Facilitating Long-term Outback Water Solutions (G-FLOWS Stage-2) Final Report

Gilfedder M, Munday T, Bestland E, Cahill K, Davies PJ, Davis A, Heinson G, Ibrahimi T, Lamontagne S, Ley-Cooper Y, Love A, Olifent V, Pichler M, Robinson N, Smith S, Sørensen C, Suckow A, Taylor AR, Thompson J, Annetts D

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Acknowledgments

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Executive Summary

Goyder FLOWS Stage-2 has worked towards improving broad knowledge about the location and interaction between groundwater resources in the northern part of the Eyre Peninsula area. This area is a priority area that was identified by the mining exploration industry for mineral exploration and potential mine developments.

Work undertaken in G-FLOWS Stage-2 supported the development of new hydrogeological framework (Figure ES1) using the approach developed by G-FLOWS Stage-1 (Munday *et al.* 2013). This approach uses a combination of regional geophysical data (magnetics), local airborne geophysical surveys (industry supplied Airborne Electromagnetic (AEM) data sets), terrain indices derived from surface topography (using MrVBF: Gallant & Dowling, 2003)), and existing South Australian regolith and geological data (through DSD) and hydrogeological data (through DEWNR). The hydrogeological framework supplements existing knowledge of the aquifer systems and their spatial variability in the northern Eyre Peninsula.

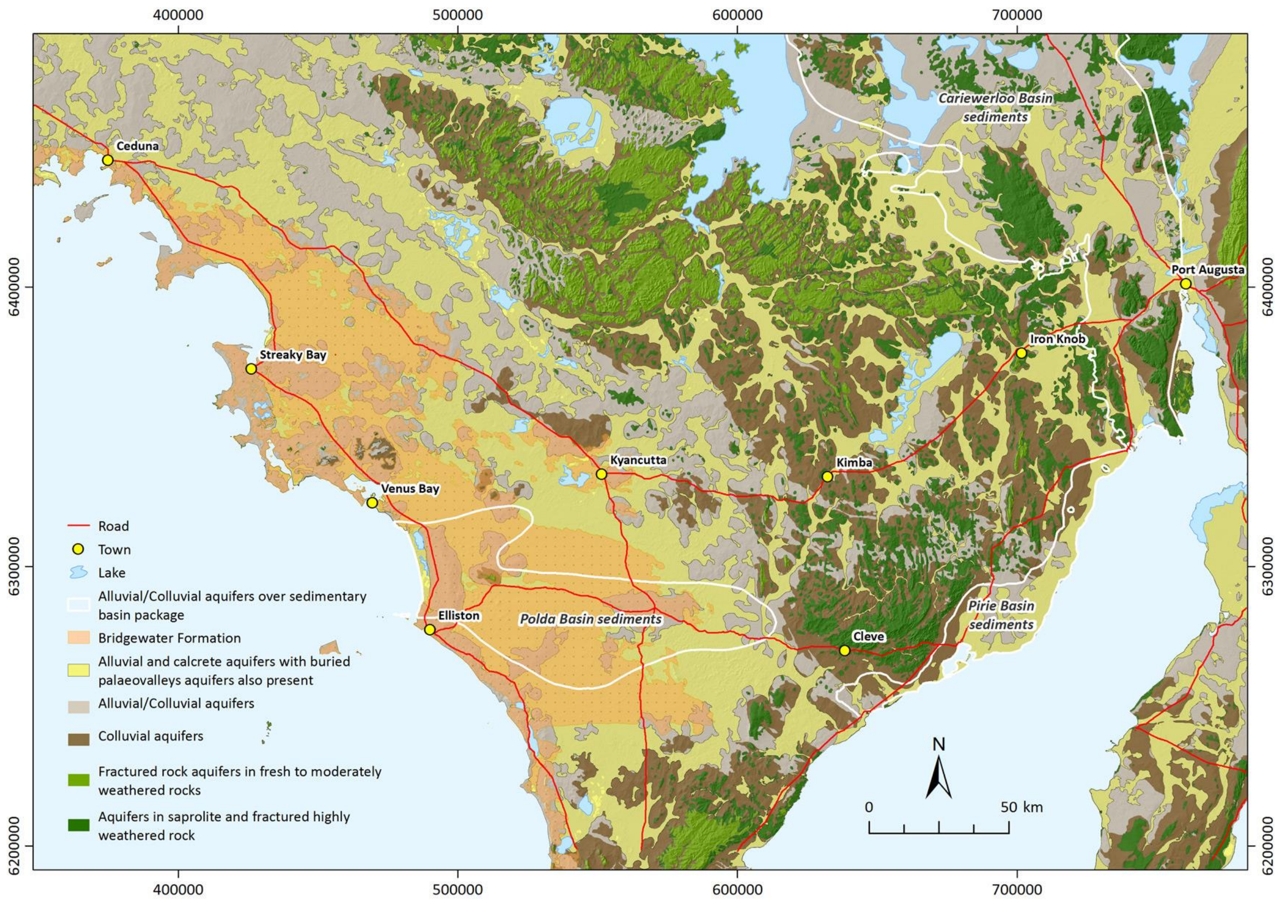

Figure ES1 – Hydrogeological framework developed for the northern Eyre Peninsula by G-FLOWS Stage-2

The project developed a methodology combining classical groundwater hydrogeology, environmental tracers, geophysics and analytical modelling, which is described in Taylor *et al.* (2015a). Of importance is the development of a detailed groundwater surface (water-table and potentiometric surface) map (that can provide important inferences about the scale, nature and behaviour of the dominant groundwater flow systems in place.

