstream and waterhole environments, there was negligible dependence observed, with the salinity of groundwater an apparent deterrent to use. In all cases a high dependence on soil and bank-water storage was apparent. There was some evidence for trees being able to switch between shallower stores of water and deeper groundwater stores in times of need as well as the capacity for hydraulic redistribution of water, that is, moving soil moisture from one part of the soil profile to another.

The effective depth of transpiration across the study area is likely to be highly variable and dependent on the predominant species of plant in each area. Canadell et al. (1996) presented a literature review covering 253 woody and herbaceous species to find that the maximum rooting depth ranged from 0.3 m bgs to greater than 60 m bgs. With respect to a tree species known to occur within the study area, Hulme (2008) suggested that historical estimations of lateral extents of 20m and vertical extents of 10m were conservative. However, deeper rooted plants such as River Red Gum and Coolibah (E. coolabah) are largely confined to riparian environments and so shallow rooted (<1 m) herbaceous perennials are speculated to provide the bulk of areal vegetative cover within the study area.

6 Data gaps and limitations

Through the process of data compilation, analysis and literature review, a number of critical data gaps were made apparent, both with respect to raw data as well as conceptual understanding. The following section provides a discussion of these data gaps and limitations considered important with respect to the development of the CHM and ultimately the numerical model construction.

6.1 Hydrochemistry

Hydrochemistry data provides a useful complementary tool to hydraulic-based studies focussed on determining groundwater flow dynamics and scale. However, uncertainties may arise if hydrochemistry data is interpreted in isolation.

With respect to proportional major ion hydrochemistry, Costelloe et al. (2015b) and Keppel et al. (2016) found that there may be near-indistinguishable similarities between results from J-K aquifer and shallower aquifer groundwaters. Such a circumstance might suggest inter-aquifer mixing of groundwater, although caution should be exercised in the absence of hydraulics or other data to support such claims. Further, the use of hydrochemistry to calculate flow vectors and rates may also be impacted by mixing and requires aquifer end member data to construct a mixing model to determine the impact on interpretation.

Finally, a dichotomy may develop between the hydrochemistry signal and the hydraulics of groundwater within an aquifer. Changes in pressure may be reflected in head data over relatively short periods of time compared to hydrochemistry, which requires particulate migration and flushing of pore spaces before such changes are equivalently reflected. Consequently, hydrochemistry data may reflect paleo-flow paths and mixing regimes that may not reflect hydraulic regime of the present day, particularly in environments where paleoclimatic variance and even neotectonics are important.

These issues have particular importance with respect to the use of tracers for groundwater dating and flow rate and vector determination. As well as mixing and multiple sources, the effects of diffusive transport across flow paths caused by low recharge rates (Priestley et al. 2017) or the impact of a dual porosity aquifer causing bimodal tracer transport rates (Suckow et al. 2020) may also impact interpretation, leading to different tracers providing different apparent ages for the same groundwater sample. Ideally, multiple traces should be used to determine groundwater velocity (Suckow et al. 2020).

6.2 Recharge and lateral inflow

Recent work suggests the current rate of recharge is much lower than the rate of discharge within the study area. This is supported by comparative rates of rainfall and evapotranspiration of the region, which suggests recharge events are limited to anomalous rainfall events or confined to localised areas. Groundwater flow and volumes within the GAB hydrogeological super-basin are currently regarded to be in a state of transience.

This presents two issues for numerical model construction. Firstly, although the interpreted potentiometric surface for the study area suggests either recharge or lateral inflow is occurring along the north-western margin of the study area, given current rates of recharge, this surface may be reflective of paleo-recharge events earlier in the Cenozoic that are still dissipating. Consequently, any modelling assumptions that imply a steady state or pseudo-steady state that use contemporaneous recharge as an input may be unsuccessful.

Secondly, the likelihood that much contemporaneous recharge is occurring in a localised and focussed way, such as through ERR or MSR, means that accurate quantification of such recharge areas and volumes are difficult to identify. For model construction, areas with evidence indicating recharge may be flagged as potential recharge areas, but recharge may only be applied to the model if needed to improve model performance. This is a potential model uncertainty, although highlighting such areas during model construction or during uncertainty analysis may discriminate where future recharge assessment works are most required moving forward.

6.3 Regional scale discharge and lateral outflow

Hydraulic heads as described by the potentiometric surface developed for the J-K Aquifer suggests outflow might occur along the southern margin of the Frome Embayment. However, there has been little study concerning outflow and the role of Lake Frome as an evaporative discharge feature for the J-K aquifer.

Crucial to any conceptual model is quantifying diffuse or preferential discharge from the J-K aquifer. Harrington et al. (2013) used core measurements and hydrochemistry to estimate hydraulic conductivities that varied by many orders of magnitude. Harrington et al. (2013) suggested that the development of preferential flow paths through the confining unit might be responsible for this difference, with the lower number representative of an undeformed confining unit and the higher number representative of where preferential flow path development had occurred. Consistent with this finding is that of Costelloe et al. (2012) who found that the hydrochemistry of groundwater from shallow aquifers from a large area of the southern GAB showed a variable degree of input from underlying artesian groundwater sources, from minimal to being the major source.

Further complicating the discretisation of vertical leakage into zones of diffuse and preferential flow path development is the many scales of deformation likely to exist. Work undertaken outside of the GAB, in the Murray–Darling Basin by Lawrie et al. (2016) suggests that even small-scale localised faulting and jointing may have hydrogeological significance in unconsolidated, near-surface sediments, forming preferential flow pathways and causing heterogeneous, vector-dependent hydraulic conductivity characteristics to form. Although these concepts are not new, it highlights the issue of scale in any modelling or conceptualisation assessment, particularly given the occurrence of structural deformation that is major and regional in scale as well as more recent and smaller in scale. Contemporaneous examples include faulting in the near surface (Halihan et al. 2020; Keppel et al. 2015b; Keppel et al. 2016) and polygonal faulting mapped at depth in Eromanga strata (Watterson et al. 2000). The conclusion provided by Harrington et al. (2013) concerning a requirement to map the spatial variables relating to groundwater discharge across the study area is sound and central to understanding this mechanism further.

6.4 Spring environments

Although there has been much progress with respect to understanding spring morphology and the source of groundwater to springs, further work is required to clarify the management approach. Recent work by Priestley et al. (2013), Crossey et al. (2013), Keppel et al. (2015a), Keppel et al. (2015b) and Keppel et al. (2020) has not only suggested that some springs within the study area may obtain groundwater from a number of different hydrogeological zones within the J-K aquifer, but some may obtain groundwater from other aquifers entirely. Consequently, a key priority is to clarify groundwater sources for springs where multiple sources are possible and to establish reference groundwater pressures near these spring groups for all relevant aquifers.

At a practicable level, representing springs within a numerical model necessitates a degree of approximation. Although there are >5,000 springs, the majority are small with flows <1 L/sec. Further, the remoteness of many springs means that estimating flow is difficult and often reliant on remote sensing techniques rather than direct measurement (White et al. 2015). Complicating the estimation of discharge from larger springs, Halihan et al. (2013) used geophysics to suggest that structures found within spring tails may also serve as additional points of discharge, which may not necessarily be visible. Consequently, the representation of individual-scale spring-vent discharge may be considered impractical in many instances or may need to involve assumptions and approximations to represent them adequately in a numerical model.

Representing springs in models has been accomplished previously using the DRAIN module in MODFLOW (for example, Welsh 2000); however, this may represent a gross simplification of the structural and hydrogeological complexity inherent in spring formation. Conversely, complex model boundary conditions may be required to numerically represent spring related structures, such as faulting (for example, McCallum et al. 2018); however, such representations are time consuming to implement and can be potentially as erroneous as simple representation if insufficient information concerning the structural controls of springs is known. Additionally, direct point discharge from spring vents is often also associated with subterranean diffuse discharge in the surrounding area. However, this area may also be partially inundated by spring waters, forming a spring-related wetland. Holmes et al. (1981) and Keppel et al. (2012) presented evidence of spring tail water infiltration into surrounding shallow sediments. For the purposes of determining total discharge from a spring environment using 2-dimensional data sets such as remote sensing, this potential mixing of waters in the near surface environment presents an issue that may be very difficult to resolve. For instance, mapping of potential diffuse discharge zones around springs using remote sensing data may inadvertently include water already accounted for in direct spring discharge, or zones of infiltration to the unconfined aquifer.

6.5 Diffuse discharge around springs

Mapping of diffuse discharge near springs also has several inherent uncertainties. With respect to diffuse discharge mapping undertaken for this study, the following limitations were identified:

- It is difficult to establish classification thresholds without field constraints. No additional field mapping was undertaken for this work and as such the previous work summarised in Matic et al. (2020) was relied upon. Detailed regolith mapping enables site-specific information to be gathered regarding regolith landforms and surface water drainage patterns.
- Soil moisture and salt crust is affected by diffuse discharge volumes and fluxes, localised rainfall and the accumulation of surface runoff from rainfall and spring discharge (Matic et al. 2020). It is very difficult to distinguish the differences and impacts of each, particularly in the absence of field observations of soil moisture.
- Salt crusts are prone to redistribution by surface runoff, rendering salt crust indicators difficult to calibrate reliably and therefore highly variable over time. Consequently, it is difficult to extend interpretation thresholds across Landsat scenes from different time periods.

An example of the uncertainty inherent in the determination of diffuse discharge mapping via the use of remote sensing data is St Mary's Pool, located within the drainage line of Petermorra Creek, north of the Frome Embayment (Figure 6.1). Mapping using the Landsat-8 normalised difference vegetation index (NDVI) indicates extensive drought-persistent vegetation within the watercourse; however, there are several potential sources of water that could be providing support. These potential sources include:

- diffuse discharge from the J-K aquifer
- shallow groundwater and bank storage and associated soil moisture with surficial alluvium within and around the watercourse
- direct discharge from St Mary's Pool draining downstream into Petermorra creek.

How springs and associated areas of diffuse discharge are represented within the numerical model remain an ongoing design and implementation issue, largely driven by the importance of a particular spring and the related local hydrogeological conditions with respect to understanding or replicating the larger hydrogeological characteristics within the model.

