The Far North Prescribed Wells Area Groundwater Model

Volume 1 – Summary

Department for Environment and Water
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Acknowledgement of Country

We acknowledge and respect the Traditional Custodians whose ancestral lands we live and work upon and we pay our respects to their Elders past and present.

We acknowledge and respect their deep spiritual connection and the relationship that Aboriginal and Torres Strait Islander people have to Country.

We also pay our respects to the cultural authority of Aboriginal and Torres Strait Islander people and their nations in South Australia, as well as those across Australia.

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Chief Executive Foreword

The Department for Environment and Water works to help South Australians conserve, sustain and prosper by valuing nature, underpinning the liveability of our state and supporting our economic prosperity.

Our effective policies, programs and assets, supported by strong governance and robust systems, provide a foundation for managing and enhancing the state's natural and built environment.

We collaborate with a diverse group of boards, councils, stakeholders and volunteers to manage natural resources and places, and water and heritage assets, which are vital to the future environmental, social and economic prosperity and wellbeing of all South Australians.

The department achieves meaningful outcomes through building trust, undertaking authentic engagement, delivering important public value, respecting First Nations groups, supporting our people and focusing on our customers.

Ben Bruce
Chief Executive
Department for Environment and Water

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1 Introduction

The Government of South Australia, Department for Environment and Water (DEW), in partnership with the Department for Energy and Mining (DEM), the South Australian Arid Lands Landscape Board (SAAL LB) and the Commonwealth Government of Australia have developed a new numerical groundwater model for the Far North Prescribed Wells Area (FNPWA). This model will be a tool to inform management of groundwater resources, both ongoing and for future major developments.

1.1 The Far North Prescribed Wells Area and Allocation Plan

The Far North Prescribed Wells Area (FNPWA) (Figure 1-1) is a management zone under which groundwater extractions are regulated and managed under the Far North Water Allocation Plan (FNWAP). Appropriate management and regulation of groundwater resources within the FNPWA is vital for the success of the mining, petroleum, pastoral and tourism industries, and for the provision of community water supplies in the South Australian Arid Lands (SAAL) Management Region pursuant to the Landscape South Australia (LSA) Act 2019.

The continued success of these industries is dependent on balancing the needs of existing users and the environment. Of significant 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 (EPBC) 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. The South Australian Government also has regulatory responsibilities under the Roxby Downs (Indenture Ratification) Act 1982 in terms of specific arrangements for the provision of water for the Olympic Dam Mine.

1.2 Strategic management principles

The development of the Far North WAP was informed by the GAB Strategic Management Plan (SMP) that was developed collaboratively by the governments of Australia, South Australia (SA), Northern Territory (NT), Queensland (QLD) and New South Wales (NSW), in consultation with the GAB Coordinating Committee (GABCC) and other stakeholders. The latest (2020) version of the GAB SMP provides a set of key principles (Figure 1-2) for governments, Aboriginal and Torres Strait Islanders, water users and other stakeholders to achieve economic, environmental, cultural, and social outcomes for the Basin and its users. Key principles of the Far North WAP are consistent with GAB SMP principles, notably to manage the take of groundwater in a manner that does not result in a decline in groundwater pressures or levels that would adversely impact on groundwater discharge to springs, upon the flow of groundwater toward sites of cultural significance or other ecological sites, or upon an existing user’s ability to access groundwater.

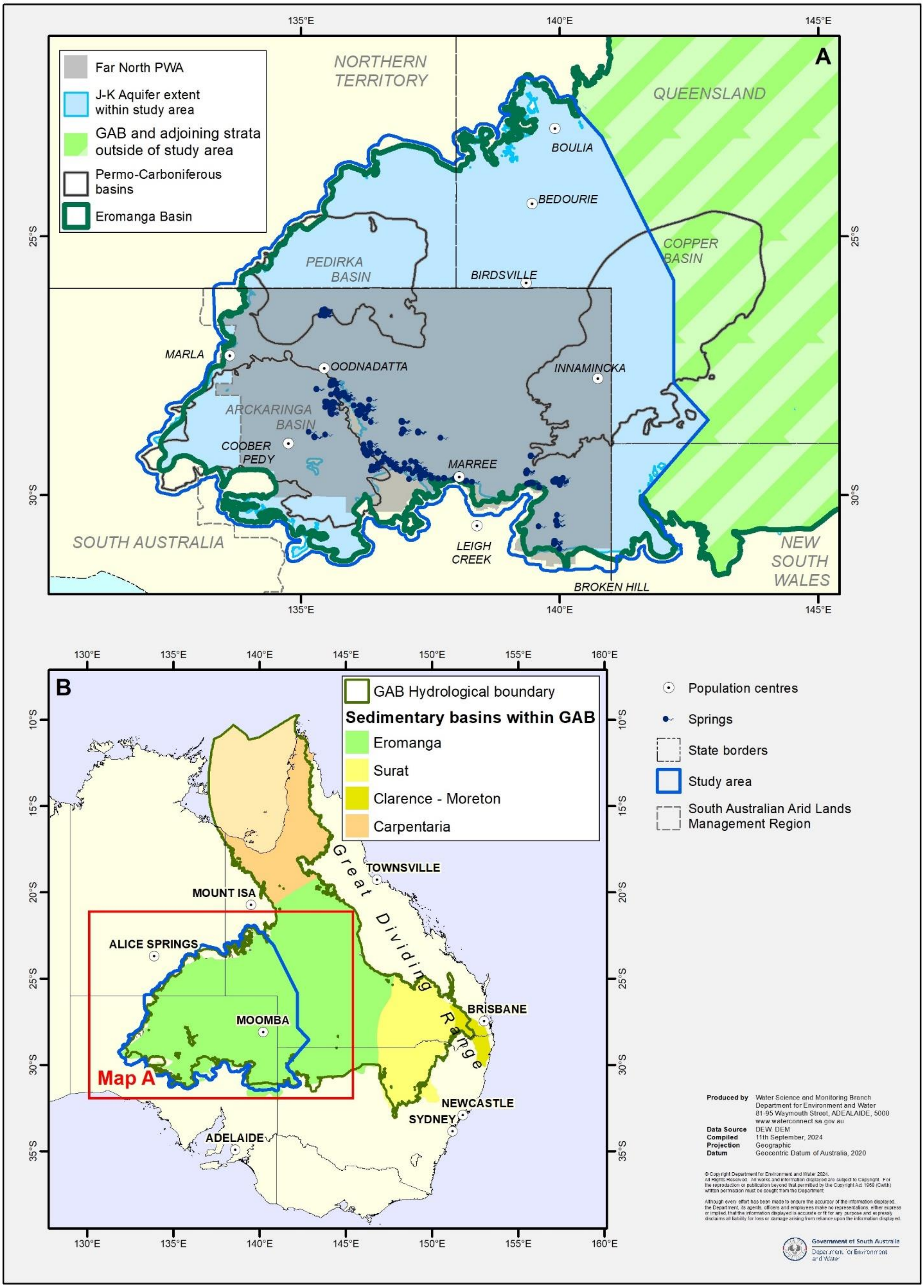

Figure 1-1: Location map of A) the Far North Prescribed Wells Area and GAB Springs in SA and model study area and B) the study area in the context of the Great Artesian Basin (GAB).

Figure 1-2: Great Artesian Basin Strategic Management Plan principles inform the Far North WAP

1.3 Current Groundwater use

Prior to the adoption of the latest Far North WAP in 2021, the total groundwater allocation was 176 ML/d (2018/2019 data) (Figure 1-3). This was made up of mining, industrial and camp supplies, co-produced water (water extracted with petroleum hydrocarbons), stock and domestic use, bore fed wetlands and other users. The majority (around 76% or 134 ML/d) was sourced from the GAB hydrogeological super-basin aquifers (Figure 1-4). Demand for water resources is expected to grow particularly in response to growth in the mineral and petroleum industries. Demand may be expected to be met via either groundwater resources found in the FNPWA or by infrastructure projects developed to import required water.

Further, The Government of South Australia is a signatory to the "Closing the GAP National Agreement. "Closing the Gap" is a national agreement that commits State and Federal governments to developing and implementing policies and programs that impact on the lives of Aboriginal and Torres Strait Islander people in a positive way. The Government of South Australia recognise that access to clean and reliable water for health, socioeconomic and cultural benefits are a key means of meeting a variety of targets set under this agreement. The new numerical groundwater model developed by the Government of South Australia will form a central tool in developing policies that secure First Nations people's access to groundwater within the FNPWA.

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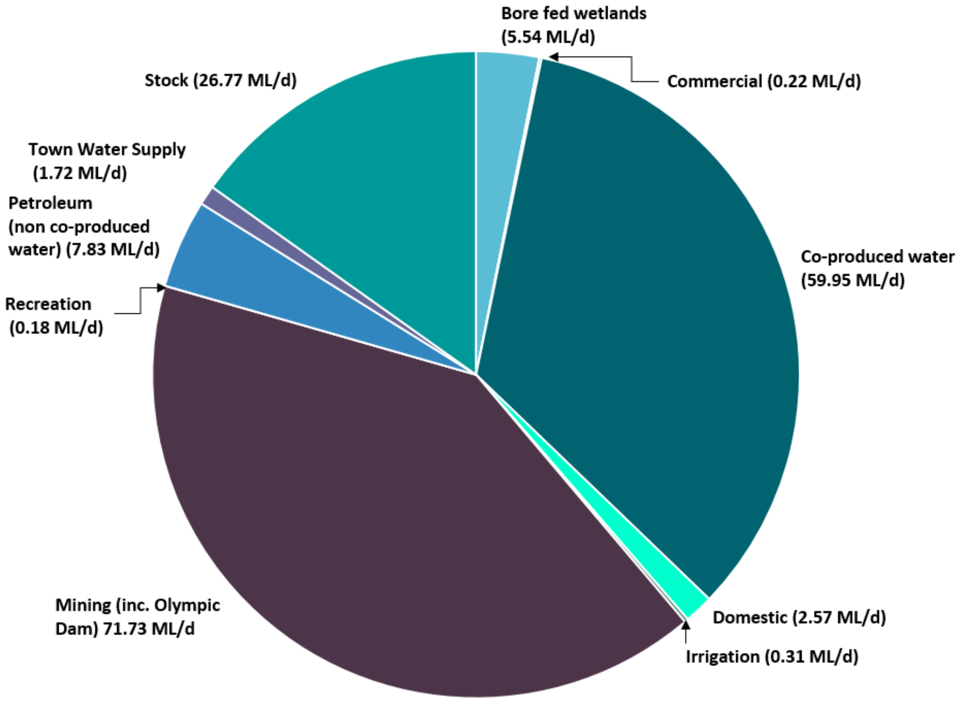

Figure 1-3: Total licensed volume (176 ML/d) presented by licence purpose description.