Key aspects of the work undertaken in G-FLOWS Stage-2 include:

- Application to the northern Eyre Peninsula of the hydrogeological framework, which combines and interprets multiple datasets from industry and government to help target finer-scale assessment of groundwater resources (see Figure 2);
- Application and further development of a range of approaches and techniques for interpretation and use of airborne geophysics to provide information on hydrogeology and groundwater:
    - Hydrogeophysical (AEM, NMR);
    - Groundwater conceptual understanding through analysis of isotopes/tracers in the Cleve Hills (northern Eyre Peninsula), which highlights the complexity of this area and suggests that local groundwater flow system processes are dominant in the region.
    - Successful application and further development of the processing and inversion strategy for employing overlapping historical and contemporary EM data affected by system uncertainties and errors.
- Communication of scientific results to a wide range of stakeholders and audiences, which included:
    - Presentations and posters at industry workshops, scientific conferences, meetings of professional associations, and universities.
    - Publications in international journals, trade journal, science magazine
- Close collaboration and goodwill with data exchange between mineral companies and stakeholders, including government agencies.

Looking to the future, the work undertaken in G-FLOWS Stage-2 can be built on in the following ways:

- Examine potential of combined regional geophysical (AEM) and surface (regolith) datasets as a means of up-scaling spatial patterns of groundwater recharge, which includes on-ground follow up to improve and validate the hydrogeological framework.
- Continued verification of AEM data through comparison with multiple lines-of-evidence, including :
    - Ground-based geophysical data at representative locations
    - Groundwater salinity data compared with AEM-derived conductivity patterns
- Undertake additional work to apply the piloted Markov chain Monte Carlo (McMC) analysis of AEM data to inform hydrogeological modelling. This could include the following:
    - Use McMC to identify different sources of uncertainty (e.g. conceptual model uncertainty, parameter uncertainty, etc.).
    - Develop a program of work to systematically reduce key sources of uncertainty.
    - Develop McMC version for parallel computing to better address computational limitations
- Work towards using inverted AEM datasets to provide detailed 3D geometry as part of geological and groundwater model development.
- Link spatial understanding of hydraulic parameter variation (from remotely sensed techniques such as NMR) to inform hydrogeological modelling.
- Extend and link existing recharge investigations across the Eyre Peninsula to assess geographic influence, as well as undertake finer-scale groundwater investigations in priority areas for exploration and potential mine development, combining local scale recharge studies linked to finer scale, targeted geophysical data acquisition (air and ground), groundwater model development and groundwater resource estimation.

1 Background

The identification and characterisation of water resources are fundamental components of the support that the Goyder Institute provides to improve the South Australian Government policies on maintaining water security. The Goyder Institute aims at making available information that helps understand the water resource itself.

Goyder FLOWS Stage-2 has worked towards improving broad knowledge about the location and interaction between groundwater resources in the northern part of the Eyre Peninsula area (Figure 1). This is a priority area identified by the mining exploration industry for mineral exploration and potential mine developments. The northern part of the Eyre Peninsula was also recognised in the RESIC study (2012) as a priority area for potential mining development where knowledge of the regional groundwater resources was inadequate (outside of the prescribed wells areas) to enable informed water infrastructure decisions to be made. There is a recognised need to advance this knowledge such that water resources do not become a limiting factor to future developments in the area, thus balancing the needs of the mining industry with those of the local water users.