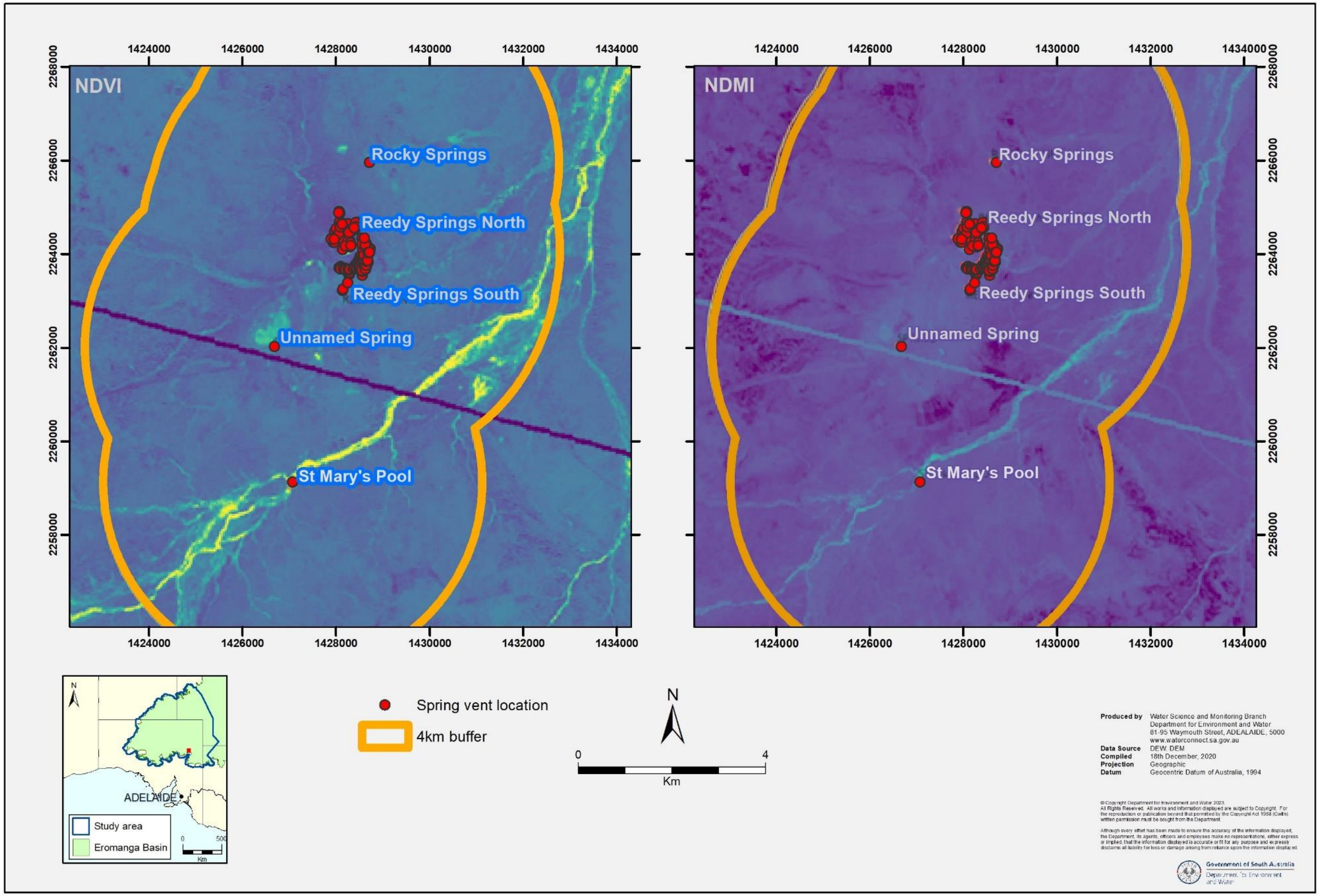


Figure 6.1: NDVI and NDMI images for St Mary's Pool Springs.

7 Closing remarks, model assumptions and conclusions

7.1 Hydrochemistry

Water quality varies significantly across the study area. Salinity varies from <1,000 mg/L TDS in eastern and central regions to >14,000 mg/L near the south-western margin near Lake Phillipson. Further, the pH is typically alkaline in eastern portions, relatively acidic in the south-western margin and near neutral elsewhere. Temperature variation is broadly commensurate with depth, varying from >25°C along the shallow western margin and within the non-artesian areas of the south-west to >95°C at depth in the eastern depocentres.

In broad terms, and with respect to major ion concentrations, groundwater emanating from the western margin recharge areas is predominantly Na^{+}+Cl^{-}+ (SO_4^{2-}), whereas groundwater emanating from the central Eromanga region is predominantly Na^{+}+HCO_3^{-}. Variations and patterns within this broad framework may relate to sub-basinal variations in flow-paths, mixing of groundwater from different parts of the basin or hydrochemical evolution related to water-rock interactions.

Stable isotopes δD and $\delta^{18}O$ samples from the western margin show notably more variation compared to those from further east, with the cause associated with closer proximity to recharge zones and shorter flow paths in the former and greater attenuation experienced by the latter. $^{87/86}Sr$ has successfully been used to identify the groundwater from fractured rock aquifers, particularly near the margins of the basins where springs occur.

Several studies have used radioisotopes to calculate a groundwater flow velocity. These are summarised below:

- Love et al. 2000 (^{36}Cl): 0.24 ± 0.03 m/y; (West of Peake and Denison Inlier)
- Phillips 1993 (^{36}Cl): 1.3 m/y
- Matthews 1997 (^{14}C): 0.8 to 2 m/y
- Love et al. 2013b (^{14}C): 0.05 m/y (East of the Peak and Denison inlier) between 3.6 and 7.6 m/y (Finke River, NT) and between 6.2 and 20.9 m/y (Hale River, NT).

7.2 Recharge and lateral inflow

Although rates of recharge and discharge still have a high degree of uncertainty, the new data and interpretation suggest that discharge is greater than recharge. Consequently, groundwater conditions in the J-K aquifer in SA, and particularly the western margin, are transient, and are probably now in a state of natural long-term slow decline controlled by paleoclimate (Rousseau-Gueutin et al. 2013; Welsh et al. 2012).

The largest proportion of inflow into the study area originates from the NT, Qld, and NSW (Figure 7.1 and Figure 7.2). An estimated total volume of 457 ML/d of lateral inflow within the J-K aquifer into the study area was calculated during this study. An unknown contribution to lateral inflow into the J-K aquifer within the study area is from the Officer Basin along the western margin of the Eromanga Basin, and inflow inferred via the interpreted potentiometric surface. Further, any lateral inflow inferred from the potentiometric surface along the north-western and western margins may be related to paleo-recharge that occurred earlier in the Cenozoic.

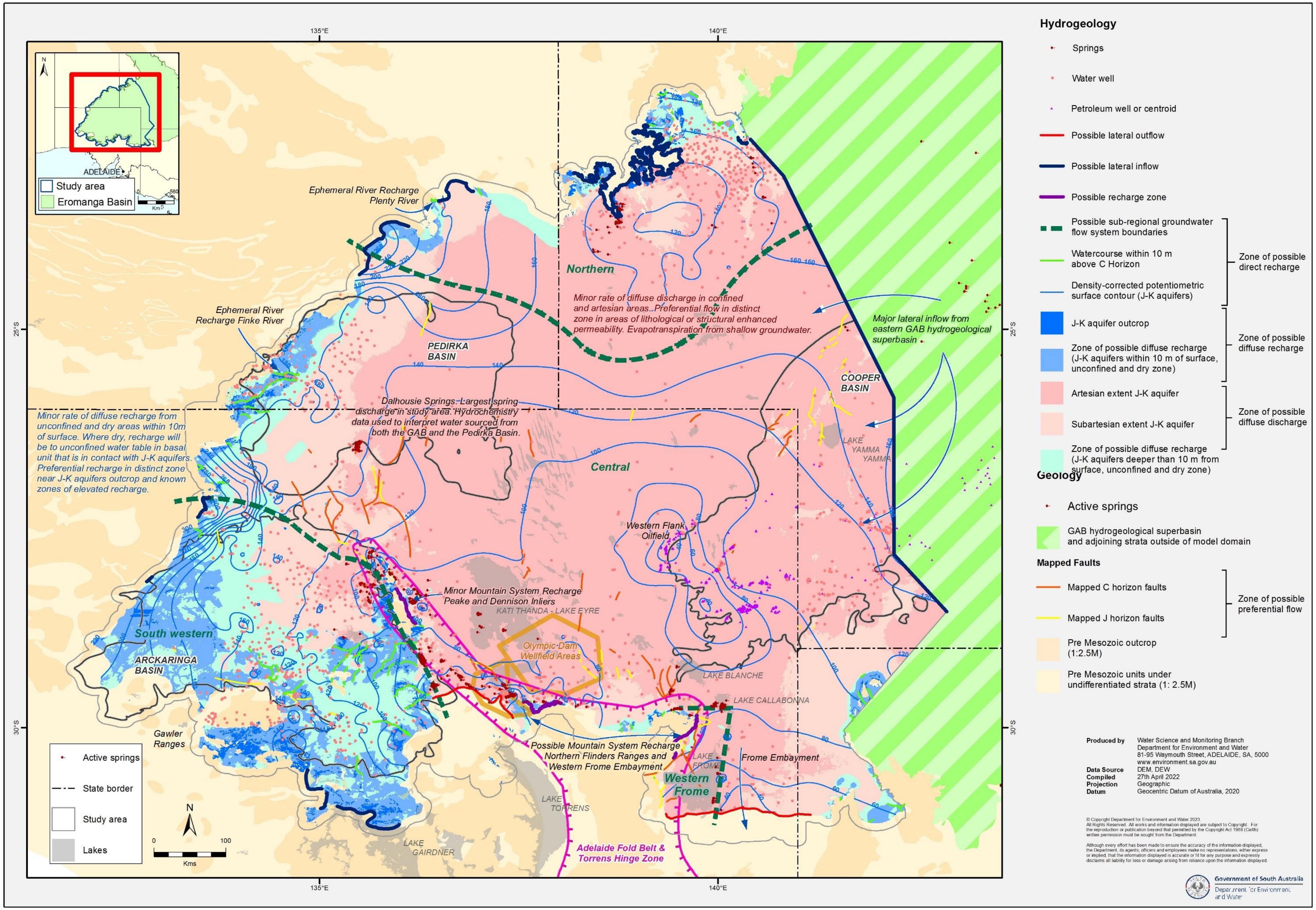


Figure 7.1: Schematic conceptual plan of recharge and discharge processes interpreted to occur within the study area

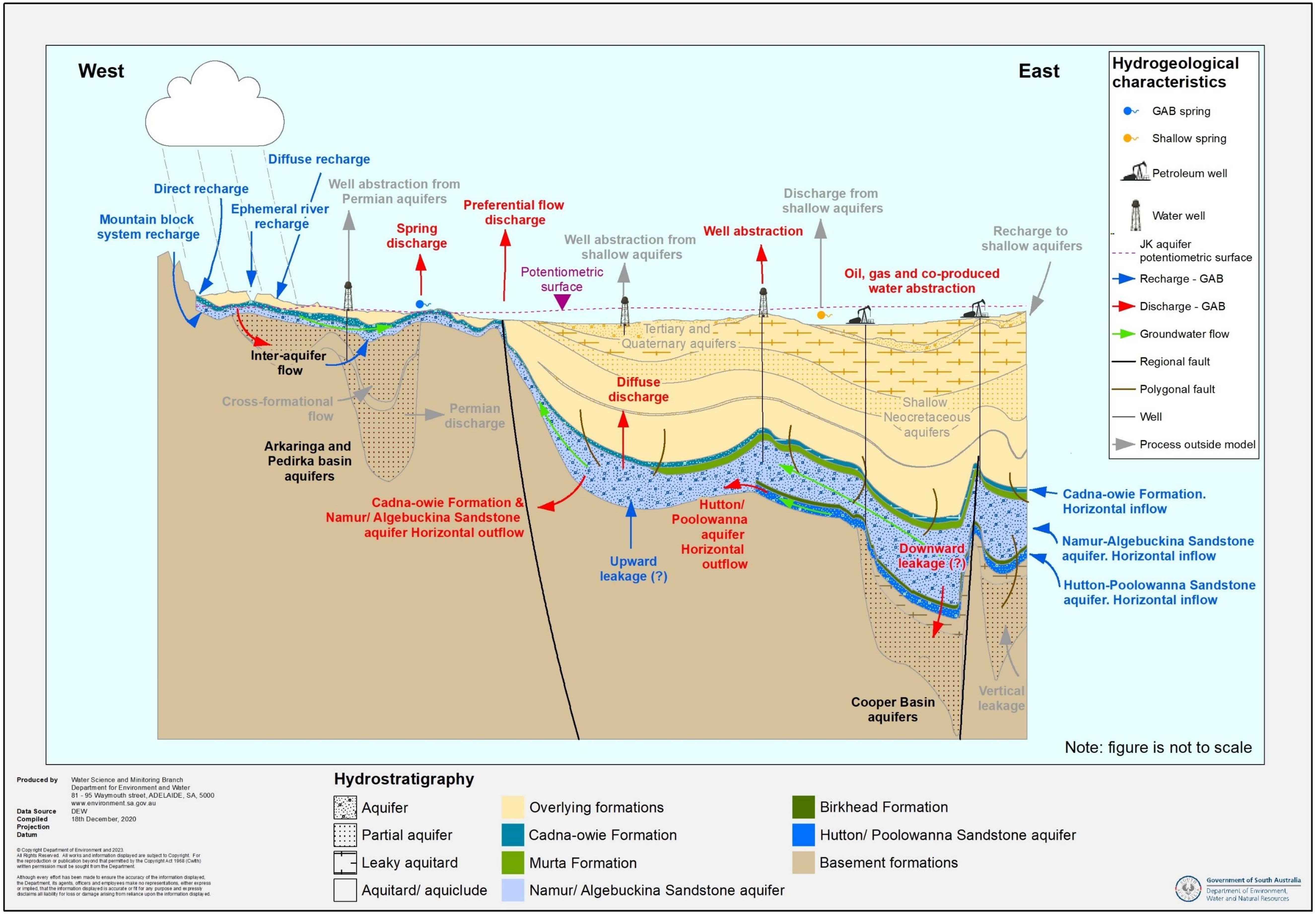


Figure 7.2: **Schematic conceptual cross-section of recharge and discharge processes interpreted to occur within the study area**

Ransley and Smerdon (2012) suggested total recharge in the western portion of the GAB to be approximately 6,600 ML/y. Areas of potential recharge near Mount Willoughby, Margaret River, and the northern Flinders Ranges may not be accounted in this, but such areas may not markedly increase this recharge estimate.