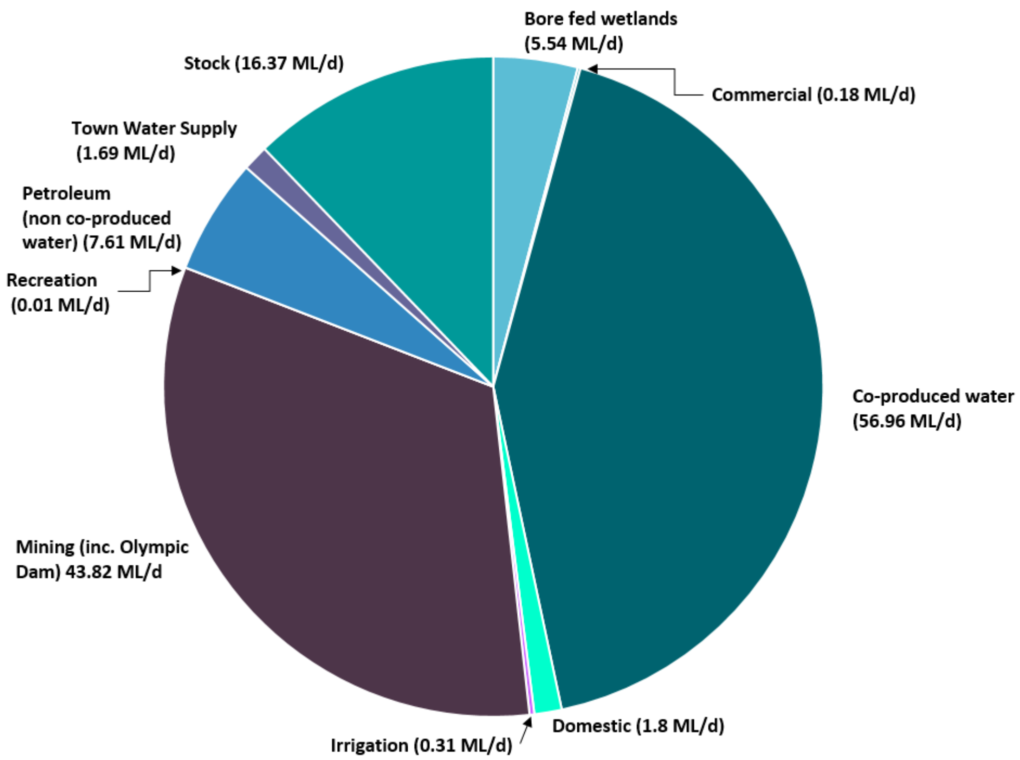

Figure 1-4: Licensed volume sourced from the GAB hydrogeological super-basin (134 ML/d) presented by licence purpose description.

The model design is to simulate groundwater flow within the Main Eromanga Aquifer Sequence, with a focus on the Far North PWA in SA. The study area (Figure 1-1) covers a total area of about 721,370 km^2 and it includes the entirety of the Eromanga Basin in SA and NT, Cooper Basin in SA, Pedirka Basin, Arckaringa Basin and the Far North Prescribed Wells Area and portions of the Eromanga Basin in Queensland and NSW and part of the Cooper Basin in Queensland. A 10 km-wide external buffer encompassing these administrative areas 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 QLD; between 125 km and 190 km from the SA border into Queensland; and between 60 km and 140 km into NSW from the SA border (Figure 1-1). 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. This boundary also closely coincides with a series of highlands located in Queensland and NSW. The spatial extent of the eastern boundary was selected consistent with best practice principles, to provide a sufficient distance 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. Technical Summary (this volume)
2. Hydrogeological framework
3. Hydraulic parameterisation
4. Groundwater flow system dynamics
5. Time-series data
6. Recharge and discharge processes
7. Water use and balance estimates
8. Model construction and calibration.

2 Model Capabilities

2.1 Previous groundwater modelling

Although several groundwater models have been developed over parts of the western GAB hydrogeological super-basin, they are subject to one or more of the following limitations when trying to utilise them to either inform management of GAB aquifers within SA or to assess cumulative drawdown impacts:

- The geographical extent is too small or inappropriate.
- The depiction of the aquifer system is over-simplified or too limited.
- The model is owned by private companies that prohibits use for regulatory water resource assessments.
- Are based on outdated hydrogeological conceptualisations that do not reflect the current understanding of basin structure, groundwater processes including recharge and discharge.
- Do not consider other interconnected basins that form important water resources in the FNPWA; and
- Are not designed to consider the cumulative impacts of multiple groundwater users.

2.2 The Far North Groundwater model

To address the gaps identified in the existing models and to provide a tool to inform management of groundwater resources in the FNPWA, DEW ensured that the Far North Groundwater Model was developed to be consistent with the latest science and knowledge and that it could be updated in the future. Further, the model is designed to address these specific groundwater regulatory and management concerns:

- Assess pressure reductions in the GAB hydrogeological super-basin aquifers resulting from extraction by existing users at full allocation against pressure drawdown values as defined in the FNWAP.
- Assess the likely range of aquifer pressure drawdown impacts resulting from increased groundwater extraction on spring wetland communities dependent or partly dependent on groundwater from the GAB hydrogeological super-basin, on existing users and at management boundaries as defined in the FNWAP.
- Assess the cumulative drawdown impacts from extractions by various groundwater users.

When applied carefully, the model can provide insight to the hydrogeology SA GAB groundwater system in the FNPWA and responses to various changes in stresses to the groundwater and springs. The unique capabilities of this model are summarised below:

- The model is the only South Australia-specific numerical groundwater model available that covers the entire Eromanga Basin (GAB) in South Australia and the NT. Whilst there are whole-of-basin numerical models, these do not have the same level of vertical or horizontal discretization available and therefore cannot provide the same results. Other models that have similar levels of detail largely only focus on the artesian component of the South Australian GAB.
- The model is currently the only South Australian-specific, non-proprietary tool available to assess large, regional scale, cumulative drawdown impacts and pressure recoveries within the GAB. Consequently, the model represents the best tool available to examine the impacts of cumulative drawdown, as well the benefits of groundwater saving measures across the entire GAB in South Australia.
- The model represents the latest attempt to incorporate or respect all the latest GAB-related groundwater science.

- The model is designed to answer questions on the groundwater hydrology of GAB springs at the complex and supergroup level and the possible impacts caused by pumping in the Main Eromanga Aquifer.
- The model is stable in both steady and transient states and is therefore mathematically optimized to provide reliable output data. This was achieved by undertaking a much finer grid discretization that what was originally planned to account for the highly complex basin architecture found within the South Australian portion of the GAB.
- The incorporation of a basement layer of nominal thickness across the entire model domain provides the opportunity to examine groundwater flow relationships between the Main Eromanga Aquifer sequence and strata below the GAB. Consequently, it is one of very few GAB numerical models that explicitly acknowledges groundwater migration to and from underlying strata as critical and as a conservative conceptual approach.
- The model is one of few that attempts to vertically discretize the Main Eromanga Aquifer Sequence into intra aquifer units of differing hydraulic property. This was undertaken with close consultation with the Energy Division within the South Australian Department of Energy and Mining, who prepared the structure surfaces for incorporation into the model.
- The model can replicate changes in groundwater levels with reasonable precision, particularly around the Kati Thanda- Lake Eyre South region, near the Olympic Dam wellfields specifically.
- The model synthesizes current data and understanding of the hydrogeology of the portion GAB in SA.
- The overall fit of the model to the magnitude of spring discharge and measured groundwater levels was considered reasonable.

Whilst the model has many benefits, like all numerical groundwater models, caution should be used when evaluating simulated results in areas with sparse calibration data, in areas where simulated results do not fit the measured data well, or results generated from pumping conditions that are substantially different from conditions used to calibrate the model. Chapter 5 discussed other limitations further.

3 Conceptualisation

3.1 Climate and landscape (Volume 2)

The study area is largely hot and arid. Prevailing rainfall is sporadic and largely sourced from weak winter cold fronts, amounting to generally less than 250 mm per year in the Far North of SA. Evaporation rates are high across the study area, around 2.3-3.6 m/y. Rivers and creeks are ephemeral and permanent surface water is restricted to some GAB springs, and to rare waterholes located within an ephemeral river and salt lake (playa) system.

The study area landscape is typically very flat, although it is bordered by highlands and plateaus. Most of the surface landform is desert, with sand dune environments across the plains and playa region, and wind-driven (aeolian) deflation the dominant morphological process. The largest playa lake of Kati Thanda Lake Eyre (9 500 km^2) is the terminus for most of the rivers and creeks in the region, and the lowest point in Australia, below sea level at about -15 metres AHD. Smaller playa lakes act as more localised drainage terminuses. River flow events are episodic, driven mainly by rains from weak winter cold fronts, although monsoonal rains in northern Australia can result in major flooding (e.g. via the Cooper Creek system), which can temporarily fill the large playa lakes.

The dominant groundwater dependent ecosystems (GDEs) found within the study area are GAB springs (Figure 1-1). These springs are iconic features of the central Australian landscape and are of great ecological, cultural, and economic importance. The isolation of GAB springs within an otherwise arid environment makes them ecological 'hotspots' where endemic flora and fauna have evolved. The GAB springs are listed under the Commonwealth EPBC Act 1999 as threatened ecological communities, and the water resource-related regulation and legislation has a primary focus of preservation of the GAB springs. Other GDEs found within the study area are associated with riparian vegetation near the ephemeral rivers and creeks. These GDEs are thought to be mainly dependent on shallow occurrences of groundwater that may be perched or separated from more extensive underlying aquifers by a low permeability confining unit.

3.2 The aquifers and confining layers of the SA GAB (Volume 2)

Most groundwater resources in the Far North PWA are contained within Eromanga Basin strata. The Eromanga Basin and chrono-stratigraphically equivalent basins in Queensland and NSW, are known collectively as the Great Artesian Basin, or GAB (Figure 1-1). The GAB 'hydrogeological super-basin' covers about 22% of the Australian land surface, including significant areas of Queensland, NSW, SA and the NT. Groundwater within the GAB hydrogeological super-basin originates from rainfall, but may have an age of more than 1 million years near the centre of the basin due to slow groundwater flow along the major continental-scale flow lines from north-east to south-west.

In the SA part of the Eromanga Basin, the most important aquifer grouping (strata sequence) is the Cadna-owie Formation and the Algebuckina Sandstone, and their lateral equivalents in the Cooper Basin sub-region, primarily the Namur Sandstone and Adori Sandstone (Figure 3-1, Table 3-1, Figure 3-2). The collective hydrostratigraphic term commonly used in SA for the aquifers and partial aquifers within these connected and extensive units is the 'J-K Aquifer'. In the Cooper Basin sub-region to the east of the study area, the fine-grained confining units of the Murta and Westbourne Formations intervene between the coarse-grained Adori and Namur Sandstone aquifer units in the deeper part of the J-K Aquifer grouping. The Hutton Sandstone and Poolowanna Formation form another important aquifer grouping that underlies the J-K aquifer in the Cooper Basin sub-region and transitions into the Algebuckina Sandstone further west. This aquifer grouping is separated from overlying aquifers in the Cooper Basin subregion by the Birkhead Formation confining layer.