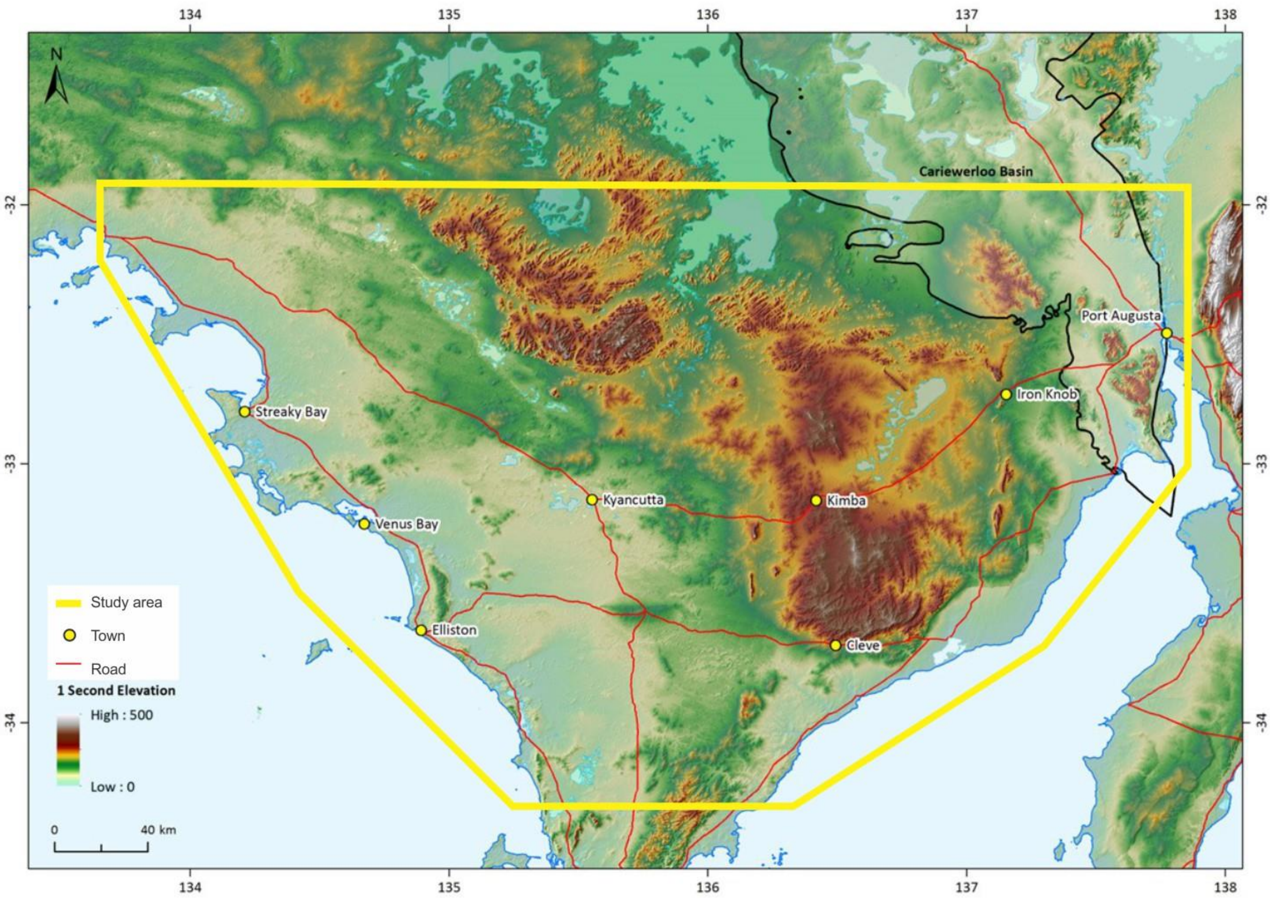

Figure 1 – Case study area in the northern Eyre Peninsula, showing main roads, towns, and land surface elevation

G-FLOWS Stage-2 builds on the approaches for conceptualising the hydrogeology of remote regions that were developed during G-FLOWS Stage-1, and also adds to the activity being undertaken in the Department of Environment, Water and Natural Resources (DEWNR) FLOWS Initiative and the Department of State Development (DSD) PACE 2020 Program.

Work undertaken in G-FLOWS Stage-2 supported the development of new hydrogeological framework for the northern Eyre Peninsula using the approach developed by G-FLOWS Stage-1 (Munday *et al.* 2013). This approach uses a combination of regional geophysical data (magnetics), local airborne geophysical surveys (industry supplied AEM data sets), terrain indices derived from DEMs (MrVBF), and existing South Australian regolith and geological data (through DSD) and hydrogeological data (through DEWNR).

With the support of the mining and exploration community, the project was given access to a suite of airborne geophysical data acquired for minerals exploration and targeting across the area. This spatial data has been processed (inverted) to inform aquifer bounds and water quality. Derived information has been linked to hydrogeological data to enhance the understanding of the broad-scale groundwater resources across the northern part of the Eyre Peninsula. This has resulted in a new hydrogeological framework (i.e. digital maps and sections) for the northern Eyre Peninsula that adds to existing work undertaken in the DEWNR non-prescribed Project (Figure 2).