Direct recharge via outcropping and sub-cropping J-K aquifer strata is interpreted. Areas where this is most likely to occur are along the north-western and western margins, although current rates are likely to be lower than what they were earlier in the Cenozoic. The area around Marla provides an observable case of direct recharge over time. Comparison of hydrograph records from monitoring wells located near Marla and rainfall records suggest direct recharge may be occurring in this region as well. Recharge in this region is likely via ephemeral swamps mapped by Sheard (1981) and Sheard (1982). As well as the hydrographs, patterns in the interpreted potentiometric surfaces also suggest this area as a recharge site. A preliminary average recharge rate of approximately 0.2 m/y was estimated using hydrograph data from the Marla region, with individual rates ranging from 0.03 to 0.5 m/y.

Regional-scale diffuse recharge to the J-K aquifer within the western portion of the study area (Figure 7.1 and Figure 7.2) was identified by Wohling et al. (2013b), who estimated the mean rate of diffuse recharge using CMB at 0.15 mm/y, (range 0.01 to 1.8 mm/y). Estimated figures were corroborated using 14C and coring results in discrete areas but are approximations at best given uncertainties in the applied method. Similarly, Kellett et al. (1999) used CMB to estimate recharge rates of 0.1 to 5 mm/y in the southern portion of the study area and Love et al. (2000) estimated 0.16 ± 0.08 mm/y. During this study, diffuse recharge rates calculated in the Mt Willoughby region of the study area suggested rates of between 0.2 and 0.9 mm/y using the CMB method.

Fulton et al. (2013) identified a portion of the Finke and Plenty rivers where direct Ephemeral River Recharge (ERR) to the J-K aquifer was occurring (Figure 7.1 and Figure 7.2). Fulton et al. (2013) linked this recharge to rainfall greater than 100 mm/y. Fulton et al. (2013) estimated the total contribution from ERR along the western margin of the Eromanga Basin at between 5,150 and 11,560 ML/y (14 to 32 ML/d). Further, Priestley et al. (2017) and Keppel et al. (2015b) found that modern groundwater within unconfined portions of the J-K aquifer within the Margaret River catchment area was indicative of ERR or recharge via fractures (Figure 7.1).

Wohling et al. (2013a) identified minor recharge occurring via Mountain System Recharge (MSR) near the Peake and Denison Inliers and potentially other elevated areas near the margins of the GAB (Figure 7.1 and Figure 7.2). However, with respect to MSR and diffuse recharge, the latest research notes that, although such recharge may be occurring, total volumes may be very small.

7.3 7.3 Discharge and lateral outflow

Hydraulic heads as described by the potentiometric surface developed for J-K Aquifer groundwater suggests outflow might occur along the southern margin of the Frome Embayment into the Precambrian and via early Phanerozoic rocks of the Stuart Shelf and the Northern Flinders Ranges (Figure 7.1). With respect to outflow from the Frome Embayment, there has been little study concerning outflow and the role of Lake Frome as an evaporative discharge feature for the J-K aquifer (Figure 7.1). Groundwater flow as described by the potentiometric surface also suggests lateral outflow might occur along parts of the southern margin of the GAB aquifer near Maree and south of Coward Springs. However, the southern and south-eastern margins of the Eromanga Basin in South Australia are bordered by the Northern Flinders Ranges and the Stuart Shelf, which largely have a higher elevation than the basin to the north and therefore may contain a hydraulic system that could constrain any outflow. Further, the areas near Maree and Coward Springs also have a high proportion of springs. BHP Billiton (2011) argued that an evaporative discharge zone concomitant with springs acts as a groundwater divide between the largely artesian groundwater of the J-K aquifer to the east and the aquifers and unconfined groundwater systems to the south and south-west.

There are currently over 5,000 GAB springs mapped within the study area, extending from Lake Frome in the south-east to Dalhousie Springs on the northern margin and encompassing regions in the centre of the study area, including the Peake and Denison Inlier (Figure 7.1 and Figure 7.2). Flow to springs occurs via preferential flow through fractures and faults developed within the overlying confining unit shales and/or thinning of the confining unit or secondarily cemented aquifer strata via uplift and erosion. Current estimates of point discharge through springs of between 60-80 ML/d are likely to be underestimated due to the method of calculation and recent vent mapping.

Diffuse discharge via vertical leakage is unlikely to occur at equal rates across the study area; rather, higher fluxes are interpreted to be found where structural deformation or erosion allows the water table to window above the land surface (Figure 7.1 and Figure 7.2). Mapped zones of diffuse discharge around springs vary between 97 and 412 km2. Inclusion of regions of J-K aquifer outcrop and sub-crop within 10 m of the surface and where groundwater is unconfined expand this area.

Whereas the zone of diffuse discharge mapped by Costelloe et al. (2015a) incorporating LTZ, MTZ and carbonate platforms within the general study area is larger than what was mapped here around springs, Costelloe et al. (2012) noted that the proportion of artesian water being evapotranspired from these areas varied from marginal to what was potentially considerable, although there was no allowance for re-infiltration of spring water allowed in this assessment. Nevertheless, Costelloe et al. (2015a) suggested that the higher phreatic evapotranspiration zones estimated by landform mapping account for 73 to 251% of the total vertical leakage component of artesian groundwater as modelled in steady state by Welsh (2000). The eastern, predominantly artesian zone being 4 to 13% and the mixing zone between these two being 5to 22%, respectively. Costelloe et al. (2015a) indicated that there is sufficient evaporative capacity within the high discharge zone mapped within the western portion of the study area to account for annual recharge.

Harrington et al. (2013) measured vertical hydraulic conductivity rates of between 8.64×10^{-5} to 8.64×10^{-4} m/d (1×10^{-9} to 1×10^{-8} m/sec) using environmental tracers from shallow groundwater wells. In contrast, Harrington et al. (2013) estimated diffuse discharge through undeformed confining unit sedimentary rocks as very small (0.2 ML/d at a rate of 3×10^{-4} to 5×10^{-4} mm/d). Consequently, Harrington et al. (2013) argued that diffuse discharge through confining units was more likely to occur where deformation had improved permeability.

7.4 Data gaps and limitations

During the compilation of datasets and information used to develop a conceptual model, a number of material data gaps and uncertainties became apparent. In brief, these include:

- ***Hydrochemistry***: data requires careful interpretation and caution where supplementary information, like multiple analytes and hydraulic information is lacking. Similarities in proportional major ion concentrations in groundwater from different aquifers may lead to inaccurate interpretations regarding inter-aquifer connectivity.
  The use of tracers to calculate groundwater velocity has limitations. Apparent ages provided by tracers may be from mixed groundwater sources, may be impacted by groundwater from different sources mixing (Bentley et al. 1986), reflect diffusive transport across flow paths caused by low recharge rates (Priestley et al. 2017) or show the impact of a dual porosity aquifer causing bimodal tracer transport rates (Suckow et al. 2020). Different tracers may give different apparent ages for the same groundwater sample (Priestley et al. 2017; Suckow et al. 2020). Ideally, multiple tracers should be employed when used to determine groundwater velocity (Suckow et al. 2020).

- ***Regional-scale recharge and lateral inflow***: Reliance on potentiometric surfaces to interpret contemporaneous lateral inflow into the study area along the north-western and western margins may be misleading. Head data may be reflective of paleo-recharge dating back to the earlier Cenozoic.

Further, much contemporaneous recharge appears restricted to localised, focused areas. Although there are studied examples such as in the NT, and near the Peake and Denison Inliers, identifying other areas is restricted to identifying areas with circumstantially similar attributes.

- ***Regional-scale discharge:*** Recent research has suggested that regional-scale diffuse discharge from the J-K aquifer is likely to occur preferentially in regions where the main confining unit has been structurally deformed. Determining where these preferential zones of diffuse leakage occur is a data gap that may need addressing at some stage.

  Mapping zones of diffuse discharge may constrain the areal extent of where evapotranspiration is most likely to occur; however, the proportion of J-K aquifer groundwater to other aquifer groundwater can vary significantly and can be difficult to quantify if end member chemistries are similar.