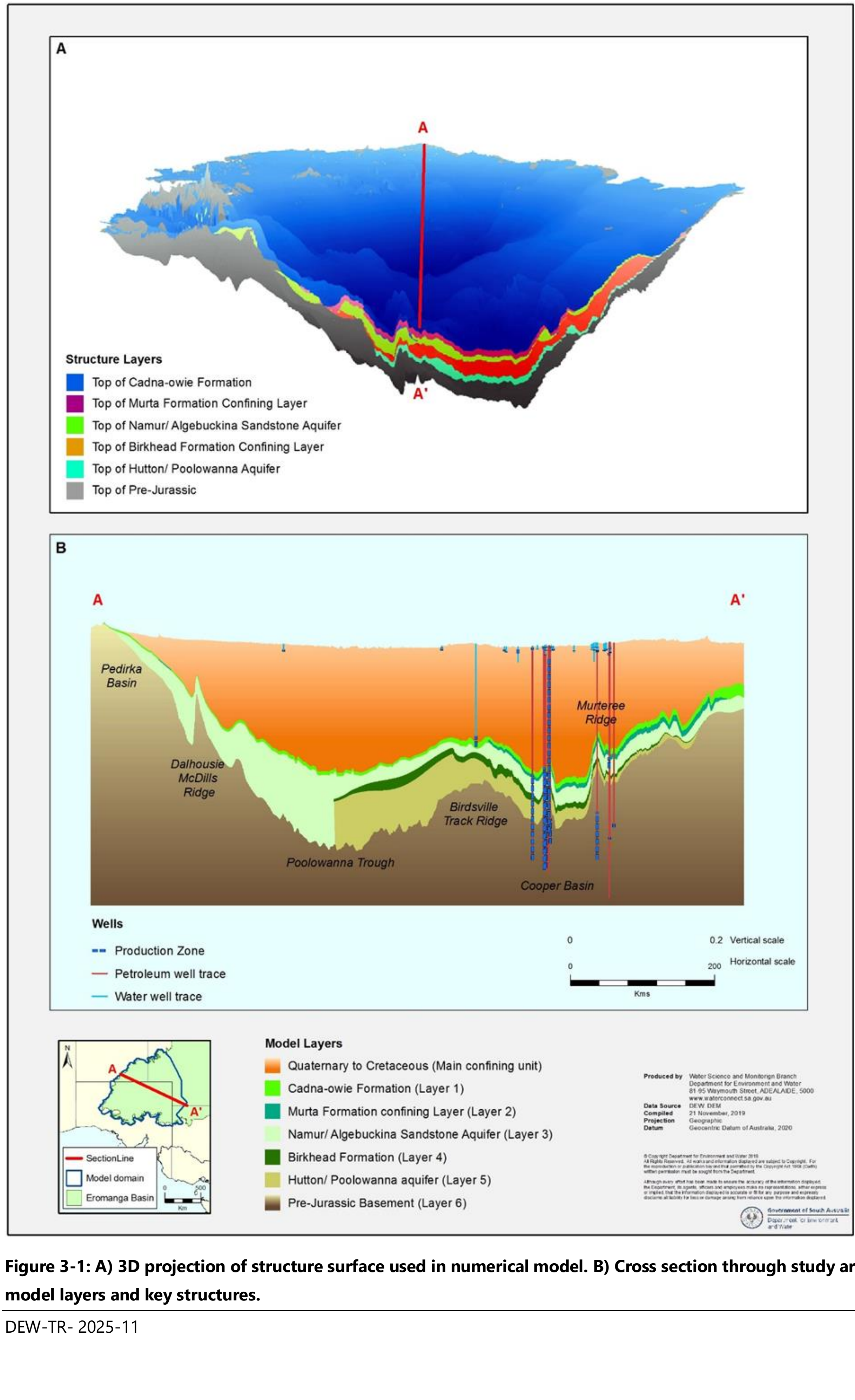

Figure 3-1: A) 3D projection of structure surface used in numerical model. B) Cross section through study area showing model layers and key structures.

Table 3-1: Summary of hydrostratigraphic unit nomenclature and relationship to model layer design.

Collective term	Western Study area					Cooper Basin sub-region, Eastern 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 off isopach interpolation. [b] Maximum thickness was interpolated in close vicinity to a mapped fault but cannot be confirmed. Confirmed thickness of 357 m based off intersection found in Well Unit no. 684200195.

The collective term 'Main Eromanga Aquifer Sequence' is used to described the strata package that is the main focus of our model construction and allows for the spatial variability in the occurrence of aquifer and confining units across the study area (Figure 3-1, Table 3-1, Figure 3-2). For model construction, the Main Eromanga Aquifer Sequence was discretised into five model layers based on the regional scale hydrostratigraphy and an underlying basement layer was added.

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. 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 (Figure 1-1, Figure 3-1). The sandstones, siltstones, shales, diamictites and coal beds in these basin sediments contain aquifers, but they also form significant petroleum hydrocarbon and coal resources under varying degrees of development. Outside of the Permo-Carboniferous basins, other major rock formations may be found, notably the metasedimentary rocks of the early Palaeozoic Warburton Basin, the Precambrian rocks of the Adelaide Geosyncline and the crystalline rocks of the Archaean.

Cross-formational flow between the Main Eromanga Aquifer Sequence and aquifer units within the underlying or overlying strata occurs where an effective confining unit is absent, where structural deformation such as faulting or jointing has either enhanced porosity or displaced different hydrostratigraphic aquifer units.

3.3 Initial aquifer properties (Volume 3)

Aquifer-property data was compiled from published and unpublished information and reports from the South Australian Government-maintained well and drillhole database SA Geodata, the oil and gas industry operating in the region and previous models for the GAB hydrogeological super-basin, as well as adjacent basins (e.g. Cooper, Pedirka and Arckaringa). An important source of permeability data was Drill Stem Tests (DST), and Modular Formation Dynamics tests (MDT) conducted by the energy industry, which was converted to an ideal fluid permeability using a literature derived conversion formula.

Data collation, interpretation and conversion studies were also conducted for this study:

- Core porosity and air permeability data was collated from industry-sourced core-plug analysis for several Eromanga Basin stratigraphic units in the Cooper Basin sub-region and converted to an ideal fluid permeability.
- Data on aquifer transmissivity (T) for the J-K aquifer was collated from pumping tests and other data.

Aquifer specific storage (S_s) and unconfined aquifer specific yield (S_y) values were derived from literature reviews and were the subject to modification during model calibration. A summary of hydraulic parameters used as initial inputs in model construction is provided in Appendix A.

3.4 Potentiometric surface and groundwater flow interpretation (Volume 4)

A key input and subsequent output of any groundwater model build is the potentiometric surface. This surface describes the level, or pressure expressed as metres of head, in the aquifer or aquifers of concern. The primary driver of groundwater flow in most groundwater systems is gravity, which is why we use groundwater levels and potentiometric surfaces to interpret groundwater flow systems. However, other interacting forces or processes can have a significant influence, for example, salinity and thermal variations can give rise to density, viscosity, and buoyancy effects. In the GAB, such influences are an important concern that require careful consideration. The temperature of water in the deeper sections of the Main Eromanga Aquifer Sequence exceeds 90°C compared to shallow groundwater temperatures of 25°C-30°C. This means that measured groundwater levels must be corrected for the effect of temperature on density in the water column to derive density-corrected head potentials for use in mapping and modelling.

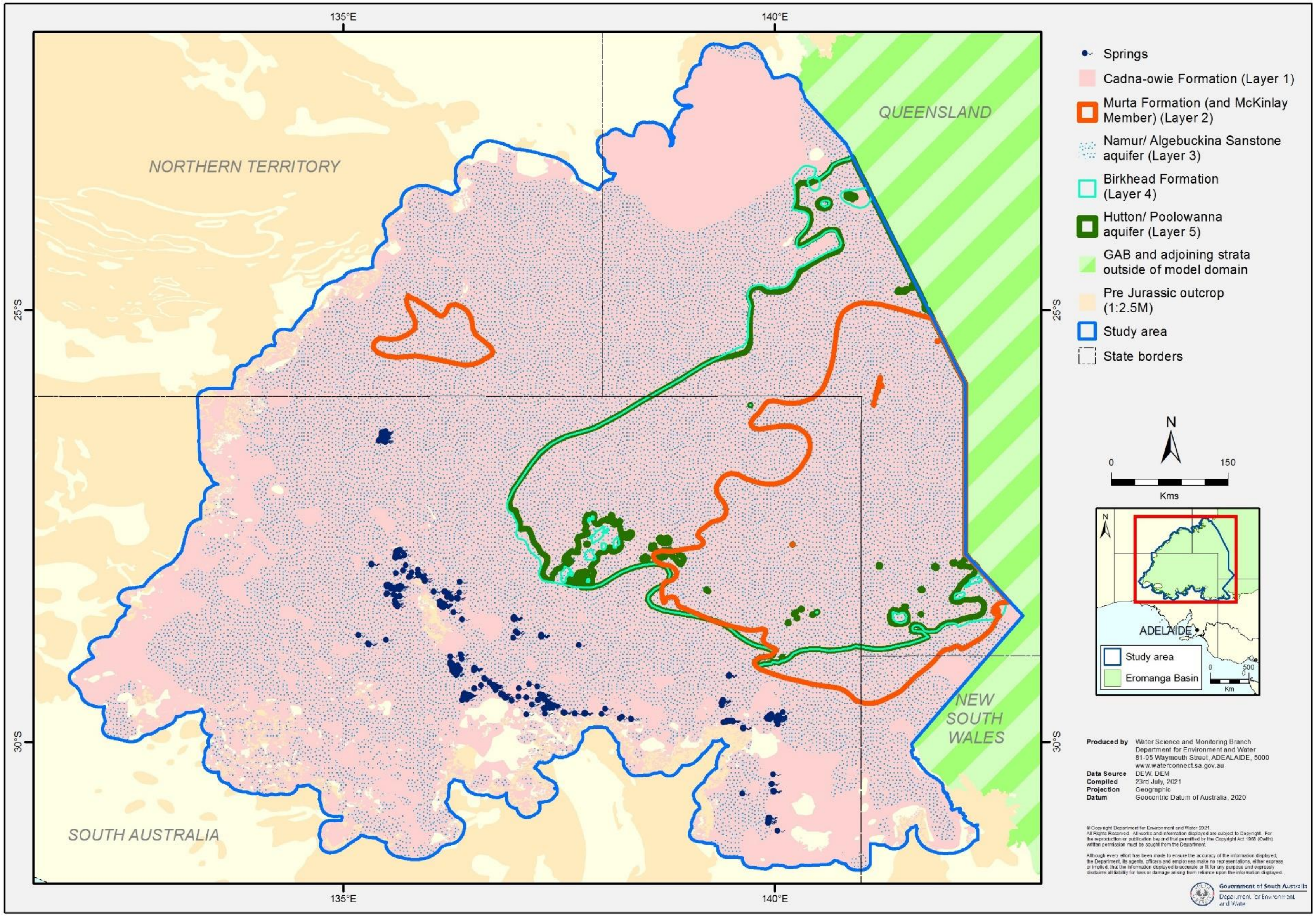

Figure 3-2: Plan view of structure surface outlines used in numerical model.

Potentiometric surfaces were developed for the two main hydrostratigraphic unit groupings within the Main Eromanga Aquifer Sequence:

- the extensive J-K Aquifer grouping (Cadna-owie / Algebuckina / Adori / Namur Sandstone); and
- the deep Hutton / Poolowanna aquifer grouping.

Multiple versions of density-corrected potentiometric surfaces of the J-K Aquifer unit were generated to determine groundwater flow directions and potential recharge and discharge areas. The choice of which potentiometric surface interpretation to use as an input target for groundwater modelling was based on assessing each one against our understanding of the hydrogeological conceptualisation and deciding which represented the best comparative fit.

For the J-K Aquifer, potentiometric surfaces show a generally radial pattern of flow with inflows and recharge from the east, north, west and parts of the south, with flows toward discharge zones near the springs in the centre of the basin, and also towards some of the southern margins (Figure 3-3A and B). Other features include steep hydraulic gradients along the western and north-western margins of the basin, and a depression near the western edge of the underlying Cooper Basin that may reflect co-produced water extraction.

Potentiometric surface contours for the Hutton Poolowanna aquifer show a general inflow into the study area from the east (Figure 3-3C).

Whilst the potential for free convection was assessed and determined to be high, we assumed that the Eromanga Basin in SA is predominantly a forced convection (gravity) flow system, for purposes of simplicity and because gravity driven flow was most likely near all GAB spring environments. However, uncertainties related to free convection can still be partially addressed within the numerical modelling workflow.

Pressure versus depth profiles using pressure data compiled from petroleum industry tests were generated to determine the distribution of formation pore pressures and to investigate the potential for vertical (upward or downward) or horizontal flow components within the Eromanga and especially the Cooper basin sub-region. Overall, when pressure measurements are compared to elevation, there is a relatively lower pressure found in deeper strata compared to those above, suggesting the potential for a downward pressure gradient.

3.5 Recharge and lateral inflow (Volume 6)

Lateral groundwater inflow forms the largest input to the study area. The potentiometric surfaces indicate lateral inflow from the north and east (NT, QLD and NSW). Recharge mechanisms include direct recharge through outcropping or sub-cropping aquifer units, via Ephemeral River Recharge (ERR), via Mountain System Recharge (MSR) or via diffuse recharge.