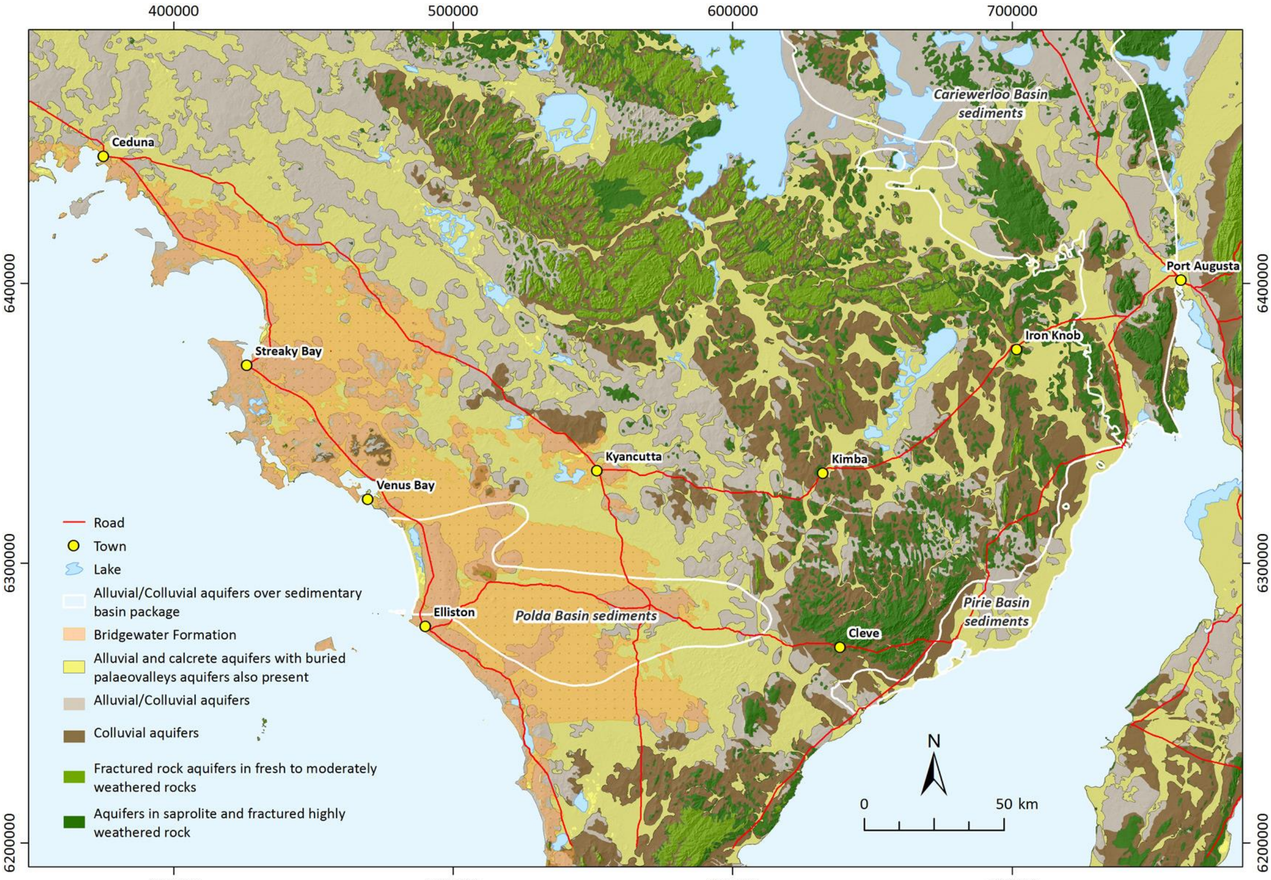

Figure 2 – Hydrogeological framework developed for the northern Eyre Peninsula by G-FLOWS Stage-2

This document is the Final Report for G-FLOWS Stage-2. It provides a synthesis and summary of key outcomes from the investigations outlined under G-FLOWS Stage-2, explaining how this large project has delivered its target objectives. This information is supported published reports and papers, which are listed in Table 1 together with details of the many presentations.

2 G-FLOWS Stage-2 Outcomes and Results

The G-FLOWS project is a staged research program, which aims to invest in the development of knowledge and information that could be employed to help support an integrated water resource management strategy, thereby facilitating the economic growth potential of priority areas as defined by the South Australian Government. Objectives for G-FLOWS Stage 2 can be summarised through the following specific deliverables:

1. Identification of case-study locations within the northern Eyre Peninsula, and justification of their selection, including work-plan.
2. Conceptual hydrogeological models for case-study areas.
3. Improved regional understanding of groundwater recharge and age in the northern Eyre Peninsula.
4. Improved understanding of hydraulic characteristics and aquifer connectivity (lateral and vertical) for key aquifers in northern part of Eyre Peninsula.
5. Interpreted (inverted) AEM data sets for key priority areas using existing data.
6. Final Report detailing hydrogeological conceptual model and aquifer connectivity knowledge for case study areas in the northern part of the Eyre Peninsula.

To help achieve these deliverables, G-FLOWS Stage-2 was divided into 5 tasks as outlined in Figure 3:

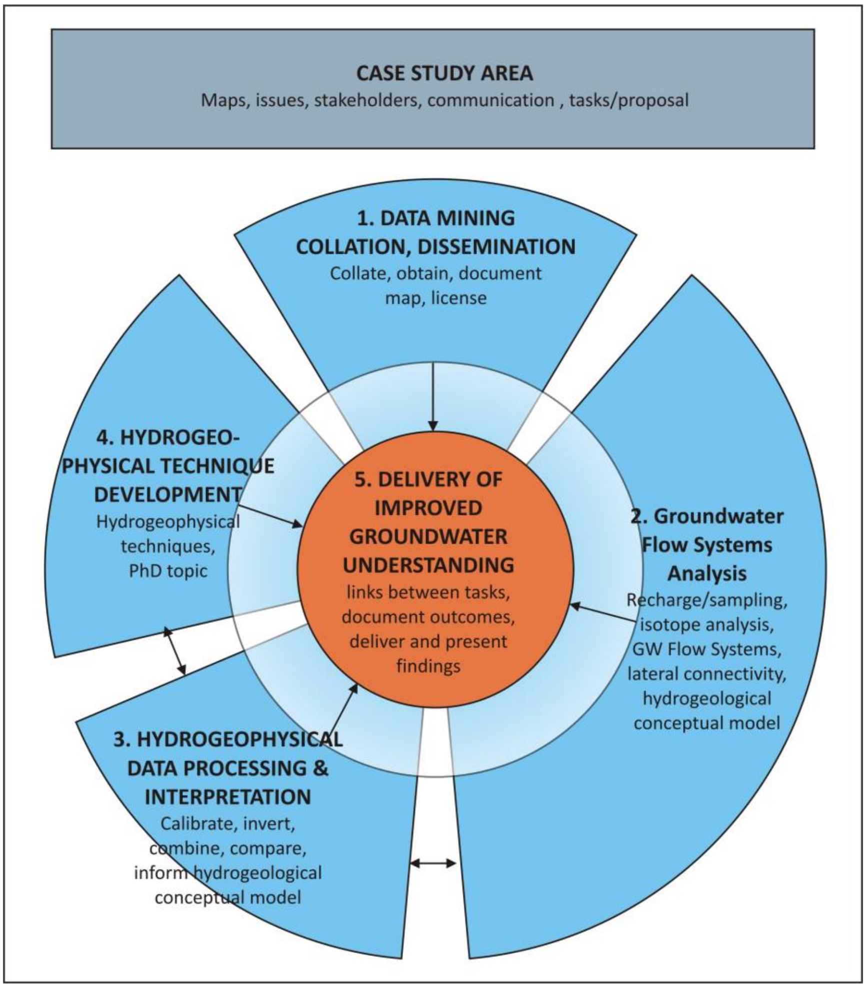

Figure 3 – Task structure of G-FLOWS Stage-2

2.1 Deliverable 1: Identification of case-study locations

The main case study area for G-FLOWS Stage-2 focused on the northern Eyre Peninsula (see Figure 1). This is a priority area that was identified by the mining exploration industry for mineral exploration and potential mine developments.

Within the broader region, G-FLOWS Stage-2 undertook focused activities that relate to the testing and assessment of environmental tracers and isotopes to better the understanding of groundwater recharge processes, aquifer connectivity and inter-aquifer leakage. These focused activities were linked to results derived from a separate DEWNR study on groundwater recharge processes to develop a better understanding of controls applicable to the north eastern Eyre Peninsula, particularly in the following two areas (shown in Figure 4):

1. **Cleve Hills** - Investigated localised aquifer connectivity and recharge as informed by data acquired along a regional transect form the east of the Cleve Hills, running south then east to the coast. Sampled bores along a broad drainage line that heads south and east out of the Kimba/Cleve region. The project team worked hard to gain access to many mapped bores in this area (a combination of clusters and a regional transect).

2. **Coastal Plain** - Used recently constructed piezometer network on the coastal plain near Whyalla, allowing sampling for a range of isotopes and tracers to explore inter-aquifer leakage. Investigated the connection between coastal aquifer and the hinterland fractured rock. This study provides information on the hydrogeology of this part of the north eastern Eyre Peninsula.

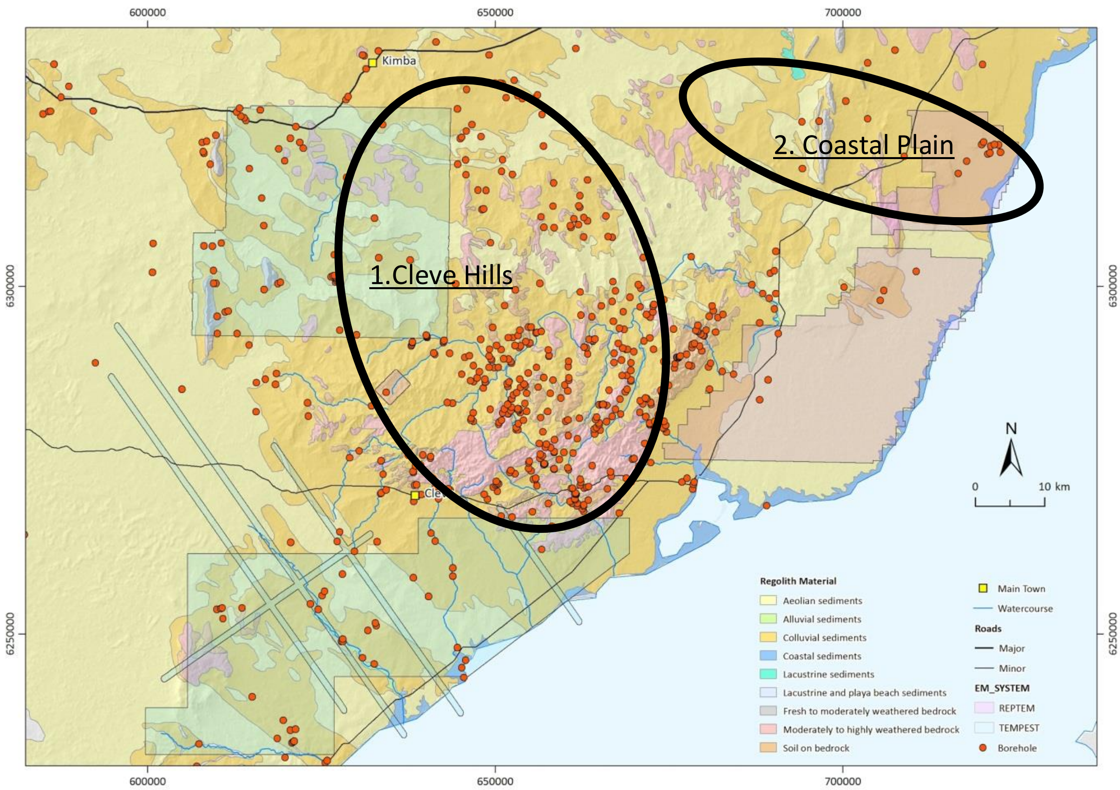

Figure 4 - Area selected in north eastern Eyre Peninsula for focused case studies. The higher borehole concentration offers greater opportunity to sample, allows for data integration with recently completed sampling of boreholes (DEWNR) and EM surveys. These areas also have existing AEM datasets