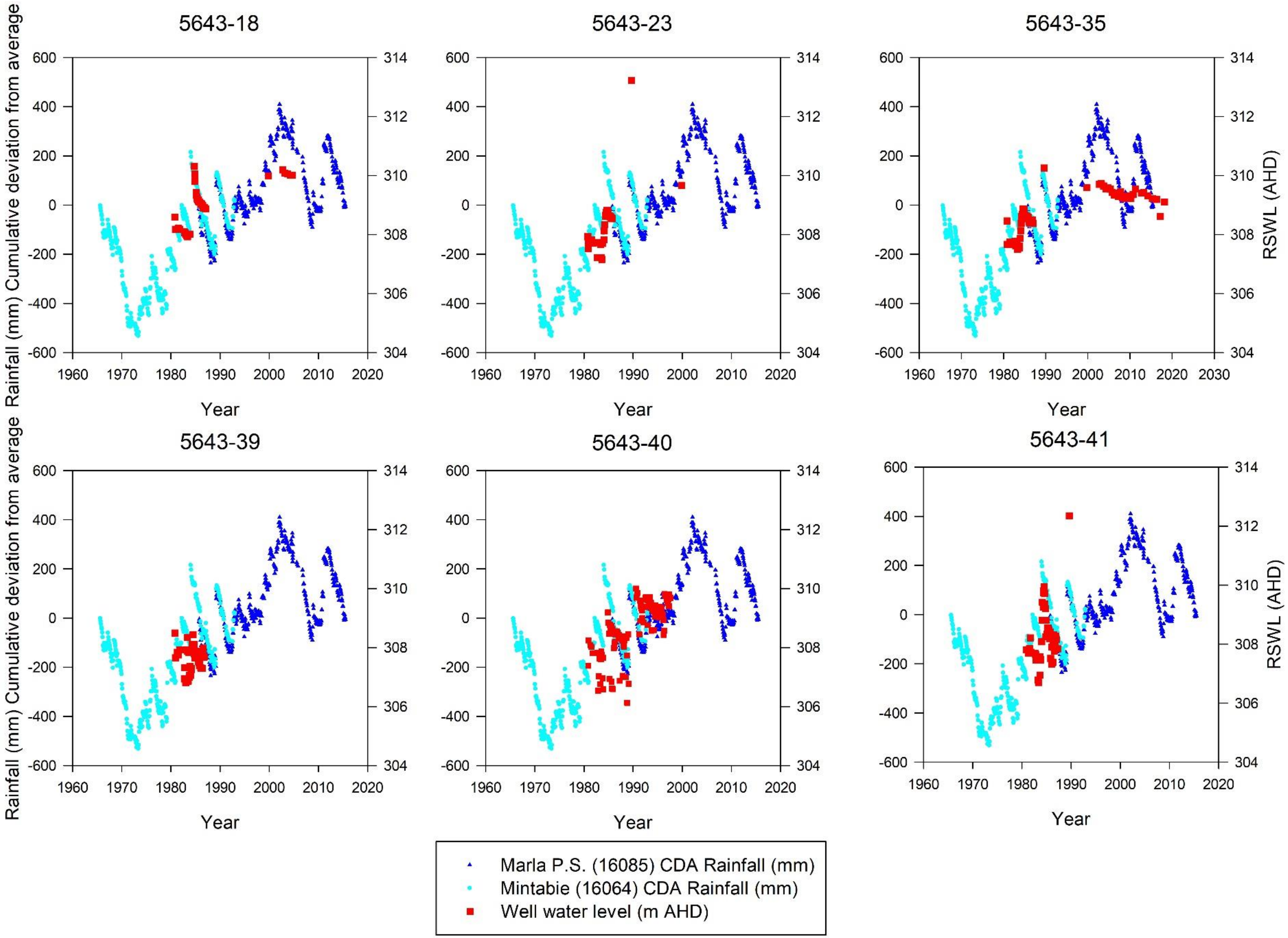
  Finally, although the potential for lateral outflow has been identified in the Frome Embayment, there is little in the way of data to confirm this assertion.

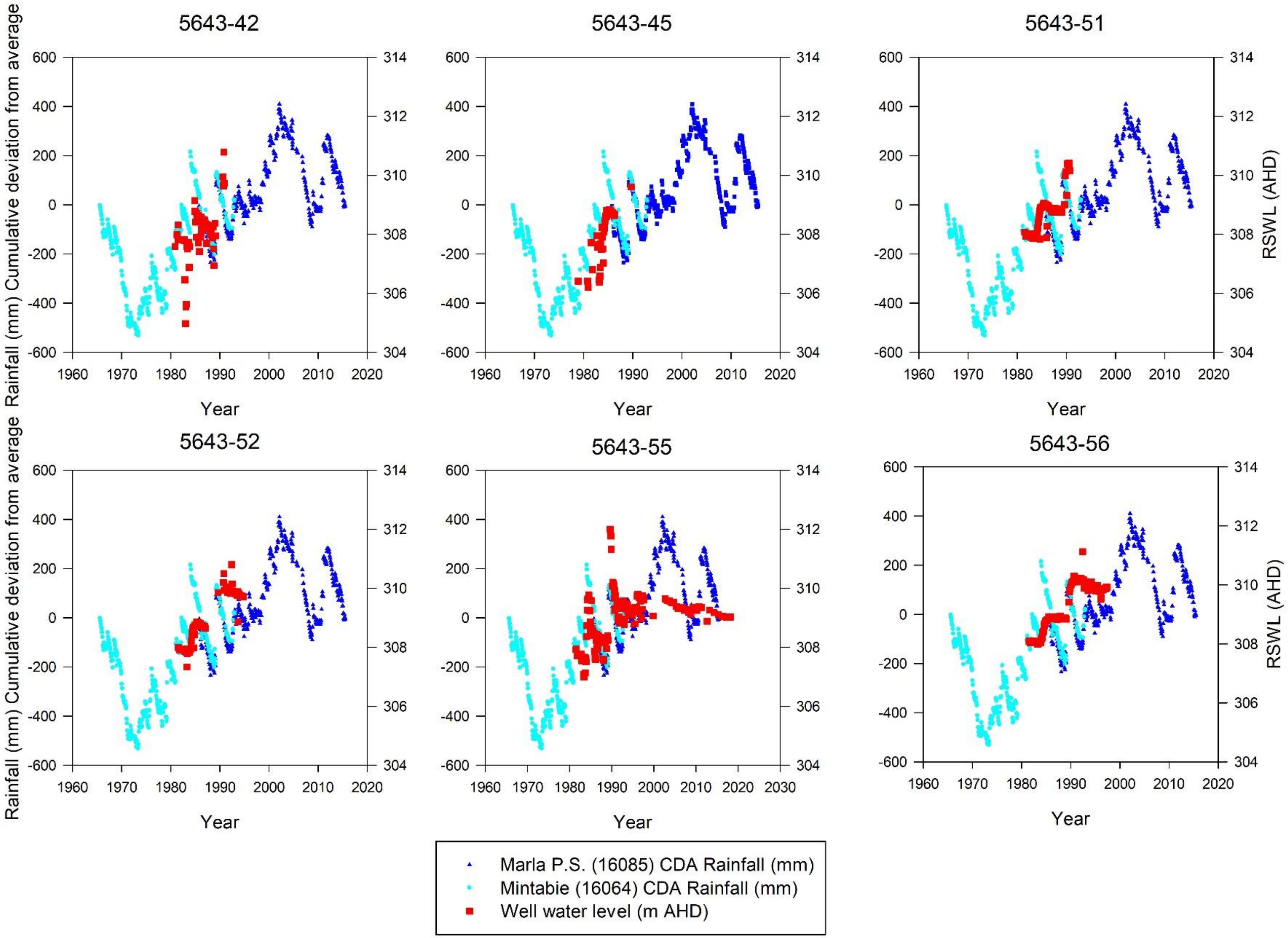
- ***Spring environments.*** Recent work suggests that springs in certain parts of the study area may have multiple groundwater sources. Further, the large number of springs with a small recorded discharge rate may require a degree of approximate representation in the numerical model. Similarly, there is uncertainty regarding whether measured discharge from a central vent represents the total discharge from all of the spring conduits, as there is the potential for associated diffuse discharge as well as sub surface discharge. The use of remote sensing techniques to try to address the issue of diffuse discharge may inadvertently include spring water that has re-infiltrated back into the near surface.

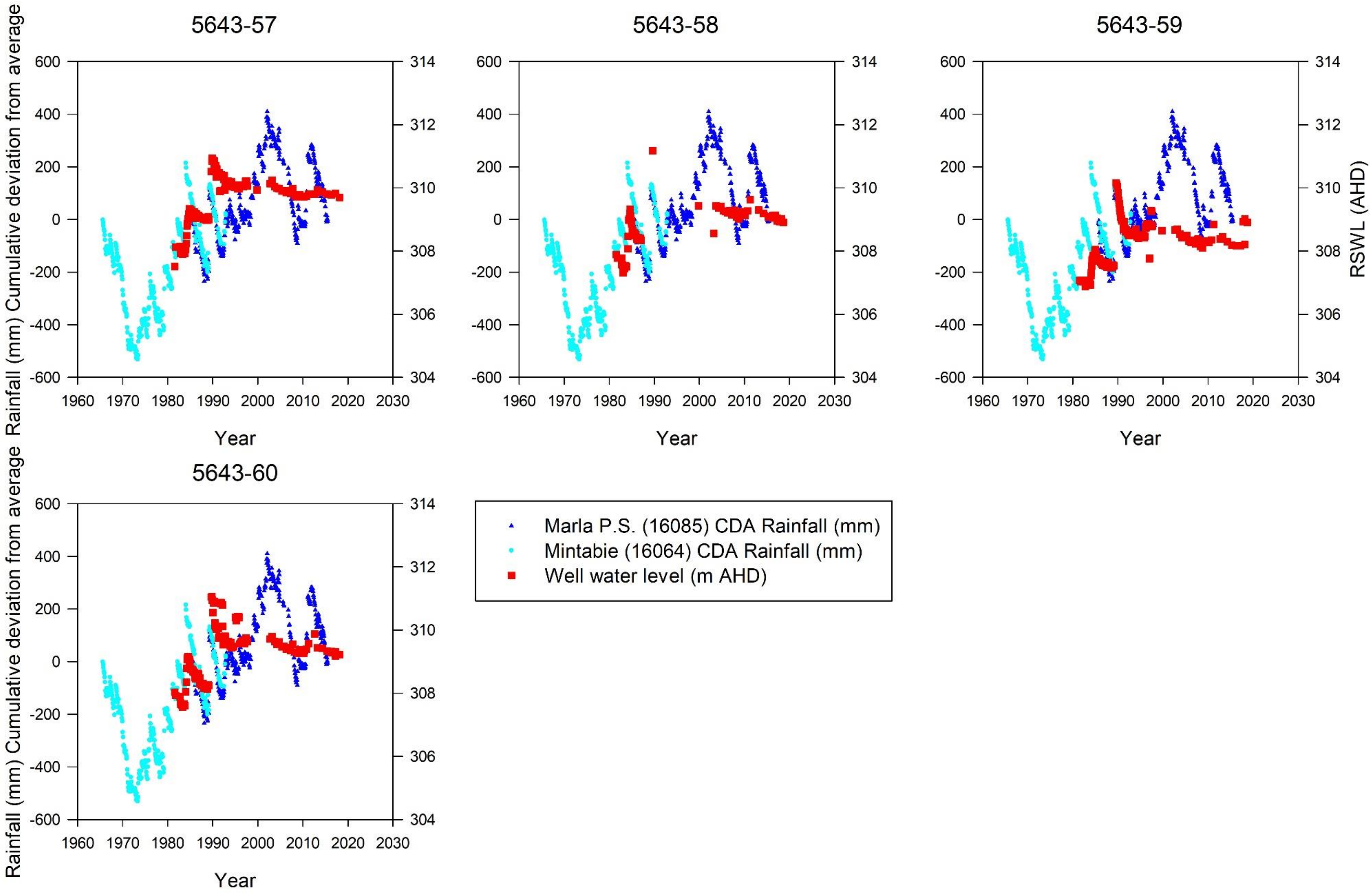
Finally, how spring discharge is represented numerically also requires approximation, not only because of the above issues but also because of difficulties representing spring structures numerically.