Direct recharge via outcropping and sub-cropping J-K aquifer strata is interpreted in areas along the north-western and western margins. A preliminary average recharge rate calculated from monitoring well data near Marla of approximately 0.2 mm/y was estimated, with individual rates ranging from 0.03 to 0.5 m/y. Recharge events are highly episodic.

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 5,150-11,560 ML/y (14–32 ML/d). Evidence for ERR in other areas is less conclusive.

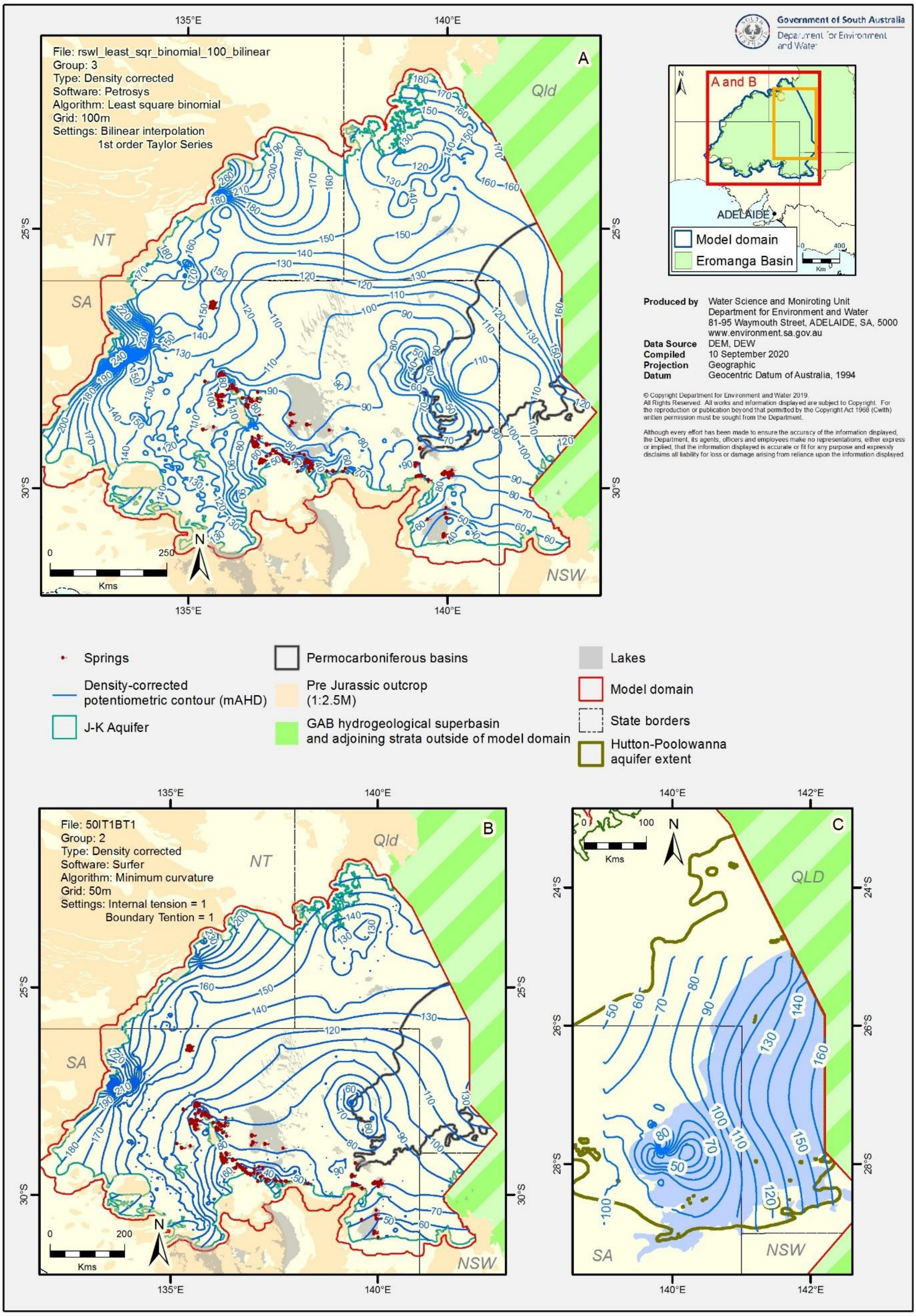

Figure 3-3: Examples of density corrected potentiometric surfaces developed for the J-K Aquifer from A) Group 3 (primary conceptualization) B) Group 2 (primary alternative conceptualization) and C) Potentiometric surface interpretation for the Hutton-Poolowanna aquifer.

Diffuse recharge from rainfall is conceptualised as most likely in areas where the depth to the J-K aquifer is less than 10 m, such as along the western and south-western margins as well as some areas along the Northern Flinders Ranges. Diffuse recharge to the J-K aquifer from rainfall within the western portion of the study area has been estimated by a previous chloride mass balance (CMB) studies at 0.01 – 5 mm/y, with an average of around 0.15 mm/y.

Mountain System Recharge (MSR) can occur via connectivity with fractured rock aquifers associated with mountain blocks and fronts on the margins of the basin. Minor MSR has been identified near the Peake and Denison Inliers and potentially other elevated areas near the margins of the GAB, but the total volumes are likely small.

3.6 Discharge and lateral outflow (Volume 6)

A major component of discharge from both the eastern and western portions of the J-K aquifer occurs from the 5,000-plus GAB springs that are mapped, extending from Lake Frome in the south-east to Dalhousie Springs on the northern margin (Figure 3-4). Current estimates of discharge through springs of 66 76 ML/d are likely underestimated due to the method of calculation and updated vent mapping since these estimates were published. Flow to springs occurs via several mechanisms, including preferential flow via fractures and faults within the overlying confining unit shales and/or thinning of the confining unit strata via uplift and erosion.

Areas of diffuse discharge near springs were mapped using multispectral remote sensing data. Depending on the methodology employed, the estimated area of diffuse discharge near springs ranges from 97 to 412 km^2. Whilst it was difficult to assign a definitive total discharge rate to this area range, a significant discharge volume estimate of between 27 395 ML/d was found. Consequently, 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.

Another major component of discharge is diffuse vertical leakage from the J-K aquifer through the main confining units of the Rolling Downs Group. Diffuse discharge 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. The following are conclusions drawn from most recent study of vertical diffuse discharge from the J-K aquifer:

- low rates of vertical leakage of groundwater from the J-K aquifer into undeformed confining units are currently estimated (3×10^{-4} to 5×10^{-4} mm/d).
- higher rates of vertical leakage are estimated where preferential pathway development may have occurred (8.64×10^{-5} to 8.64×10^{-4} m/d).

Volumetric determination of diffuse discharge fluxes determined require mapping to constrain their areal extent.

Non-spring zone-related groundwater evapotranspiration may occur in areas where the J-K aquifer strata is near-surface, or where groundwater discharges to the shallow phreatic water table contained within shallower strata where conditions allow. For flux estimations based on evapotranspiration estimations and landform mapping, difficulty in accounting for near surface contributions to the water balance, such as localised recharge to the shallow water table become apparent. For the conceptual hydrogeological model, diffuse discharge via evapotranspiration is considered most likely in areas where the water table is within 10 m of the surface. Actual areal annual evapotranspiration rates of 100 350 mm/y indicate sufficient capacity to account for the low rates of incident annual rainfall, while average pan evaporation rates are much higher at around 3,000 mm/y.

3.7 Time series data (Volume 5)

Most of the data on groundwater pressure, reduced standing water level (RSWL) and salinity was sourced from the SA Geodata database. Most of the time-series data is sourced from the FNPWA Monitoring Network (Figure 3-4), which is based upon the GAB monitoring network established by the SA Government in the 1970's and is largely composed of pastoral bores. Other time series data assessed was sourced from privately maintained networks, notably the Olympic Dam monitoring network in the southern portion of the study area (Figure 3-4), and from mine monitoring networks at Prominent Hill, Cairn Hill and Peculiar Knob.

Since more co-ordinated monitoring began in the 1970's, groundwater pressures in the area between the Cooper Basin and Kati Thanda – Lake Eyre have seen declines of tens of metres, likely to be associated with extractions associated with pastoralism, petroleum hydrocarbon extraction associated with the Cooper Eromanga oil and gas fields, and with groundwater extraction from the Olympic Dam wellfield areas. Some data available prior to the 1970's indicate pressure declines extending into the pre-1970's period.

Pressures and water levels in other areas generally appear stable, although some localised increases suggest that the impact of GAB well capping programs can be observed in monitoring data. Localised increases in pressure are particularly notable near the spring zones.

Spring flow time series data is largely sourced from the Olympic Dam Annual Environmental Protection and Management Program, relating to the Kati Thanda-Lake Eyre south region (Figure 3-4) where Olympic Dam mining operations have monitored spring flow since the early 1980's. Trends are considered to generally reflect groundwater impacts associated with wellfield extraction. Additional data since the late 1990's from four springs in the Dalhousie Springs group (Figure 3-4) were also assessed and no notable trends were observed.

The groundwater model is designed with capacity to 'unpack' these various water user effects.

Salinities are relatively steady, generally <2500 mg/L TDS across most of the study area in the eastern and central regions where the aquifer is thick and confined but increasing to >14,000 mg/L in some areas near the south-western margin where the aquifer is thin and unconfined, and the water table is shallow.

3.8 Groundwater use (Volume 7)

Groundwater use data was collated from various sources and is affected by a range of assumptions and limitations, especially so for stock and domestic usage. Stock and domestic volumes are largely based on conservative estimates and observable infrastructure (e.g. 0.3 or 0.4 L/s per trough or small dam) or reported yield rates, or on pumping rates or usage volumes where available. This conservative estimation approach yields a maximum usage estimate and, is very likely to be lower in reality.

Metering information for town water supply bores and privately managed bore fields (e.g. for mining projects) was utilized where available. Petroleum and gas co-produced water extraction volumes were obtained from government databases or from private industry. The volume of oil and gas abstracted from the GAB reservoir/aquifer was also accounted for by using industry conversion factors for water use equivalents. For all other wells where a water use was identified, extraction rates were estimated from water licence information.

Figure 3-6 presents a location map of wells used in the water usage estimates. All extraction from the artesian portion of the basin was initially for stock and domestic purposes, estimated to have begun in the late 19th century and peaking around 220 ML/d in the mid-1970's (Figure 3-5). A large percentage of the initial stock and domestic water extraction went to waste, as many unlined bore drains were used as delivery systems and flow was often uncontrolled. From the mid 1970's, a decline in extraction is indicated until an average of around 160 ML/d is reached around the mid 1980's.