2.2 Deliverable 2: Conceptual hydrogeological models for case-study areas

G-FLOWS Stage-1 developed a method that has been further developed and applied as part of G-FLOWS Stage-2. This method was used to build an enhanced hydrogeological framework for the northern Eyre Peninsula. The framework builds on contemporary topography by combining a published terrain analysis technique (MrVBF: Gallant and Dowling, 2003) with understanding of bedrock geology and regolith (Figure 5) throughout the area, allied with the information contained within the airborne geophysics (see Figure 2 for the result).

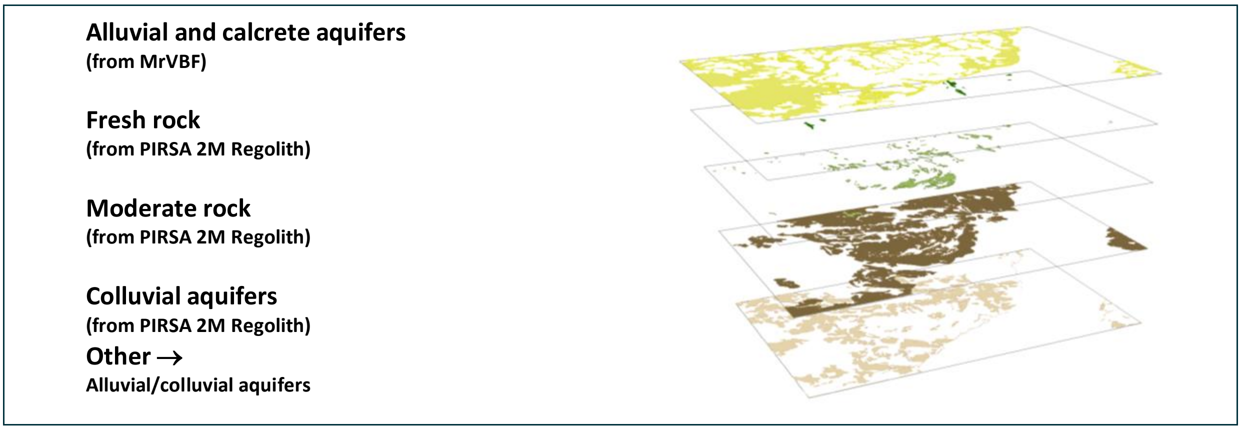

Figure 5 - Perspective view of layers used to produce the hydrogeological framework model

This framework provides an extended map of aquifer systems across the Eyre Peninsula. One of the challenges for G-FLOWS Stage-2 was to supplement existing knowledge of the aquifers and their spatial variability in the northern Eyre Peninsula. Figure 6 is a previously published map of the aquifer systems of the Eyre Peninsula (from Berens *et al.* 2011).