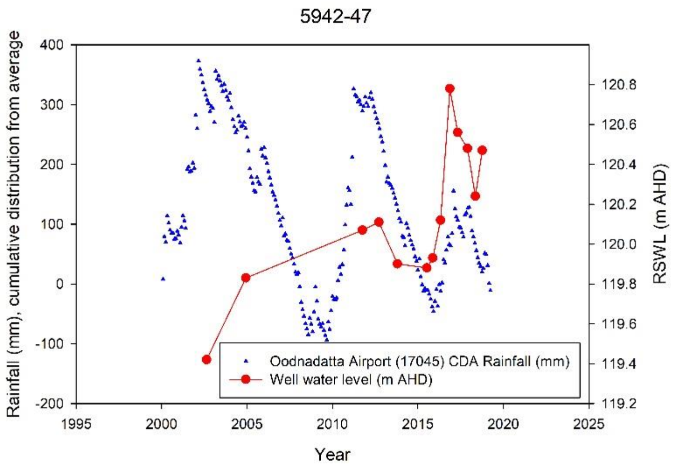
8 Appendices

A. Hydrographs and cumulative rainfall deviation from the average (CRD) rainfall plots, Marla monitoring network and Oodnadatta


5643-18
5643-23
5643-35
5643-39
5643-40
5643-41
Rainfall (mm) Cumulative deviation from average
RSWL (AHD)
Year
600
400
200
0
-200
-400
-600
314
312
310
308
306
304
1960
1970
1980
1990
2000
2010
2020
2030
Marla P.S. (16085) CDA Rainfall (mm)
Mintabie (16064) CDA Rainfall (mm)
Well water level (m AHD)


5643-42
5643-45
5643-51
5643-52
5643-55
5643-56
Rainfall (mm) Cumulative deviation from average
RSWL (AHD)
Year
Marla P.S. (16085) CDA Rainfall (mm)
Mintabie (16064) CDA Rainfall (mm)
Well water level (m AHD)


5643-57
5643-58
5643-59
5643-60
Rainfall (mm) Cumulative deviation from average
RSWL (AHD)
Year
600
400
200
0
-200
-400
-600
314
312
310
308
306
304
1960 1970 1980 1990 2000 2010 2020 2030
Marla P.S. (16085) CDA Rainfall (mm)
Mintabie (16064) CDA Rainfall (mm)
Well water level (m AHD)


5942-47
Rainfall (mm), cumulative distribution from average
RSWL (m AHD)
Year
Oodnadatta Airport (17045) CDA Rainfall (mm)
Well water level (m AHD)
400
300
200
100
0
-100
-200
120.8
120.6
120.4
120.2
120.0
119.8
119.6
119.4
119.2
1995
2000
2005
2010
2015
2020
2025

9 Units of measurement

9.1 Units of measurement commonly used (SI and non-SI Australian legal)

Name of unit	Symbol	Definition in terms of other metric units	Quantity
day	d	24 h	time interval
gigalitre	GL	10^6 m^3	volume
gram	g	10^{-3} kg	mass
hectare	ha	10^4 m^2	area
hour	h	60 min	time interval
kilogram	kg	base unit	mass
kilolitre	kL	1 m^3	volume
kilometre	km	10^3 m	length
litre	L	10^{-3} m^3	volume
megalitre	ML	10^3 m^3	volume
metre	m	base unit	length
microgram	µg	10^{-6} g	mass
microlitre	µL	10^{-9} m^3	volume
milligram	mg	10^{-3} g	mass
millilitre	mL	10^{-6} m^3	volume
millimetre	mm	10^{-3} m	length
minute	min	60 s	time interval
second	s	base unit	time interval
tonne	t	1000 kg	mass
year	y	365 or 366 days	time interval

9.2 Shortened forms

bgs below ground surface

pH acidity

pMC percent of modern carbon

10 Glossary

Act (the) — In this document, refers to the *Natural Resources Management (SA) Act 2004,* which supersedes the *Water Resources (SA) Act 1997*

Ambient — The background level of an environmental parameter (e.g. a measure of water quality such as salinity)

Ambient water monitoring — All forms of monitoring conducted beyond the immediate influence of a discharge pipe or injection well, and may include sampling of sediments and living resources

Ambient water quality — The overall quality of water when all the effects that may impact upon the water quality are taken into consideration

Aquiclude — In hydrologic terms, a formation that contains water but cannot transmit it rapidly enough to furnish a significant supply to a well or spring

Aquifer — An underground layer of rock or sediment that holds water and allows water to percolate through

Aquifer, confined — Aquifer in which the upper surface is impervious (see 'confining unit') and the water is held at greater than atmospheric pressure; water in a penetrating well will rise above the surface of the aquifer

Aquifer test — A hydrological test performed on a well, aimed to increase the understanding of the aquifer properties, including any interference between wells, and to more accurately estimate the sustainable use of the water resources available for development from the well

Aquifer, unconfined — Aquifer in which the upper surface has free connection to the ground surface and the water surface is at atmospheric pressure

Aquitard — A layer in the geological profile that separates two aquifers and restricts the flow between them

ArcGIS — Specialised GIS software for mapping and analysis developed by ESRI

Arid lands — In South Australia, arid lands are usually considered to be areas with an average annual rainfall of less than 250 mm and support pastoral activities instead of broadacre cropping

Artesian — An aquifer in which the water surface is bounded by an impervious rock formation; the water surface is at greater than atmospheric pressure, and hence rises in any well, which penetrates the overlying confining aquifer

Artificial recharge — The process of artificially diverting water from the surface to an aquifer; artificial recharge can reduce evaporation losses and increase aquifer yield; see also 'natural recharge', 'aquifer'

Basin — The area drained by a major river and its tributaries

BoM — Bureau of Meteorology, Australia

Bore — See 'well'

Buffer zone — A neutral area that separates and minimises interactions between zones whose management objectives are significantly different or in conflict (e.g. a vegetated riparian zone can act as a buffer to protect the water quality and streams from adjacent land uses)

^{14}C — Carbon-14 isotope (percent modern Carbon; pMC)

Catchment — That area of land determined by topographic features within which rainfall will contribute to runoff at a particular point

CFC — Chlorofluorocarbon; measured in parts per trillion (ppt)

Climate change — The balance of incoming and outgoing solar radiation which regulates our climate. Changes to the composition of the atmosphere, such as the addition of carbon dioxide through human activities, have the potential to alter the radiation balance and to effect changes to the climate. Scientists suggest that changes would include global warming, a rise in sea level and shifts in rainfall patterns.

CMB — Chloride mass balance

Cone of depression — An inverted cone-shaped space within an aquifer caused by a rate of groundwater extraction that exceeds the rate of recharge; continuing extraction of water can extend the area and may affect the viability of adjacent wells, due to declining water levels or water quality

Confining unit — A rock unit impervious to water, which forms the upper bound of a confined aquifer; a body of impermeable material adjacent to an aquifer; see also 'aquifer, confined'

CSG — coal seam gas

CSIRO — Commonwealth Scientific and Industrial Research Organisation

δD — Hydrogen isotope composition, measured in parts per thousand (**‰**)

Dams, off-stream dam — A dam, wall or other structure that is not constructed across a watercourse or drainage path and is designed to hold water diverted or pumped from a watercourse, a drainage path, an aquifer or from another source; may capture a limited volume of surface water from the catchment above the dam

Dams, on-stream dam — A dam, wall or other structure placed or constructed on, in or across a watercourse or drainage path for the purpose of holding and storing the natural flow of that watercourse or the surface water

Dams, turkey nest dam — An off-stream dam that does not capture any surface water from the catchment above the dam

DEW — Department for Environment and Water

DEWNR — Department of Environment, Water and Natural Resources (Government of South Australia)

DfW — former Department for Water (Government of South Australia)

dGPS — differential Global Positioning System

DO — Dissolved Oxygen

DOC — Dissolved Organic Carbon

Domestic purpose — The taking of water for ordinary household purposes; includes the watering of land in conjunction with a dwelling not exceeding 0.4 hectares

Dryland salinity — The process whereby salts stored below the surface of the ground are brought close to the surface by the rising watertable. The accumulation of salt degrades the upper soil profile, with impacts on agriculture, infrastructure and the environment.

DSS — Dissolved suspended solids

DWLBC — former Department of Water, Land and Biodiversity Conservation (Government of South Australia)

EC — Electrical conductivity; 1 EC unit = 1 micro-Siemen per centimetre (µS/cm) measured at 25°C; commonly used as a measure of water salinity as it is quicker and easier than measurement by TDS

Ecology — The study of the relationships between living organisms and their environment

Ecological processes — All biological. physical or chemical processes that maintain an ecosystem

Ecological values — The habitats, natural ecological processes and biodiversity of ecosystems

Ecosystem — Any system in which there is an interdependence upon, and interaction between, living organisms and their immediate physical, chemical and biological environment

Endemic — A plant or animal restricted to a certain locality or region

Environmental values — The uses of the environment that are recognised as being of value to the community. This concept is used in setting water quality objectives under the Environment Protection (Water Quality) Policy, which recognises five environmental values — protection of aquatic ecosystems, recreational water use and aesthetics, potable (drinking water) use, agricultural and aquaculture use, and industrial use. It is not the same as ecological values, which are about the elements and functions of ecosystems.

Ephemeral streams or wetlands — Those streams or wetlands that usually contain water only on an occasional basis after rainfall events. Many arid zone streams and wetlands are ephemeral.

Erosion — Natural breakdown and movement of soil and rock by water, wind or ice; the process may be accelerated by human activities

Evapotranspiration — The total loss of water as a result of transpiration from plants and evaporation from land, and surface water bodies

Fresh — A short duration, small volume pulse of streamflow generated by a rainfall event that temporarily, but noticeably, increases stream discharge above ambient levels

Fully-penetrating well — In theory this is a well-hole that is screened throughout the full thickness of the target aquifer; in practice, any screen that is open to at least the mid 80% of a confined aquifer is regarded as fully-penetrating.

GAB — Great Artesian Basin

GDE — Groundwater dependent ecosystem

Geological features — Include geological monuments, landscape amenity and the substrate of land systems and ecosystems

Geomorphic — Related to the physical properties of the rock, soil and water in and around a stream

Geomorphology — The scientific study of the landforms on the Earth's surface and of the processes that have fashioned them

GIS — Geographic Information System; computer software linking geographic data (for example land parcels) to textual data (soil type, land value, ownership). It allows for a range of features, from simple map production to complex data analysis

Groundwater — Water occurring naturally below ground level or water pumped, diverted and released into a well for storage underground; see also 'underground water'

Groundwater Data — Interactive map and search tool for viewing information about South Australia's wells with access to well details including, graphs showing water salinity and water level. It provides a variety of search methods, including filtering the results. [*waterconnect.sa.gov.au/Systems/GD/*]

Head (hydraulic) — Sum of datum level, elevation head and pressure head. The altitude to which water will rise in a properly constructed well. In unconfined aquifers it is the groundwater elevation, and in confined aquifers it is the potentiometric head.

Hydraulic conductivity (K) — A measure of the ease of flow through aquifer material: high K indicates low resistance, or high flow conditions; measured in metres per day

Hydrogeology — The study of groundwater, which includes its occurrence, recharge and discharge processes, and the properties of aquifers; see also 'hydrology'

Hydrography — The discipline related to the measurement and recording of parameters associated with the hydrological cycle, both historic and real time

Hydrology — The study of the characteristics, occurrence, movement and utilisation of water on and below the Earth's surface and within its atmosphere; see also 'hydrogeology'

Infrastructure — Artificial lakes; dams or reservoirs; embankments, walls, channels or other works; buildings or structures; or pipes, machinery or other equipment

Injection well — An artificial recharge well through which water is pumped or gravity-fed into the ground

Irrigation — Watering land by any means for the purpose of growing plants

Kati Thanda-Lake Eyre — Lake Eyre was co-named with the name used by the Arabana people in December 2012

Kati Thanda-Lake Eyre National Park — was proclaimed in November 2013 to recognise the significance of Lake Eyre to the Arabana people and co-name the lake Kati Thanda-Lake Eyre.

Lake — A natural lake, pond, lagoon, wetland or spring (whether modified or not) that includes part of a lake and a body of water declared by regulation to be a lake. A reference to a lake is a reference to either the bed, banks and shores of the lake or the water for the time being held by the bed, banks and shores of the lake, or both, depending on the context.

Land — Whether under water or not, and includes an interest in land and any building or structure fixed to the land

Licence — A licence to take water in accordance with the Act; see also 'water licence'

Licensee — A person who holds a water licence

LMWL — Local meteoric water line

m AHD — Defines elevation in metres (m) according to the Australian Height Datum (AHD)

MAR — Managed aquifer recharge (MAR) is a process where water is intentionally placed and stored in an aquifer for later human use, or to benefit the environment.