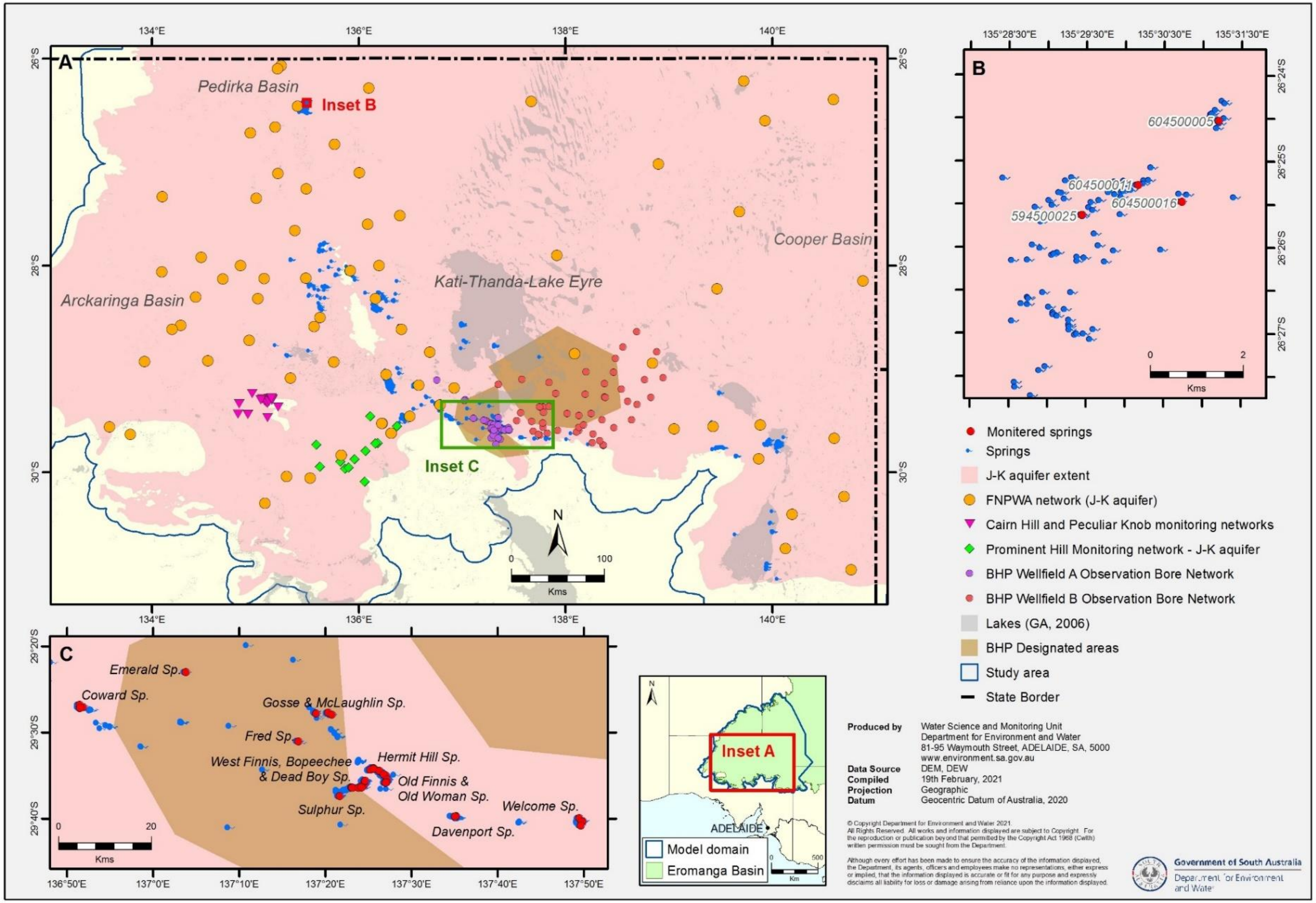

Figure 3-4: Location map of well and spring monitoring networks assessed for this study.

This decline in usage was largely due to the adoption of more efficient delivery systems, such as troughs and piping, as well as rehabilitation of uncontrolled flowing wells through schemes curated by government, industry and community, such as the Great Artesian Basin Sustainability Initiative (GABSI) and more recently the Improving Great Artesian Basin Drought Resilience (IGABDR) scheme. In the SA non-artesian portion of the study area, groundwater extraction has steadily increased for the better part of the 20th century, eventually stabilizing at near current day levels around the early 21st century (Figure 3-5).

Groundwater extraction related to mining and petroleum developments in the artesian portion of the basin began around the mid 1980's, which tended to balance the contemporaneous decline in stock and domestic extraction. Mining-related groundwater use is dominated by the Olympic Dam operation, which has largely remained stable at around 35 ML/d since the early 21st century. Petroleum and gas co-produced water extraction has largely remained between 15 and 25 ML/d from the mid-1990's until about 2010 and has since risen closer to the 60 ML/d licensed volume limit (Figure 3-5).

Within the Queensland portion of the study area, total annual volume estimates for stock, domestic, industrial and co-produced groundwater display a largely steady increase to around 23 ML/d from the late 19th century to early 21st century, with two periods of steeper increases around the late 1910's and in the 1950's to 1960's. A sharp increase in extraction occurs in the mid 2000's when records for co-production from the petroleum industry commence. It is likely that co-production occurred much earlier than implied by the records.

In the NT part of the basin, total annual volume estimates for stock, domestic and industrial groundwater were typically small until the 1950's, when a sharp increase in extraction occurs. Extraction increases substantially around the mid-1960's due to the impact of petroleum exploration and associated uncapped bore completions and bore failure. Large variations in total flow after 1990 may be partly attributable to difficulties in estimating flow from these bores A subsequent general stabilisation in water use apparent in the most recent data is attributed to the rehabilitation of several free-flowing wells, including abandoned petroleum exploration wells that were converted to water wells over the past 20 years.

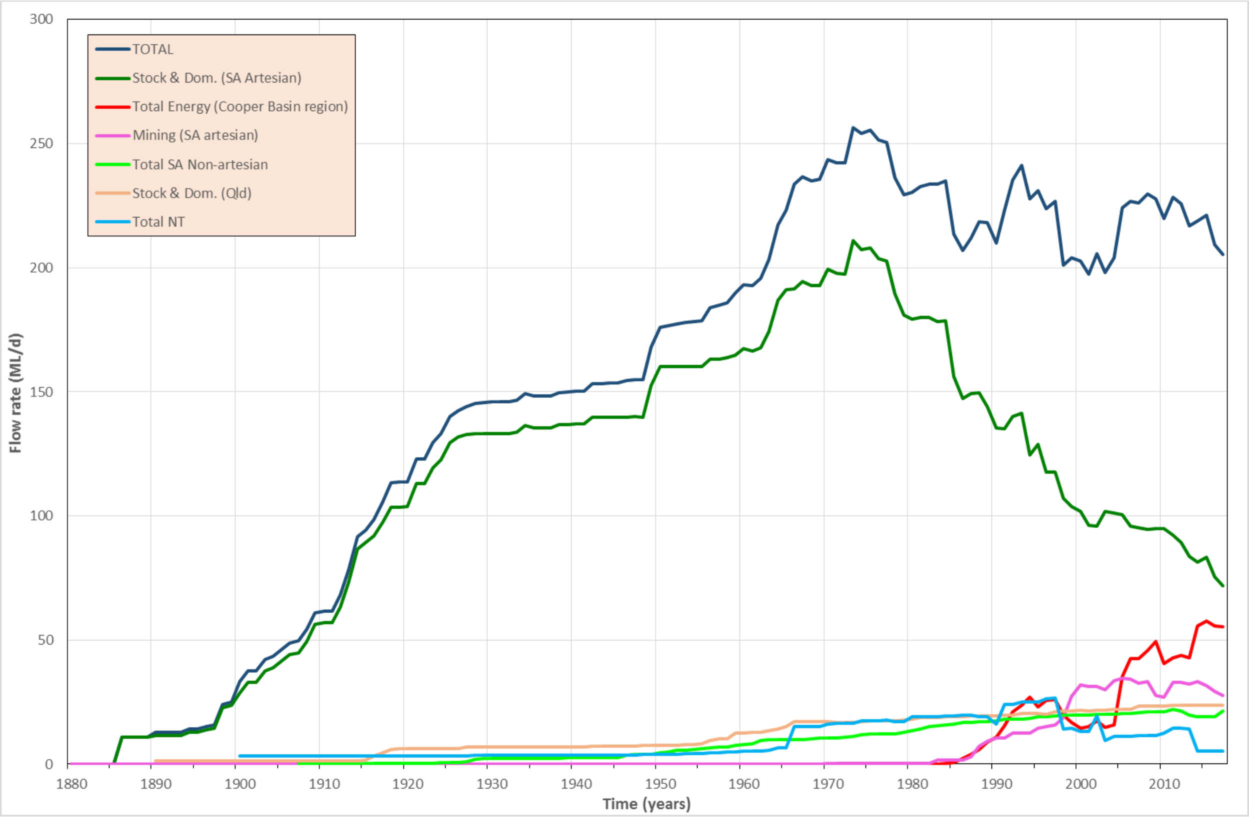

Figure 3-5: Estimated total groundwater use over time within the study area.

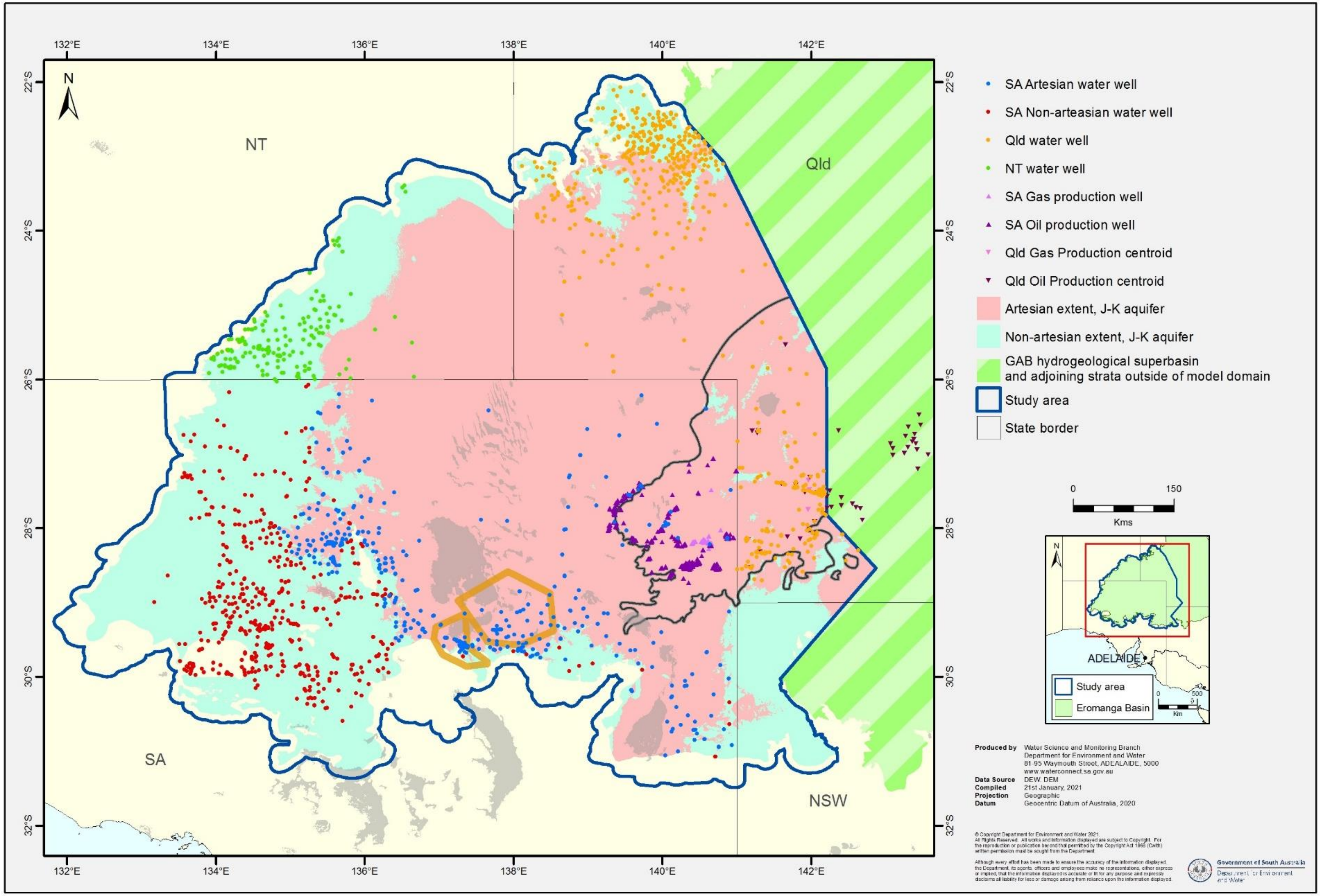

Figure 3-6: Location map of wells used in groundwater use estimates.