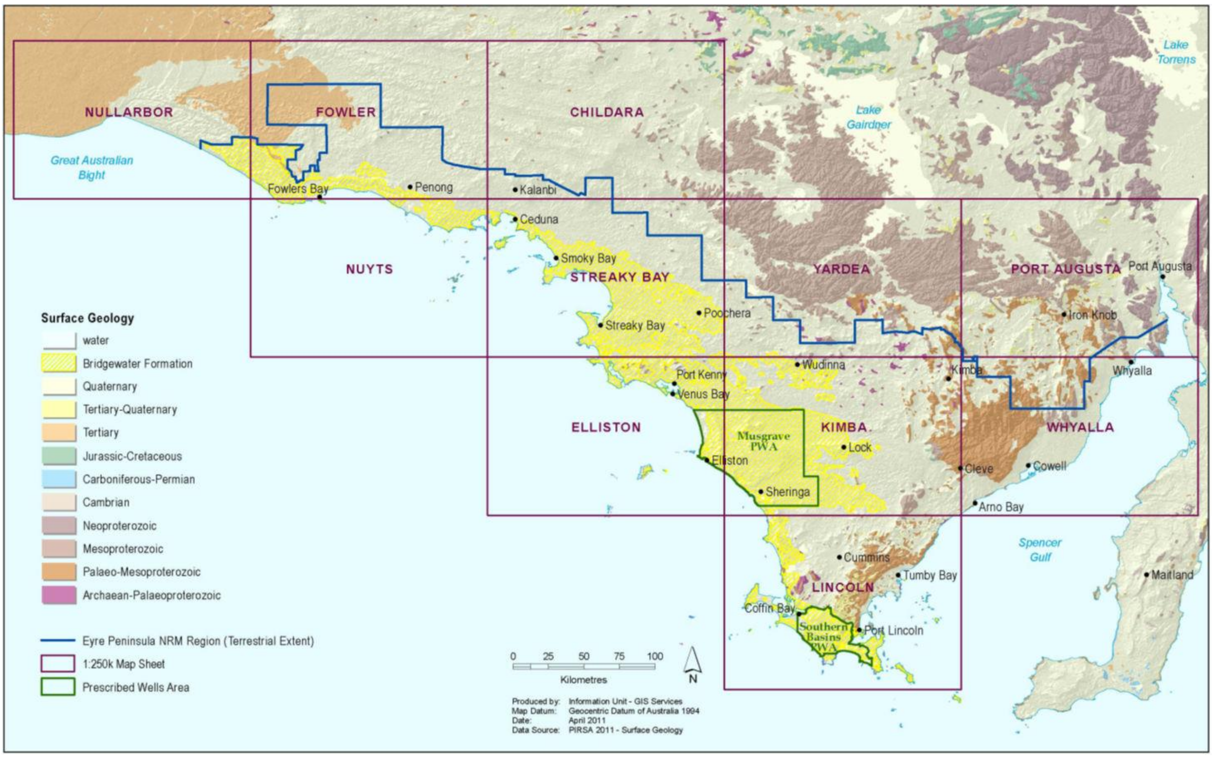

Figure 6 - Aquifer systems of the Eyre Peninsula (from Berens *et al.* 2011)

The hydrogeological framework developed in G-FLOWS Stage-2 provides more detail than the existing published map see (Figure 6). Figure 7 shows inset details for both the existing published map (Figure 6) and the new hydrogeological framework map (Figure 2), which highlights the finer details of the palaeovalley systems (showing as yellow in Figure 7b). These systems are potentially significant aquifers in their own right, and are now revealed in more detail. The new framework adds significantly to the knowledge of these systems that had previously been compiled by DSD.

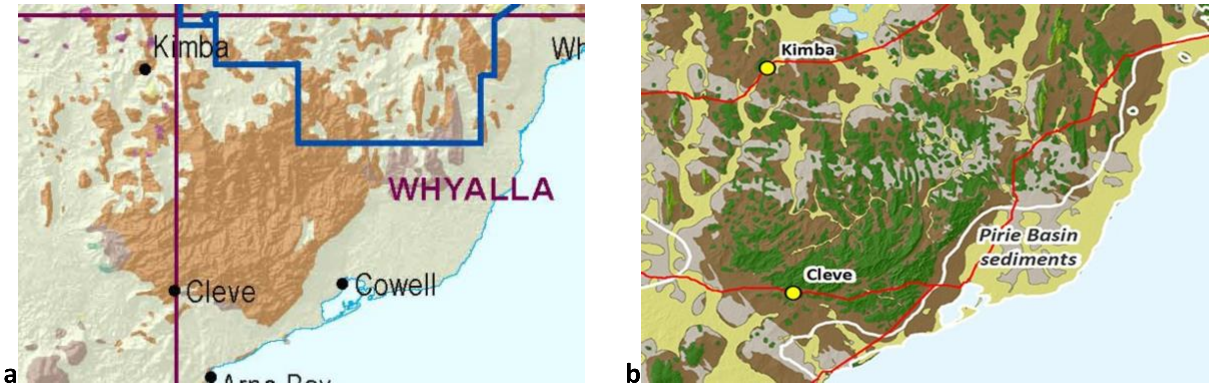

Figure 7 – Inset of details from: (a) published map (see Figure 6: Berens *et al*. 2011), and (b) G-FLOWS Stage-2 hydrogeological framework (see Figure 2). For scale/legend please refer to the source figures)

2.3 Deliverable 3: Groundwater recharge and age

Recharge rates for the region were estimated using the Chloride Mass Balance approach (Eriksson and Khunakasem, 1969). These are generally low, ranging between 0–2 mm/year for most samples barring the anomalously fresh sample Upland-1 with an estimate of 13.1 mm/year. The one sample from the unconsolidated aquifer of the Coastal Plain region has a very low recharge rate estimate of 0.13 mm/year, reflective of the low rainfall in this region. This indicates that modern recharge into this aquifer is very low to minimal. These ranges in recharge are similar to those estimated by Risby and Harrington (2014) for wells in the Cleve Hills region. Note that these estimates should be treated as the absolute minimum recharge rates to be expected in this region.

Regional scale work involved sampling in and amongst the Kimba/Cleve hills and the adjacent palaeovalleys (Figure 8) and was conducted to characterise groundwater sourced from Tertiary sand aquifers and fractured rock aquifers (see Figure 2) that may be a potential industry water source. This area also has existing airborne electromagnetic (AEM) surveys and investigations including drilling by Archer Exploration. The combination of groundwater investigations coupled with interpretation of the AEM and drilling by Archer has contributed to a conceptual hydrogeological understanding at local to regional scales for the hills area. Wells were sampled in a transect along the northern boundary of the study area (shown in Figure 8) from the Cleve hills east towards the Uranium SA coastal plain site. A separate transect was sampled in the east of the study area, moving south from the Hills and through the palaeovalleys towards Arno Bay.