Metadata — Information that describes the content, quality, condition, and other characteristics of data, maintained by the Federal Geographic Data Committee

Model — A conceptual or mathematical means of understanding elements of the real world that allows for predictions of outcomes given certain conditions. Examples include estimating storm runoff, assessing the impacts of dams or predicting ecological response to environmental change

MODFLOW — A three-dimensional., finite difference code developed by the USGS to simulate groundwater flow

Molar (M) — A term describing the concentration of chemical solutions in moles per litre (mol/L)

Monitoring — (1) The repeated measurement of parameters to assess the current status and changes over time of the parameters measured (2) Periodic or continuous surveillance or testing to determine the level of compliance with statutory requirements and/or pollutant levels in various media or in humans, animals, and other living things

Natural recharge — The infiltration of water into an aquifer from the surface (rainfall, streamflow, irrigation etc). See also recharge area, artificial recharge

Natural resources — Soil, water resources, geological features and landscapes, native vegetation, native animals and other native organisms, ecosystems

NRM — Natural Resources Management; all activities that involve the use or development of natural resources and/or that impact on the state and condition of natural resources, whether positively or negatively

NWC — National Water Commission

δ^{18}**O** — Oxygen isotope composition, measured in parts per thousand (**‰**)

Observation well — A narrow well or piezometer whose sole function is to permit water level measurements

ORP — Oxidation Reduction Potential

Owner of land — In relation to land alienated from the Crown by grant in fee simple — the holder of the fee simple; in relation to dedicated land within the meaning of the *Crown Lands Act 1929* that has not been granted in fee simple but which is under the care, control and management of a Minister, body or other person — the Minister, body or other person; in relation to land held under Crown lease or licence — the lessee or licensee; in relation to land held under an agreement to purchase from the Crown — the person entitled to the benefit of the agreement; in relation to any other land — the Minister who is responsible for the care, control and management of the land or, if no Minister is responsible for the land, the Minister for Sustainability, Environment and Conservation.

Paleochannels — Ancient buried river channels in arid areas of the state. Aquifers in paleochannels can yield useful quantities of groundwater or be suitable for ASR

Percentile — A way of describing sets of data by ranking the dataset and establishing the value for each percentage of the total number of data records. The 90th percentile of the distribution is the value such that 90% of the observations fall at or below it.

Permeability — A measure of the ease with which water flows through an aquifer or aquitard, measured in m/d

Piezometer — A narrow tube, pipe or well; used for measuring moisture in soil, water levels in an aquifer, or pressure head in a tank, pipeline, etc.

PIRSA — Primary Industries and Regions South Australia (Government of South Australia)

Population — (1) For the purposes of natural resources planning, the set of individuals of the same species that occurs within the natural resource of interest. (2) An aggregate of interbreeding individuals of a biological species within a specified location

Porosity — The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment (Middlemis, 2000).

Porosity, effective — The volume of the inter-connected void spaces through which water or other fluids can travel in a rock or sediment divided by the total volume of the rock or sediment.

Porosity, Primary — The porosity that represents the original pore openings when a rock or sediment formed (Middlemis, 2000).

Porosity, Secondary — The porosity that has been caused by fractures or weathering in a rock or sediment after it has been formed (Middlemis, 2000).

Potentiometric head — The potentiometric head or surface is the level to which water rises in a well due to water pressure in the aquifer, measured in metres (m); also known as piezometric surface

Prescribed water resource — A water resource declared by the Governor to be prescribed under the Act, and includes underground water to which access is obtained by prescribed wells. Prescription of a water resource requires that future management of the resource be regulated via a licensing system.

Prescribed well — A well declared to be a prescribed well under the Act

Production well — The pumped well in an aquifer test, as opposed to observation wells; a wide-hole well, fully developed and screened for water supply, drilled on the basis of previous exploration wells

PWA — Prescribed Wells Area

Recharge area — The area of land from which water from the surface (rainfall, streamflow, irrigation, etc.) infiltrates into an aquifer. See also artificial recharge, natural recharge

RSWL —Reduced Standing Water Level measured in meters AHD (Australian Height Datum). The elevation of the water level is calculated by subtracting the Depth to Water (DTW) from the reference elevation. A negative value indicates that the water level is below mean sea level.

SA Geodata — A collection of linked databases storing geological and hydrogeological data, which the public can access through the offices of PIRSA. Custodianship of data related to minerals and petroleum, and groundwater, is vested in PIRSA and DEW, respectively. DEW should be contacted for database extracts related to groundwater

Salinity — The concentration of dissolved salts in water or soil, expressed in terms of concentration (mg/L) or electrical conductivity (EC)

SDE — South Australian government dataset containing all other spatially explicit data not housed by SA GEODATA, HYDSTRA, or BDBSA

Seasonal— Pertaining to a phenomena or event that occurs on a on a seasonal basis

Specific storage (S_s) — Specific storativity; the amount of stored water realised from a unit volume of aquifer per unit decline in head; measured in m^{-1}

Specific yield (S_y) — The volume ratio of water that drains by gravity to that of total volume of the porous medium. It is dimensionless

Stock use — The taking of water to provide drinking water for stock other than stock subject to intensive farming (as defined by the Act)

Storativity (S) — Storage coefficient; the volume of groundwater released or taken into storage per unit plan area of aquifer per unit change of head; it is the product of specific storage Ss and saturated aquifer thickness (dimensionless)

Surface water — (a) water flowing over land (except in a watercourse), (i) after having fallen as rain or hail or having precipitated in any another manner, (ii) or after rising to the surface naturally from underground; (b) water of the kind referred to in paragraph (a) that has been collected in a dam or reservoir

Sustainability — The ability of an ecosystem to maintain ecological processes and functions, biological diversity, and productivity over time

SWL — Standing Water Level (meters) recorded for the water well. This is the distance from the ground surface to the water surface. A negative value indicates that the water level is above ground level.

TDS — Total dissolved solids, measured in milligrams per litre (mg/L); a measure of water salinity

Tertiary aquifer — A term used to describe a water-bearing rock formation deposited in the Tertiary geological period (1–70 million years ago). Also known as the Paleogene to Neogene period.

Threatened species — Any species that is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range

Transmissivity (T) — A parameter indicating the ease of groundwater flow through a metre width of aquifer section (taken perpendicular to the direction of flow), measured in m^2/d

Tributary — A river or creek that flows into a larger river

Turbidity — The cloudiness or haziness of water (or other fluid) caused by individual particles that are too small to be seen without magnification, thus being much like smoke in air; measured in Nephelometric Turbidity Units (NTU)

Underground water (groundwater) — Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground

USGS — United States Geological Survey

Volumetric allocation — An allocation of water expressed on a water licence as a volume (e.g. kilolitres) to be used over a specified period of time, usually per water use year (as distinct from any other sort of allocation)

Water allocation — (1) In respect of a water licence means the quantity of water that the licensee is entitled to take and use pursuant to the licence. (2) In respect of water taken pursuant to an authorisation under s.11 means the maximum quantity of water that can be taken and used pursuant to the authorisation

WAP — Water Allocation Plan; a plan prepared by a water resources planning committee and adopted by the Minister in accordance with the Act

Water body — Includes watercourses, riparian zones, floodplains, wetlands, estuaries, lakes and groundwater aquifers

Water column — a section of water extending from the surface of a body of water to its bottom. In the sea or ocean, it is referred to as 'pelagic zone'

Watercourse — A river, creek or other natural watercourse (whether modified or not) and includes: a dam or reservoir that collects water flowing in a watercourse; a lake through which water flows; a channel (but not a channel declared by regulation to be excluded from this definition) into which the water of a watercourse has been diverted; and part of a watercourse

Water dependent ecosystems — Those parts of the environment, the species composition and natural ecological processes, that are determined by the permanent or temporary presence of flowing or standing water, above or below ground; the in-stream areas of rivers, riparian vegetation, springs, wetlands, floodplains, estuaries and lakes are all water dependent ecosystems

Water licence — A licence granted under the Act entitling the holder to take water from a prescribed watercourse, lake or well or to take surface water from a surface water prescribed area; this grants the licensee a right to take an allocation of water specified on the licence, which may also include conditions on the taking and use of that water; a water licence confers a property right on the holder of the licence and this right is separate from land title

Water plans — The State Water Plan, water allocation plans and local water management plans prepared under Part 7 of the Act

Water quality data — Chemical, biological, and physical measurements or observations of the characteristics of surface and groundwaters, atmospheric deposition, potable water, treated effluents, and wastewater, and of the immediate environment in which the water exists

Water quality information — Derived through analysis, interpretation, and presentation of water quality and ancillary data

Water quality monitoring — An integrated activity for evaluating the physical, chemical, and biological character of water in relation to human health, ecological conditions, and designated water uses

Water resource monitoring — An integrated activity for evaluating the physical., chemical., and biological character of water resources, including (1) surface waters, groundwaters, estuaries, and near-coastal waters; and (2) associated aquatic communities and physical habitats, which include wetlands

Water resource quality — (1) The condition of water or some water-related resource as measured by biological surveys, habitat-quality assessments, chemical-specific analyses of pollutants in water bodies, and toxicity tests. (2) The condition of water or some water-related resource as measured by habitat quality, energy dynamics, chemical quality, hydrological regime, and biotic factors

Well — (1) An opening in the ground excavated for the purpose of obtaining access to underground water. (2) An opening in the ground excavated for some other purpose but that gives access to underground water. (3) A natural opening in the ground that gives access to underground water

Wetlands — Defined by the Act as a swamp or marsh and includes any land that is seasonally inundated with water. This definition encompasses a number of concepts that are more specifically described in the definition used in the Ramsar Convention on Wetlands of International Importance. This describes wetlands as areas of permanent or periodic to intermittent inundation, whether natural or artificial., permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tides does not exceed six metres.

11 References

Aldam R and Kuang KS 1988, An investigation of structures controlling discharge of spring waters in the South Western GAB. Department of Mines and Energy, Adelaide, South Australia.

Alexander EM and Dodds AR 1997, Chapter 4: Infrastructure and Groundwater'. in Morton JGG and Drexel JF (eds) *Petroleum Geology of South Australia Volume 3 – Officer Basin*. Department of Mines and Energy Resources, South Australia, pp 29-34.

Altmann MJ and Gordon HM 2004, *Oil on the Patchawarra Flank: Some implications from the Sellicks and Christies oil discoveries*, Petroleum Exploration Society of Australia, Special Publication, EABS04: pp. 29–34.

Appelo CAJ and Postma D 2005, *Geochemistry, groundwater and pollution*. 2nd edn, CRC Press, Boca Raton, Florida, USA.

Bentley HW, Phillips FM, Davis SN, Habermehl MA, Airey PL, Calf GE, Elmore D, Gove HE and Torgersen T 1986, 'Cl-36 dating of very old groundwater: 1. The Great Artesian Basin, Australia', *Water Resources Research*, 22:1991–2001.

BHP 2018, *Olympic Dam Great Artesian Basin Wellfields Report 1 July 2017 – 30 June 2018*, Report No. ODENV058, BHP Billiton. Adelaide.

BHP Billiton 2011, *Olympic Dam Expansion Supplementary Environmental Impact Statement Chapter 12: Groundwater* http://www.bhpbilliton.com/-/media/bhp/regulatory-information-media/copper/olympic-dam/0000/draft-eis-main-report/odxeischapter12groundwater.pdf, accessed 12th June 2021.

Boucaut WRP, Dunstan NC, Krieg GW and Smith PC 1986, *The geology and hydrogeology of the Dalhousie Springs, Witjira National Park. South Australia*, Report Book, 86/13, Government of South Australia, Department of Mines and Energy, Adelaide.