3.9 Preliminary groundwater balance (Volume 7)

As groundwater extractions form a dominant groundwater system output, along with spring and related diffuse discharges, a preliminary water balance for the SA part of the basin was developed as a means of providing an initial basic 'sanity check' for the numerical modelling. The preliminary water balance (Table 3-2) suggests that the J-K aquifer within SA is not in steady state, but rather in a state of transience where estimated outflows exceed inflows. This difference is reflected in a change in storage of the aquifer system, evidenced by changes in groundwater levels, which tend to be concentrated in sub-regional areas where extraction is concentrated.

The predominant groundwater system input is lateral inflow from Queensland and the Northern Territory, although the volume is estimated within a level of uncertainty spread over about two orders of magnitude, reflecting the range of aquifer properties and hydraulic gradient estimates that underpin it. In contrast, direct recharge is about an order of magnitude lower than the median lateral inflow, although the relative variance is much smaller. Lateral outflow, spring discharge, well extraction and vertical leakage are all estimated within about an order of magnitude albeit with a reasonably high degree of uncertainty. Further work, including the modelling task, is required reduce the uncertainty in this preliminary water balance.

Table 3-2: Preliminary water balance for the J-K aquifer within SA.

Inflow (ML/d)	Median value (ML/d)	Uncertainty range (ML/d)	Δ Storage (ML/d)	Net Uncertainty range (Inflow minus Outflow (ML/d)	Outflow (ML/d)	Median/ adopted Value (ML/d)	Uncertainty range (ML/d)
Lateral inflow	475	(59 to 4219)			Lateral outflow	73	(8 to 443)
Recharge	20	(10 to 30)			Wells	134	(134-160)
					Spring discharge	66	(66-76)
Vertical leakage	not quantified				Vertical leakage (inc. diffuse discharge near springs)	274	(20 to 690)
Total Inflow	**495**	**(69 to 4,249)**	**-52**	**(-159 to 2,880)**	**Total outflow**	**547**	**(228 to 1,369)**

3.10 Water quality and hydrochemistry (Volume 6)

Examining variations in water quality and hydrochemistry can be used to inform interpretations on recharge, discharge and groundwater flow patterns. Salinity is generally less than 2500 mg/L TDS across the bulk of the study area from the eastern to the central to western regions where confined aquifer conditions prevail. However, there are some occurrences of salinity up to 5000 mg/L TDS in the Cooper Basin sub-region on the east, and south from there to the Frome Embayment (Figure 3-7A). In the western parts of the basin, there are some values up to 10 000 mg/L TDS due to the influence of high rates of evapotranspiration within a recharge zone located within an arid environment. In the south-western margins, salinity increases further beyond 10 000 mg/L, although that possibly indicates a discrete sub-regional flow system. The pH is typically alkaline in eastern portions, relatively acidic in the south-western margin and near neutral elsewhere.

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 $Na^{+}+HCO_3^{-}$ (Figure 3-7B). 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 in order of 1-2 m/year, but within a wide range from 0.05 to 7.6 m/year.

3.11 Conceptual Hydrogeological Model summary diagrams (Volume 6)

Based on the content in the previous chapters, Figure 3-8 and Figure 3-9 summarise the conceptual model of the key hydrogeological framework and processes that is implemented in the numerical groundwater modelling. These diagrams display the following key features:

- Lateral inflow from Queensland and the NT is an important part of the water balance. Recharge via direct and diffuse infiltration from rainfall, ephemeral river recharge (ERR), mountain block system recharge are also considered. The most important of these recharge areas is ERR associated with the Finke and Plenty Rivers.
- Discharge and outflow are predominantly through GAB springs and groundwater extraction via wells. Well extraction is predominantly for stock and domestic, mining and as a by-product of oil and gas extraction (co-produced water). Outflow via the Frome Embayment is also considered.
- Groundwater flow into and out of the Basement below the J-K Aquifer is important for conceptualisation, particularly inflow in the northwestern portion of the study area.
- There may be several sub-basinal flow systems present within the J-K aquifer within the study area as defined by the potentiometric surface and hydrochemistry. Important ones can be found in the north, central and southwestern portions of the study area.
- Groundwater within the J-K Aquifer over most of the study area is artesian, with most confined and unconfined occurrences found to the west and southwest.

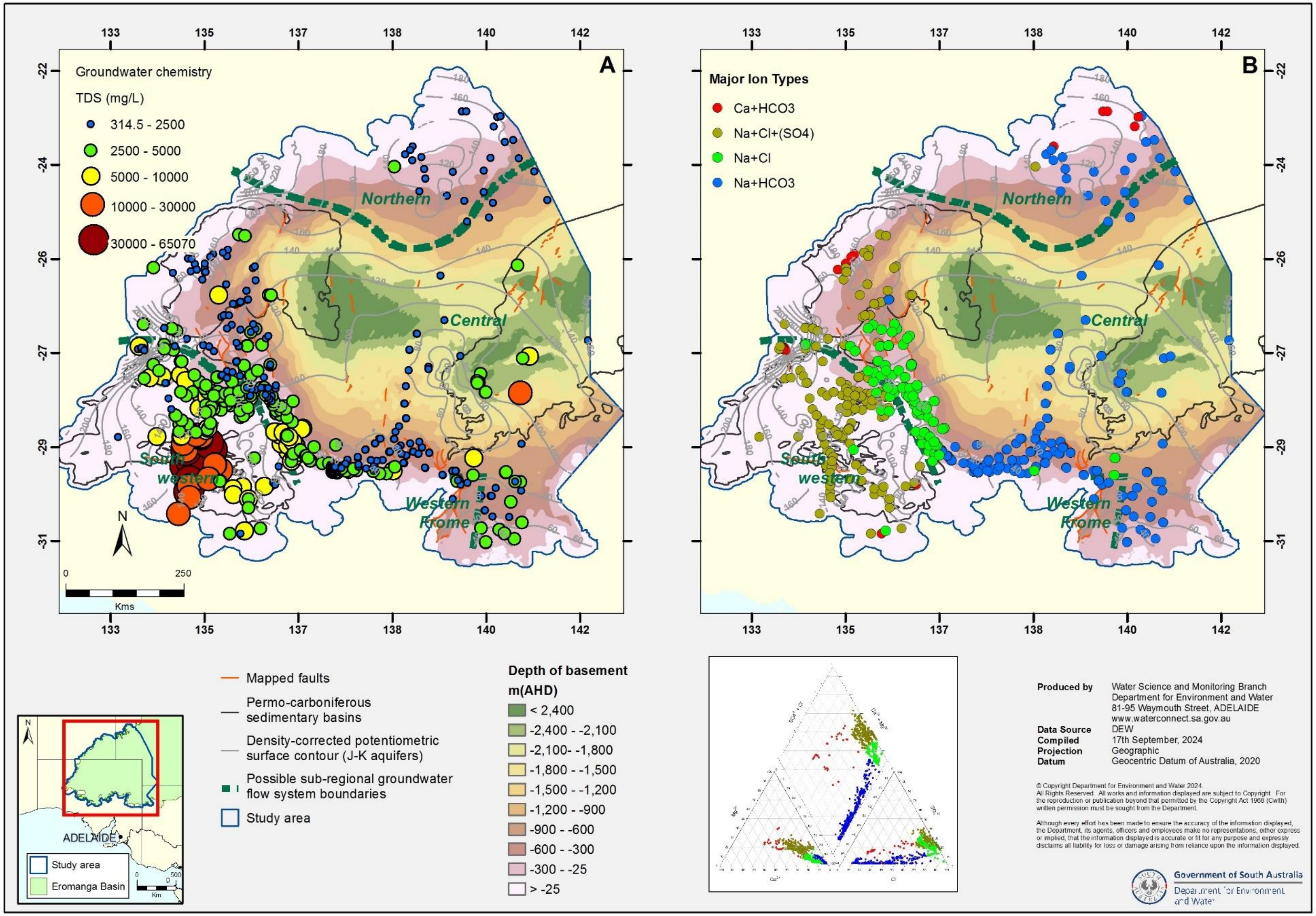

Figure 3-7 Hydrochemistry of the study area A) TDS (mg/l) distribution. B) Proportional major ion distribution

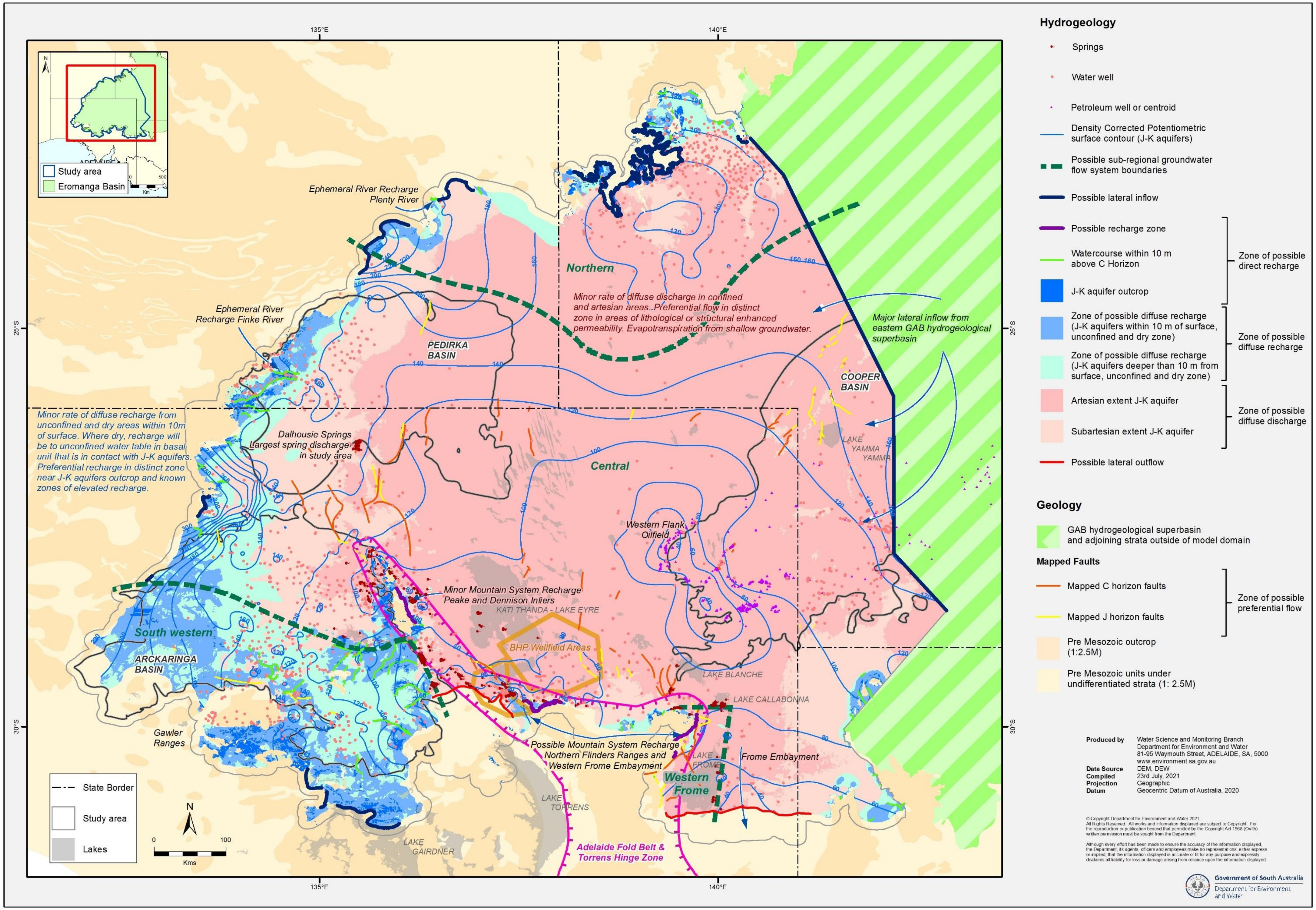

Figure 3-8: Schematic conceptual plan of recharge and discharge processes interpreted to occur within the study area.