Bureau of Meteorology BoM 2016, *Average annual & monthly evapotranspiration*, http://www.bom.gov.au/jsp/ncc/climate_averages/evapotranspiration/index.jsp, accessed 14 December 2020.

Bureau of Meteorology (BoM) 2019, *Climate Data Online*, http://www.bom.gov.au/climate/data/, accessed 23 July 2019.

Canadell J, Jackson RB, Ehleringer JR, Mooney HA, Sala OE and Schulze ED 1996, 'Maximum rooting depth of vegetation types at the global scale', *Oecologia,* 108:583–595.

Chebotarev II 1952, *The Hydrology of the Pirie-Torrens Basin*. DM No. 521/49, Rept. Bk. No. 42/26. Government of South Australia, Department of Mines and Energy, Adelaide.

Clark I and Fritz P 1997, *Environmental Isotopes in Hydrogeology*, doi: 10.1201/9781482242911.

Costelloe JF, Irvine EC, Western AW and Tyler M 2012, 'Identifying fluvial recharge and artesian upwards leakage contributions to arid zone shallow, unconfined groundwater', *Chemical Geology,* 326–327:189–200.

Costelloe JF, Matic V, Western AW, Walker JP and Tyler M 2011, 'Field estimates of Groundwater discharge – Great Artesian Basin, South Australia', 19th International Congress on Modelling and Simulation, Perth, Australia. 12–16 December 2011 http://mssanz.org.au/modsim2011, accessed 2nd February, 2019.

Costelloe JF, Matic V, Western AW, Walker JP and Tyler M 2015a, 'Determining vertical leakage from the Great Artesian Basin, Australia, through up-scaling field estimates of phreatic evapotranspiration', *Journal of Hydrology,* 5(29):1079–1094.

Costelloe JF., Matic V, Western AW, Walker JP and Tyler M 2015b, *Estimating leakage around the southwestern margin of the Great Artesian Basin*. Final report for the Australian Research Council (ARC) Linkage project LP0774814 – 'Quantifying near-surface diffuse discharge from the southwest Great Artesian Basin'. https://www.researchgate.net/publication/280240319_Estimating_leakage_around_the_southwestern_margin_of_the_Great_Artesian_Basin, accessed 25th November, 2011.

Costelloe JF, Payne EG, Woodrow IE, Irvine EC, Western AW and Leaney F 2008, 'Water use by arid zone riparian trees in highly saline environments, Australia', *Oecologia* 156:43-52, doi: 10.1007/s00442-008-0975-4.

Crosbie RS, Morrow D, Cresswell RG, Leaney FW, Lamontagne S and Lefournour M 2012, *New insights into the chemical and isotopic composition of rainfall across Australia*, CSIRO Water for a Healthy Country Flagship, Australia.

Crossey L, Priestley S, Shand P, Karlstrom K, Love A and Keppel M 2013, 'Source and Origin of western GAB Springwater', in Love A, Shand P, Crossey L, Harrington G and Rousseau-Gueutin P (eds) *Allocating Water and Maintaining Springs in the Great Artesian Basin, Volume III: Groundwater Discharge of the Western Great Artesian Basin*, National Water Commission, Canberra, pp. 10-33

Curewitz D and Karson JA 1997, Structural settings of hydrothermal outflow: Fracture permeability maintained by fault propagation and interaction. *Journal of Volcanology and Geothermal Research*, 79(3-4): 149-168.

Davies P and Crosbie R 2014, *Australian chloride deposition rate. v4*, CSIRO, Data Collection, doi: 10.4225/08/545BEE54CD4FC.

Dubsky M and McPhail A 2001, *Environmental Impact Research Report (EIR), SA Cooper Basin Well Operations, Statement of Environmental Objectives (SEO): Water Pressure & Salinity Module*. SA Chamber of Mines & Energy. Adelaide.

Fulton S, Wohling, D, Love AJ and Berens V 2013, 'Ephemeral river recharge', in Love AJ, Wohling D, Fulton S, Rousseau-Gueutin P and De Ritter S (eds) *Allocating Water and Maintaining Springs in the Great Artesian Basin Volume II: Groundwater Recharge, Hydrodynamics and Hydrochemistry of the Western Great Artesian Basin*, National Water Commission, Canberra, pp. 37-82

Gee GW, Zhang ZF, Tyler SW, Albright WH and Singleton MJ 2004, *Chloride-mass-balance for predicting increased recharge after land-use change*. Lawrence Berkley National Laboratory. Retrieved from https://escholarship.org/uc/item/3w70793z accessed 21st June, 2023.

Golder 2015, ODGAB Groundwater Model. *Olympic Dam Expansion IPS – GAB modelling*. Prepared for BHP Billiton. Report no.: 147668004-012-Rev0_ODGAB_Modelling Report. Adelaide.

Gotch T 2013, 'Spatial survey of springs', in Lewis M, White D, and Gotch T, (eds) *Allocating Water and Maintaining Springs in the Great Artesian Basin, Volume IV: Spatial Survey and Remote Sensing of Artesian Springs of the Western Great Artesian Basin,* National Water Commission, Canberra, pp. 13-69.

Habermehl MA 1980, 'The Great Artesian Basin, Australia', *BMR Journal of Geology and Geophysics*, 5:9–37.

Halihan T, Love A, Keppel M and Berens V 2013, 'Analysis of subsurface mound spring connectivity in shale of the western margin of the Great Artesian Basin, South Australia', *Hydrogeology Journal*, 21(7), doi: 10.1007/s10040-013-1034-8.

Halihan T, Love A, Keppel M, Dailey MKM, Berens V and Wohling D 2020, 'Evidence for groundwater mixing at Freeling Spring Group, South Australia', *Hydrogeology Journal,* 28:313–323, doi: 10.1007/s10040-019-02069-x.

Hamilton SK, Bunn SE, Thoms MC and Marshall JC 2005, 'Persistence of aquatic refugia between flow pulses in a dryland river system (Cooper Creek, Australia)', *Limnology and Oceanography*, 50(3):743–754.

Harrington GA, Smerdon BD, Gardner PW, Taylor AR and Hendry J 2013, 'Diffuse discharge. In: Allocating Water and Maintaining Springs in the Great Artesian Basin', in Love AJ, Shand P, Crossey L, Harrington GA and Rousseau-Gueutin P (eds) *Volume III: Groundwater Discharge of the Western Great Artesian Basin*. National Water Commission, Canberra, pp. 115-132.

Herczeg AL, Torgersen T, Chivas AR and Habermehl MA 1991, 'Geochemistry of ground waters from the Great Artesian Basin, Australia', *Journal of Hydrology,* 126:225–245.

Hollins S., Hughes CE, Crawford J, Cendón DI and Meredith KT 2018, 'Rainfall isotope variations over the Australian continent: implications for hydrology and isoscape applications', *Science of the Total Environment,* 645:630-645, doi: 10.1016/j.scitotenv.2018.07.082.

Holmes JW, Williams AF, Hall JW and Henshcke CJ 1981, 'Measurements of discharges from some of the mound springs in the desert of northern South Australia', *Journal of Hydrology*, 49(3-4):329-339.

Howe PJ, Baird DJ and Lyons DJ 2008, 'Hydrogeology of the South-East Portion of the Arckaringa Basin and South-West Portion of the Eromanga Basin, South Australia', in Lambert M, Daniell TM and Leonard M (eds) Engineers Australia, Proceedings of Water Down Under 2008. Modbury, South Australia, pp. 573–585.

Hulme KA 2008, *Eucalyptus camaldulensis (river red gum) Biogeochemistry: an Innovative Tool for Mineral Exploration in the Curnamona Province and Adjacent Regions*. [Honours Thesis] University of Adelaide, accessed. 21st June, 2023.

Inverarity K 2014, *Electrical Geophysics of Carbonate Mound Spring Complexes of the South-Western Great Artesian Basin* [PhD Thesis], The University of Adelaide, accessed21st June 2023.

Jack RL 1923, 'The composition of the waters of the Great Australian Artesian Basin in South Australia and its significance', *Transactions of the Royal Society of South Australia*, 316–321.

Karlstrom KE, Keppel MN, Love AJ and Crossey L 2013, 'Structural and Tectonic History', in Keppel MN, Love AJ, Karlstrom KE, Priestley (eds) *Hydrogeological Framework of the Western Margin of the Great Artesian Basin, Australia*. National Water Commission, Canberra.

Kellett J, Veitc, S, McNaught I and van der Voort A 1999, *Hydrogeological Assessment of a Region in Central Northern South Australia*, BRS Australia, Canberra.

Keppel MN 2013, *The geology and hydrochemistry of calcareous mound spring wetland environments in the Lake Eyre South region, Great Artesian Basin, South Australia*. [PhD Thesis], Flinders University, Adelaide,

Keppel M, Gotch T, Inverarity K, Niejalke D and Wohling D 2016, *A hydrogeological and ecological characterisation of springs near Lake Blanche, Lake Eyre Basin, South Australia*, DEWNR Technical report 2016/03, Government of South Australia, Department of Environment, Water and Natural Resources, Adelaide.

Keppel M, Inverarity K and Wohling D 2015a, *A hydrogeological-based conceptualisation of springs in the Neales River catchment and Lake Cadibarrawirracanna regions, Lake Eyre Basin, South Australia*, DEWNR Technical report 2015/13, Government of South Australia, Department of Environment, Water and Natural Resources, Adelaide.

Keppel M, Miles C, Harding C, Turner D, Costelloe J, Clarke K and Lewis M 2017, *An examination of ecosystem dependence on shallow groundwater systems in the Western Rivers region, Lake Eyre Basin, South Australia – Volume 1*: DEWNR Technical report 2017/04, Government of South Australia, Department of Environment, Water and Natural Resources, Adelaide.

Keppel MN, Post VEA, Love AJ, Clarke JDA and Werner AD 2012, 'Influences on the carbonate hydrochemistry of mound spring environments, Lake Eyre South region, South Australia', *Chemical Geology*, 296-297:50-65.

Keppel M, Post V, Love A, Werner A, Clarke J and Halihan T 2018, 'Modelling size constraints on carbonate platform formation in groundwater upwelling zones',. *Scientific Reports*, 8, 17,460 https://www.nature.com/articles/s41598-018-35771-z, accessed 29th November, 2018.

Keppel M, Wohling D, Jensen-Schmidt B and Sampson L 2015b, *A hydrogeological characterisation of the Arckaringa Basin*, DEWNR Technical report 2015/03, Government of South Australia, Department of Environment, Water and Natural Resources, Adelaide.

Keppel M, Wohling D, Love A and Gotch T 2020, 'Hydrochemistry Highlights Potential Management Issues for Aquifers and Springs in the Lake Blanche and Lake Callabonna Regions, South Australia', *Proceedings of the Royal Society of Queensland* Special Edition: Springs of the Great Artesian Basin (GAB), 126, http://www.royalsocietyqld.org/2020-springs-special-issue-vol-126/, accessed 15th December, 2020.

Krieg GW, Alexander E and Rogers PA 1995, 'Eromanga Basin', in Drexel JF and Preiss W (eds) *The Geology of South Australia*, Geological Survey of South Australia, Adelaide, pp 101–105.

Lau JE, Dodds AR, Tewkesbury P and Jacobson G 1995a, 'Groundwater systems' (Scale 1:1 000 000), Plate 9, in Lindsay JF (ed.) *Geological atlas of the Officer Basin, South Australia*, Australian Geological Survey Organisation, Canberra, and South Australian Department of Mines and Energy, Adelaide.