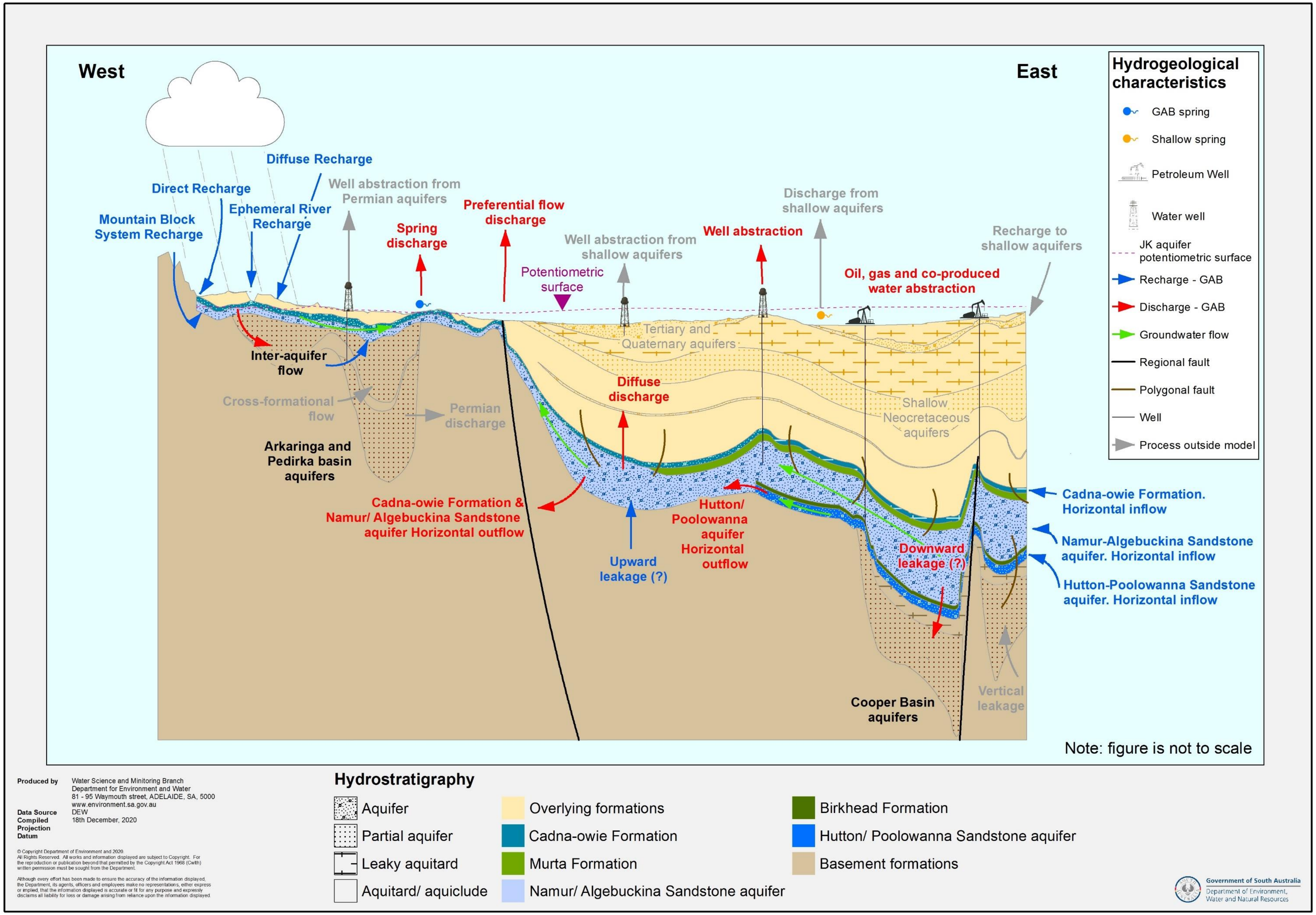

Figure 3-9: Schematic conceptual cross section of recharge and discharge processes interpreted to occur within the study area.

4 Model construction and history matching (Volume 8)

This chapter provides a summary of design, construction and history matching (transient calibration) for the Far north groundwater model. The design is based on data, conceptualisation and terminology summaries in the previous chapter.

4.1 Software used

The groundwater flow software used is the industry-standard MODFLOW-USG (USG-TRANSPORT). The defining feature of this software is that it employs an unstructured grid for simulating groundwater flow using a control volume finite-difference technique (Panday, 2018). Consequently, a model cell can be any shape. The main advantage of the unstructured grid capability is computational efficiency by allowing fine layer and grid resolution in the areas and points of interest without overburdening the model with unnecessary layer and grid-cell computations in areas of less interest. Groundwater Vistas version 8 (v8) is used as the primary Graphical User Interface (GUI) for pre- and post-processing of the model input and output data. MODFLOW and its USG variants are integrated into Groundwater Vistas v8.

4.2 Model construction and design

Whilst Modflow USG can manage several mesh grid designs, ultimately a Voronoi mesh was chosen for initial model design and construction following the conclusion of test modelling of three options. The Voronoi mesh grid provided the most computationally efficient and stable option of all the options trialed.

Groundwater model construction by necessity requires a boundary that provides a logical limit of investigation for examining groundwater behaviour. Consequently, a key decision in early model design is setting this boundary and assigning summarized groundwater behaviour conditions (or boundary condition) that can reasonably simulate groundwater behavior at the boundary of the model. The central part of the eastern boundary represents lateral inflow of groundwater from the east into the model domain. The northern and southern parts of the eastern boundary are characterized by no-flow conditions as they align with a groundwater divide and drainage lines approximately parallel to regional groundwater flow directions, respectively. Further, we selected the spatial extent of the eastern boundary to provide sufficient distance away from the areas of interest in South Australia such that the hydraulic conditions along the boundary do not dominate the simulation results.

As previously discussed, the numerical model comprises six layers, resolved into three major GAB (J-K) aquifer units, two intervening GAB confining units and the underlying units treated as a single-layer 'basement.' (Figure 3-2 and Table 3-1). The potential for connectivity between the GAB (J-K) and underlying aquifers or partial aquifers has important ramifications for our understanding of the total groundwater volumes accessible via the J-K aquifer. The sedimentary rock aquifers or partial aquifers underlying the J-K aquifer are commonly associated with the Arckaringa, Pedirka, and Cooper Basins. Fractured rock aquifers may also underlie a further portion of the J-K aquifer. These underlying aquifers are lumped together and collectively referred to as the 'basement' for model construction purposes. The underlying 'basement' is modelled with a nominal thickness of 100 m and variable boundary conditions to allow for broad upward or downward leakage (Table 3-1). Groupings of the geological formations and members into these six major hydrostratigraphic aquifer or confining units is based on relative hydrogeological properties and connectivity, mapping resolution and importance with respect to abstraction of groundwater.

4.3 Boundary conditions and initial hydralic parameter values

Head-dependent flow boundaries (General Head Boundaries or GHB) and Specified Gradient Boundary (SGB) are used to define inflow boundary conditions around much of the eastern, northern, and western margins of the model domain, whereas GHB are applied on the southern margin in the Frome Embayment to represent outflow. No-flow boundaries are applied elsewhere along much of the southern margin, with smaller areas on the eastern and northern margins where potentiometric surface interpretations suggest no inflow or outflow is occurring. Head-dependent flow boundaries in some areas of Layer 1 (Cadna-owie Formation) represent zones of preferential or diffuse discharge from the confining units above, such as around springs and some fault zones. Inflow and outflow of groundwater through the top of Layer 1 is simulated using conductance term values that referred to as the "Bulldog Shale Conductance". Internal to the model domain, springs and extraction wells are simulated as local discharge boundaries using MODFLOW Drain and Groundwater Vistas Analytical Well Packages.

The initial hydraulic parameter values were derived from core- and field-based estimates collated and interpreted specifically for this study. Where they are available, these hydraulic property values are used in preference to those derived from literature and previous modelling.

4.4 Model implementation and history matching

The numerical model is developed in a series of stages, consistent with best practice guidance (Barnett et al. 2012). To begin, a preliminary pseudo-steady-state model is built for testing and refinement of initial conditions. Using the pseudo-steady-state model as a foundation, a transient groundwater flow model was then constructed, with stress periods and time-varying boundary conditions added.

The numerical model is calibrated, or history matched, based on observed groundwater levels and spring discharge, accounting for historical groundwater extraction. The model calibration consists of changing values of the model input parameters such that the results provide matches to field conditions within acceptable criteria. The model history matching period covers 1900 to 2019. The history-matching processes involved both manual trial-and-error and automated inverse methods of optimal parameter estimation using the software package PEST. The history matching targets are measured groundwater levels recorded between 1900 and 2019 at selected wells, and field estimated spring discharge rates from 1980 to 2019. This data provides the opportunity to calibrate the model to transient stresses on extensive temporal and spatial scales.

The fit between measured or observed calibration targets and their simulated equivalent model outputs describes how well model history matching was achieved. The difference between the observation targets and simulated equivalent values is described as the "residual." A residual is regarded as a direct indication of a model's ability to simulate past trends and conditions; and it can be used to assess predictive uncertainty of the model. A positive residual indicates an underestimation of simulated values by the model, and a negative residual indicates an overestimation.

With respect to the model's history matching performance against groundwater level, the residuals for the 1900 – 2019 calibration period showed that 77 percent of simulated heads exceeded the measured groundwater levels with a mean residual value of –9.4 m, (i.e., an overestimation of 9.4 m). In contrast, 23 percent simulated heads were less than measured groundwater levels with a mean residual value of 6.7 m, (i.e., an underestimation of 6.7 m). About 37 percent of simulated potentiometric heads for all layers were within plus or minus 5 m of the observed values; about 66 percent were within plus or minus 10 m; about 88 percent were within plus or minus 15; about 95 percent were within plus or minus 20 m; about 1 percent were greater than 20 m.

In addition to groundwater level as reported from monitoring wells, 41 springs in the SA GAB were used as spring discharge rate targets. The general trend of spring discharge is well simulated by the model. The field-estimated mean discharge rate from the years 1980 to 2019 ranges between 0.0012 L/s and 9.897 L/s; the simulated mean discharge rate ranges between 0.024 L/s and 10.325 L/s. The difference between the simulated and observed mean discharge rate (for the years 1980 to 2019) ranged from 0.003 L/s (Welcome WWS013) and 1.158 L/s (Gosse LGS004).

4.5 Sensitivity, uncertainty and scenario analysis

Before this model could be used for its intended purpose, a simple sensitivity and uncertainty analysis of the calibrated model and a predictive scenario was examined. Sensitivity and uncertainty analysis are conducted by varying the input parameters one by one and determining if by doing this it would cause significant changes in the model's predictions, but insignificant change in calibrated model output. A predictive scenario involves designing a question concerning how groundwater in the modeled study area is to be managed.

The analysis was designed to examine potential changes in spring discharge and groundwater level using the high and low end of plausible range of model parameters. The model parameters were individually varied by factors ranging from 0 to 1000 (factor of 1.0 represents no variation of calibrated model parameter values). The sensitivity and uncertainty of the model is estimated by several metrics, including changes in root mean square error (RMSE) and relative change in predictive output as compared to baseline output. For the calibrated model, change in potentiometric head RMSE and change in spring discharge RMSE are the output of interest and for the predictive model change in total spring discharge and drawdown at spring vent relative to a base case predicted model simulation are the output of interest.

The results from examination of the uncertainty of the model are summarised below.

- Parameters that are of minimal concern because both the calibrated model and the predictive model are insensitive to change included GHB Conductance, diffuse recharge, Bulldog Shale conductance, hydraulic conductivity anisotropy (K_v/K_h), specific storage, specific yield and specified gradient boundary.

- The pumping rate was the only parameters that caused significant changes in the calibrated model residuals but insignificant changes in the model predictions.

- Parameters where both the calibrated model and predictive models are sensitive to changes included the spring conductance and horizontal hydraulic conductivity.

- Finally, the model did not contain any parameters to which the calibrated model is insensitive, but the predictive model is sensitive.

5 Data gaps, limitations, and recommendations

The model is based on an extremely thorough review and interpretation of available data, it has been successfully calibrated and meets its modelling objectives. However, given the breadth and history of the study area, it is not surprising that many data gaps were encountered. Below is a summary of the most important data gaps identified that will be reviewed and investigated in future iterations of the model.

- There were many design and history matching challenges encountered. Design challenges centred around the fact that the model domain occupies a large geographic area, and this required a grid type and size that both satisfy model objectives and the conceptual model, but at the same time achieve reasonable and manageable computational times and file size. To manage computational time, the grid was coarsened as much as possible without considerably affecting the model objectives and results of interest.
- History matching was hampered by poor data availability, including water level, hydraulic properties (especially vertical hydraulic conductivity), spring discharge rates, and vertical hydraulic gradient between aquifers. The available observation data are not equally available for all the model layers and are also not equally distributed spatially and temporally. Comprehensive measured groundwater head, groundwater extraction volumes and spring discharge data are available only for OD wellfields. Available spring flow rate are reported in aggregates, individual spring flow rate is not available.
- The model does not attempt to replicate density driven flow. The computational requirements to replicate convective flow were too great to attempt incorporation during this model build, particularly given the design objectives of the model that emphasised third party use using commonly available software. Whilst not currently replicated, DEW is very supportive of continued research, including smaller scale modelling, that will enable properly described and constrained replication of convective flow in future model iterations.
- After extensive analysis, it was necessary to use a simple method for groundwater density correction, as using multiple, smaller scale density correction constants across the model domain proved to be too difficult to accomplish. Consequently, density correction favours accuracy near springs, as this is a key risk receptor the model was designed to help manage.
- There was insufficient information to accurately describe the initial condition and so this has been approximated for the purposes of this model. This is a common problem for GAB numerical models as there is very little, to no historical information collected prior to groundwater extraction. This may lead to systematic misreporting of head across the model domain. Further, this problem is exacerbated by the very slow response times between recharge events experienced by the hydrogeological system, which are best described using paleoclimatic cycles.
- Grid discretisation could not be completed to a sufficiently fine scale to permit every spring and well to be individually replicated. In some areas, spring and well locations required aggregation to allow model stability. Consequently, at more localised scales model predictions become less accurate. As before, this is not a unique problem for regional-scale GAB numerical models.
- Explicit groundwater flow between hydrostratigraphic units is restricted to the Main Eromanga Aquifer Sequence. Upward groundwater migration is replicated using conductance terms whilst downward flow is approximated using the inclusion of a basement layer of nominal thickness. Whilst these give the model some flexibility to explore inter-aquifer flow relationships, this can only be accomplished in an approximate manner.

- Faults are not explicitly replicated in the current model build. Whilst their importance in spring conduit formation, inter-aquifer relationships, preferential flow development, and definition of sub-basinal groundwater systems is recognised, it would be potentially misleading to simulate this without any specific hydrogeological information to constrain this. Further, replicating groundwater flow through fault structures would have added significant complexity to what was already a very complex model build.
- Most hydrograph data across the model domain used to calibrate the model is sourced from dual purpose wells that are used for both monitoring and extraction of water. Whilst every care is taken during monitoring to collect a representative sample, the potential of error cannot be confidently removed.
- There is very little reliable monitoring information to constrain spring flow. The groundwater source for springs is assumed to be entirely from the Main Eromanga Aquifer Sequence, with possibly some contribution from the basement layer where inferred. Also, the model is not designed to explore the complexities of groundwater flow through individual spring conduit architectures and all the strata through which they occur; smaller scale localised models would be better able to accomplish this.
- Water use data for stock and domestic use is estimated using a simple formulation in the absence of sufficient metering data. Whilst the formulation is considered conservative for risk assessment purposes, in the context of numerical model calibration, overestimating water use may lead to overcompensation in other hydraulic parameters, such as hydraulic conductivity, during calibration.

While some of these data gaps and limitations, such as the lack of the data collected before groundwater pumping began can never be addressed ideally, other data gaps and limitations may be conceivably addressed as more investment in data collection is made. Some of the key recommendations to address data gaps and limitations encountered during this model build are detailed below:

- Spring discharge data acquisition to be improved including increasing the number of monitored springs and monitoring frequency. As many springs are in remote areas which are difficult to access, innovative ways of remotely monitoring spring discharge or use of dependable proxies should be explored.
- Knowledge of groundwater abstraction across the study area should be improved, either through direct monitoring or refined estimates.
- Cooper Basin oil and gas industry data should be thoroughly analysed with the aim of establishing knowledge and data gaps. Investigations should be undertaken to improve the conceptual understanding of interactions between the Eromanga and the underlying Cooper Basin. The model could then be revised to simulate the Cooper Basin as well as the Eromanga Basin.
- Research should be conducted to investigate whether free convection, due to temperature differences, is among the key drivers of groundwater flow within the study area.
- A comprehensive uncertainty analysis should be undertaken if funding is available.
- Future modelling programs may consider refinement of the major hydrostratigraphic units and the overlying and underlying units.

6 Accessing the Model

Members of the public may be able to access the Far North groundwater model to conduct research and assessments via an access agreement between the applicant and the Government of South Australia. Prior to an agreement being established, the Department for Environment and Water will collaborate with the applicant to ensure that the model is being used appropriately, cognizant of the limitations of the model. Further, the Government of South Australia will retain intellectual property rights over all versions of the Far North groundwater model, inclusive of those modified versions developed by third party users. At the end of use, all third parties will be expected to return copies of the model along with details as to any modifications that were made.

The Government of South Australia strictly forbids unapproved use of the Far North Groundwater Model, which includes retaining copies of the model for unauthorized use or profiting through use of the model via works not discussed or approved by the South Australian Government.

7 Appendices

A. Summary of Hydraulic parameters

Table 7-1: Summary of estimated lateral hydraulic conductivity (K_h) values for formations (m/d).

Formation	Region (defined by the basins underlying the Eromanga basin)					
	Simpson	*Cooper*	*Arckaringa*	*Pedirka*	*Stuart Shelf*	*Generic Min-Max*
Cadna-owie Fm.		8×10^{-2}	20.0	7.0		0.1-100
Murta Fm.		1.44×10^{-8} – 4.43				
McKinlay Member		1.44×10^{-8} – 6.34				
Algebuckina Sst	22.1				22.1	0.1-100
Namur Sst		1.18×10^{-4} – 5.48				
Hooray Sst		0.12				<18.7
Westbourne Fm.		0.1				
Adori Sst		0.77				10 (mean)
Birkhead Fm.		1.44×10^{-8} – 1.85				
Hutton Sst/ Poolowanna Fm.		1.5×10^{-4} -4.35				<170
Generic Basement						1×10^{-4}-0.3

Table 7-2: Summary of estimated K_v values for formations (m/d).

Collective Term	Region	Hydrostratigraphic Unit	K_v (m/d)
Main Confining Unit		Rolling Downs Group	3.46×10^{-9} 8.64×10^{-4}
Main Eromanga Aquifer Sequence	Cooper Basin	Cadna-owie Fm.	0.7 2
		Murta Fm.	
		Namur-Algebuckina Sandstone Aquifer	0.7 2
		Birkhead Formation	4.31×10^{-5}
		Hutton-Poolowanna Aquifer	
Pre-Jurassic Basement	Generic Pre-Jurassic Basement	Generic Pre-Jurassic Basement	4.15×10^{-8} 2
	Arckaringa Basin	Mt Toondina Fm.	
		Stuart Range Fm.	4.15×10^{-8} – 3.46×10^{-5}
		Boorthanna Fm.	
	Pedirka Basin	Purni Fm.	0.05
		Crown Point Fm.	
	Warburton Basin	Generic Warburton Basin	0.19
	Arrowie Basin	Stuart Shelf (Tent Hill Fm.)	8×10^{-4}

Table 7-3: Summary of estimated S_y and S_s values.

Collective Term	Region	Hydrostratigraphic Unit	S_s (1/m)	S_y (-)
Main Confining Unit		Rolling Downs Group	4.3×10^{-6} 1 x 10^{-3}	
Main Eromanga Aquifer Sequence	Cooper Basin	Cadna-owie Fm.	1.75×10^{-6} 1.9 x 10^{-3}	8×10^{-6} 7
		Murta Fm.		
		Namur-Algebuckina Sandstone Aquifer	3×10^{-7} 1.9×10^{-3}	0.1 – 0.3*
		Birkhead Fm.	5.8×10^{-7}	
		Hutton-Poolowanna Aquifer		0.05 – 0.25*
Pre-Jurassic Basement		Generic Pre-Jurassic Basement	1 x 10^{-5}	
	Arckaringa Basin	Mt Toondina Fm.	1×10^{-5}	
		Stuart Range Fm.		
		Boorthanna Fm.		
	Pedirka Basin	Purni Fm.	1.1^{-6} 1 x 10^{-4}	0.04 – 0.32*
		Crown Point Fm.		0.11 – 0.32*
	Arrowie Basin	Stuart Shelf	4 x 10^{-5} – 0.02	

*Estimated based on effective porosity.

8 Units of measurement

8.1 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

8.2 Shortened forms

bgs	below ground surface
EC	electrical conductivity (µS/cm)
pH	acidity
pMC	percent of modern carbon
Ma	Million years

9 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 (for example, 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 — An aquifer in which the upper surface is impervious (see 'confining layer') 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 estimate the sustainable use of the water resources available for development from the well

Aquifer, unconfined — An 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 Environmental Systems Research Institute.

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 broad acre 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 (for example, 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

dD — 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 water table. 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 recognized 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 5 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 because 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

GHB – General Head Boundary – A MODFLOW package that is used to simulate flow of groundwater into or out of model domain

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/]*

HSU – Hydrostratigraphic unit A geologic formation, part of a formation, or a group of formations with similar hydrologic characteristics or properties (e.g. hydraulic conductivity or permeability) relating to groundwater flow.

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 in real time

Hydrology — The study of the characteristics, occurrence, movement and use 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 or 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 Site-specific long-term covariation of hydrogen and oxygen stable isotope ratios in local precipitation

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 an ecological response to environmental change.

MODFLOW — A 3-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 and artificial recharge.

Natural resources — Soil, water resources, geological features and landscapes, native vegetation, native animals and other native organisms or 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 positive or negative

NWC — National Water Commission

$d^{18}O$ — 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; 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 Aquifer Storage Recovery.

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^2/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 an unconsolidated material that contains pores or voids, commonly expressed as a volume.

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 based on 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 seasonal basis

SGB – Specified gradient boundary; a MODFLOW-USG package use to simulate groundwater flux across model boundary as a function of prescribed hydraulic gradient at the boundary

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)

(S) — Storativity; storage coefficient; the volume of groundwater released or taken into storage per unit plan area of aquifer per unit change of head; it is 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 other 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 (for example, kilolitres) to be used over a specified period, 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;(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 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 several 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 6 metres.

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