Lau JE, Dodds AR, Tewkesbury P and Jacobson G 1995b, 'Groundwater salinity' (Scale 1:1 000 000), Plate 10, in: Lindsay JF (ed.) *Geological atlas of the Officer Basin, South Australia*, Australian Geological Survey Organisation, Canberra, and South Australian Department of Mines and Energy, Adelaide.

Lawrie K, Brodie RS, Christensen NB, Gibson D, Halas L, Symington N, Tan KP, Sandiford M, Ziramov S, Urosevic M, Elliot Grunewald E and Phil Hayes P 2016 Neotectonic intra-plate fault zone mapping and hydrogeology in floodplain sediments: an inter-disciplinary approach, ASEG Extended Abstracts, 2016:1, 1-9, DOI: 10.1071/ASEG2016ab400. https://www.tandfonline.com/doi/pdf/10.1071/ASEG2016ab400 access 27th June, 2023

Leaney F, Crosbie R, O'Grady A, Jolly I, Gow L, Davies P, Wilford J and Kilgour P 2011, *Recharge and discharge estimation in data poor areas: Scientific reference guide*. CSIRO: Water for a Healthy Country National Research Flagship. Canberra.

Leonard M 2008, 'One hundred years of earthquake recording in Australia', *Bulletin of the Seismological Society of America*, 98(3):1458–1470.

Liu J, Fu G, Song X, Charles SP, Zhang Y, Han D and Wang S 2010, 'Stable isotopic compositions in Australian precipitation', *Journal of Geophysical Research*, 115, D23307, 1–16.

Louden KE 1995, 'Variations in crustal structure related to intraplate deformation – evidence from seismic-refraction and gravity profiles in the Central Indian Basin', *Geophysical Journal International*, 120(2):375–392.

Love AJ, Herczeg AL, Sampson L, Cresswell RG and Fifield LK 2000, 'Sources of chloride and implications for Cl-36 dating of old groundwater, southwestern Great Artesian Basin, Australia', *Water Resources Research*, 36(6):1561–1574.

Love A, Shand P, Crossey L, Harrington GA and Rousseau-Gueutin P (eds) 2013a, *Allocating Water and Maintaining Springs in the Great Artesian Basin, Groundwater Discharge of the Western Great Artesian Basin*, National Water Commission, Canberra.

Love A, Wohling D, Fulton S, Rousseau-Gueutin P and De Ritter S (eds) 2013b, *Allocating water and Maintaining Springs in the Great Artesian Basin, Volume II: Groundwater Recharge, Hydrodynamics and Hydrochemistry of the Western Great Artesian Basin*, National Water Commission, Canberra.

McCallum J, Simmons C, Mallants D and Batelaan O 2018, Simulating the groundwater flow dynamics of fault zones MODFLOW Un-Structured Grid: A comparison of methods for representing fault properties and a regional implementation, National Centre for Groundwater Research and Training report for the Department of the Environment and Energy. https://www.dcceew.gov.au/sites/default/files/documents/simulating-the-groundwater-flow-dynamics-of-fault-zones.pdf. Accessed 1st June, 2018.

Matic 2018, *Assessing the utility of remote sensing in estimating groundwater discharge along the southwest margin of the Great Artesian Basin, South Australia* [PhD] thesis], University of Melbourne, accessed.2nd September, 2019.

Matic V, Costelloe JF and Western AW 2020, 'An integrated remote-sensing mapping method for groundwater dependent ecosystems associated with diffuse discharge in the Great Artesian Basin, Australia', *Hydrogeology Journal,* 28:325–342, doi: 10.1007/s10040-019-02062-4.

Matthews ID 1997, *Hydrogeology of the Great Artesian Basin in the Northern Territory*, Report No. 52/96A, Government of the Northern Territory, Water Resources Division, Lands, Planning and Environment, Darwin,.

Middlemis H 2000, *Murray Darling Basin Commission Groundwater Flow Modelling guideline*. Aquaterra Consulting Pty Ltd, https://www.mdba.gov.au/sites/default/files/archived/mdbc-GW-reports/2175_GW_flow_modelling_guideline.pdf, accessed 21st June, 2023.

Phillips FM 1993, 'Comment on "Reinterpretation of 36Cl data: physical processes, hydraulic interconnections and age estimates in groundwater systems" by E. Mazor', *Applied Geochemistry*, 8:643–647.

Priestley S, Shand P, Love AJ, Crossey L and Karlstrom K 2013, 'Hydrochemistry', in Love AJ, Wohling D, Fulton S, Rousseau-Gueutin P and De Ritter S (eds) *Allocating water and maintaining springs in the Great Artesian Basin Volume II: Groundwater recharge, hydrodynamics and hydrochemistry of the Western Great Artesian Basin*. National Water Commission, Canberra, pp 171–201.

Priestley SC, Shand P, Love AJ, Crossey LJ, Karlstrom KE, Keppel MN, Wohling DL and Rousseau-Gueutin P 2020, 'Hydrochemical variations of groundwater and spring discharge of the western Great Artesian Basin, Australia: implications for regional groundwater flow', *Hydrogeology Journal,* 281–11, doi: 10.1007/s10040-019-02107-8.

Priestley SC, Wohling DL, Keppel MN, Post VEA, Love AJ, Shand P, Tyroller L and Kipfer R 2017 'Detecting inter-aquifer leakage in areas with limited data using hydraulics and multiple environmental tracers, including 4He, 36Cl/Cl, 14C and 87Sr/86Sr', *Hydrogeology Journal,* 25:2031–2047, doi: 10.1007/s10040-017-1609-x.

Ransley TR, Radke BM, Feitz AJ, Kellett JR, Owens R. Bell J, Stewar, G and Carey H 2015, *Hydrogeological Atlas of the Great Artesian Basin*, Geoscience Australia, Canberra, doi: 10.11636/9781925124668.

Ransley TR and Smerdon BD. (eds) 2012, *Hydrostratigraphy, hydrogeology and system conceptualisation of the Great Artesian Basin*, A technical report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment, CSIRO Water for a Healthy Country Flagship, Canberra, Australia. https://publications.csiro.au/rpr/download?pid=csiro:EP132693&dsid=DS5, accessed 4th February, 2016.

Rousseau-Gueutin P, Simon S, Love A, Post V, Doublet C, Simmons C, Wohling D and Fulton S 2013, 'Groundwater flow and hydrodynamics', in Love AJ, Wohling D, Fulton S, Rousseau-Gueutin P and De Ritter S (eds) *Allocating water and Maintaining Springs in the Great Artesian Basin, Volume II: Groundwater Recharge, Hydrodynamics and Hydrochemistry of the Western Great Artesian Basin*. National Water Commission, Canberra.

Sandiford M and Quigley M 2009, 'TOPO-OZ: Insights into the various modes of intraplate deformation in the Australian continent', *Tectonophysics,* 474(1-2):405–416.

Schulz-Rojahn JP 1993, 'Calcite-cemented zones in the Eromanga Basin: clues to petroleum migration and entrapment', *APEA Journal*, 33(1):63–76.

Sheard MJ 1981, *Marla Town Water Supply Investigation – Progress Report No. 1*. Rept. Bk. 81/81, Government of South Australia, Department of Mines and Energy, Adelaide.

Sheard MJ 1982, *Marla Town Water Supply Investigation – Completion Report*. Rept. Bk. 82/59. Government of South Australia, Department of Mines and Energy, Adelaide.

Smerdon BD, Welsh WD and Ransley TR (eds) 2012, *Water resource assessment for the Western Eromanga region*. A report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment, CSIRO Water for a Healthy Country Flagship, Canberra, Australia.

Smith PC 1976, *Australian National Railways Tarcoola–Alice Springs Railway Groundwater Completion Report, second tender progress report no. 7*, Government of South Australia, Department of Mines, Geological Survey Engineering Division, report book no. 46/65, GS no. 5743, Eng. Geol. no. 76-29, DM no. 329/75./s10040-015-1248-z.

South Australian Arid Lands Natural Resources Management Board (SAAL NRM) 2009, *Water Allocation Plan for the Far North Prescribed Wells Area*, South Australian Arid Lands Natural Resources Management Board, South Australia, Adelaide..

Suckow A, Deslandes A, Raiber M, Taylor AR, Davies P, Gerber C and Leaney F 2020, 'Reconciling contradictory environmental tracers ages in multi-tracer studies to characterize the aquifer and quantify deep groundwater flow: an example from the Hutton Sandstone, Great Artesian Basin, Australia', *Hydrogeology Journal,* 28:1–11, doi: 10.1007/s10040-019-02107-8.

Tetzlaff G and Bye JAT 1978, 'Water balance of Lake Eyre for the flooded period January 1974 - June 1976', *Transactions of the Royal Society of Australia*, 102:91–96.

Turner D, Clarke K, White D and Lewis M 2015, *Mapping areas of Great Artesian Basin diffuse discharge*, DEWNR Technical report 2015/55, by the University of Adelaide to the Government of South Australia, Department of Environment, Water and Natural Resources, Adelaide.

U.S. Geological Survey (USGS) 2004, *Resources on Isotopes*, https://wwwrcamnl.wr.usgs.gov/isoig/period/o_iig.html, accessed 17 April 2020.

Watterson J, Walsh J, Nicol A, Nell PAR and Bretan PG 2000, 'Geometry and origin of a polygonal fault system', *Journal of the Geological Society*, 157:151–162.

Welsh WD 2000, GABFLOW: *A steady state groundwater flow model of the Great Artesian Basin*, Bureau of Rural Sciences, Canberra, Australian Capital Territory.

Welsh WD, Moore CR, Turnadge CJ, Smith AJ and Barr TM 2012, *Modelling of climate and groundwater development*. A technical report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. Canberra.

White D, Lewis M, Green G and Gotch T 2015, 'A generalizable NDVI-based wetland delineation indicator for remote monitoring of groundwater flows in the Australian Great Artesian Basin', *Ecological Indicators*, 60:1309–1320, doi: 10.1016/j.ecolind.2015.01.032.

Williams AF 1974, *Sampling and measurement of Great Artesian Basin mound springs, South Australia*. South Australia, Report Book, 74/204, Government of South Australia, Department of Mines, Adelaide.

Wohling D, Fulton S, Love AJ, Dailey M, Halihan T, Berens V, Purtschert R and Shand P 2013a, 'Mountain System Recharge', in Love AJ, Wohling D, Fulton S, Rousseau-Gueutin P and De Ritter S (eds) *Allocating water and maintaining springs in the Great Artesian Basin Volume II: Groundwater recharge, hydrodynamics and hydrochemistry of the Western Great Artesian Basin*, National Water Commission, Canberra, pp 82–119.

Wohling D, Fulton S, Love A, and Scanlon B 2013b, 'Diffuse Recharge', in Love A, Wohling D, Fulton S, Rousseau-Gueutin P and De Ritter S (eds) *Allocating water and maintaining springs in the Great Artesian Basin Volume II: Groundwater recharge, hydrodynamics and hydrochemistry of the Western Great Artesian Basin* National Water Commission, Canberra, pp 8–35.

Wolaver BD, Priestley SC, Crossey LJ, Karlstrom KE and Love AJ 2020, 'Elucidating sources to arid land Dalhousie Springs in the Great Artesian Basin (Australia) to inform conservation', *Hydrogeology Journal,* 28:279–296 doi:10.1007/s10040-019-02072-2.

Woods PH 1990, *Evaporative discharge of groundwater from the margin of the Great Artesian Basin near Lake Eyre South Australia* [PhD thesis], Flinders University, Adelaide, accessed 3rd January 2008.

Youngs BC 1971, *The Hydrology of the Gidgealpa Formation of the western and central Cooper Basin*. Report Book no.: RB 00768. Government of South Australia, Department of Mines, Adelaide.

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