A final field trip sampled an additional four wells within the AEM survey around Kimba/Darke Peak, to gain a better understanding of the Tertiary sand aquifers and fractured rock aquifers. Target sites where access had been granted and groundwater infrastructure confirmed is shown in orange in Figure 8. In addition, a few more samples were collected at Uranium SA from coastal plain aquifers adjacent the Kanaka Bed Sands to help with the interpretation of connectivity between aquifers, and a shallow sample from the Quaternary formation as well as a seawater sample to help interpret the location of the groundwater/seawater interface.

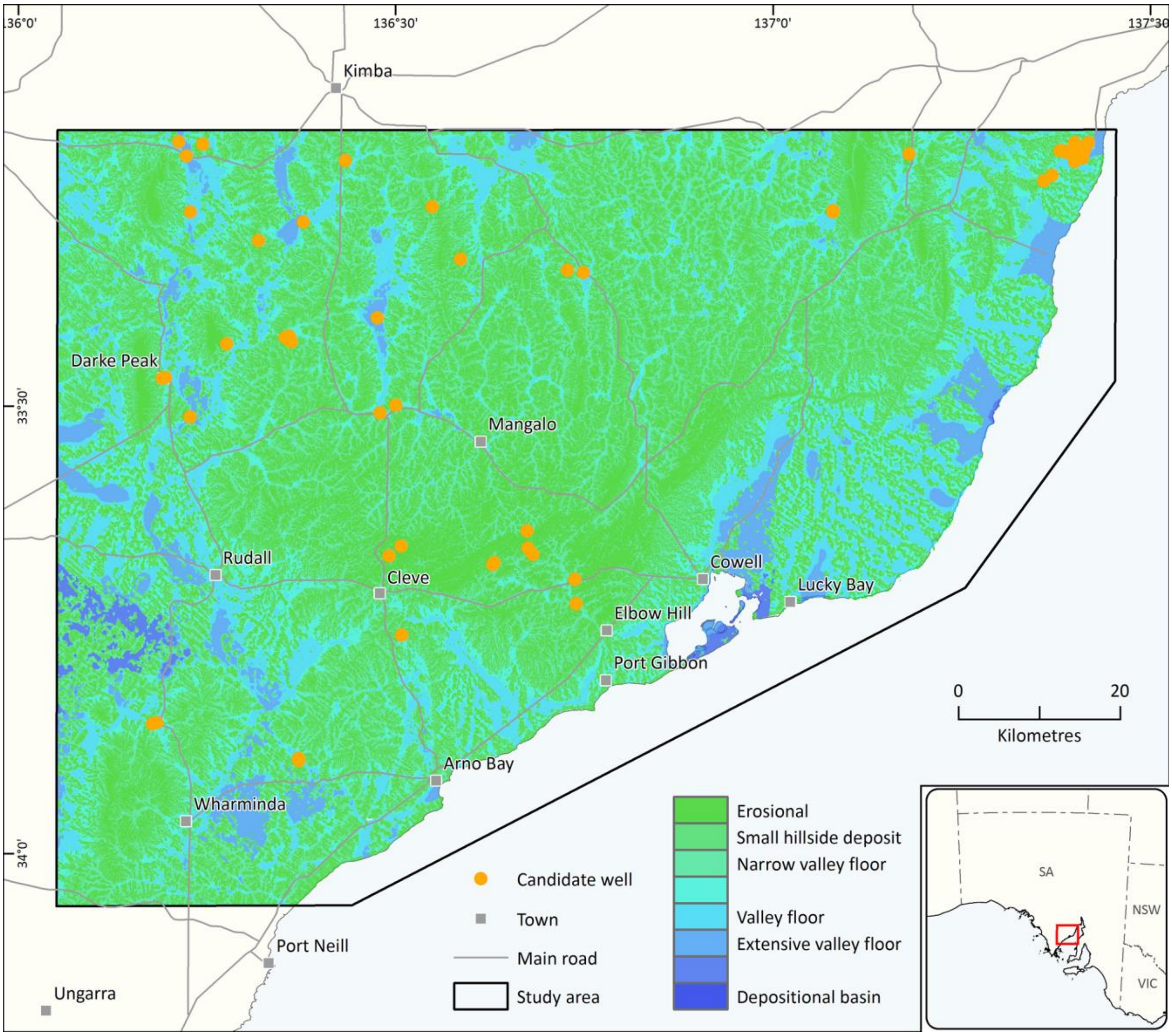

Figure 8 – North east Eyre Peninsula case study areas, showing candidate wells for sampling. Background is surface topography (MrVBF) that shows low flat parts on the landscape in darker blue

The field program successfully accessed and sampled 27 groundwater sites and two surface water sites across both industry and private land and has submitted ~300 samples for laboratory analysis. Laboratory analysis includes major ion chemistry, stable isotope composition (§^{2}H and §^{18}O), tritium (^{3}H), anthropogenic gas tracers (chlorofluorocarbons (CFC-11 and CFC-12) and sulfur hexafluoride (SF_6)), strontium isotopes (^{87}Sr/^{86}Sr), carbon isotopes (^{14}C and ^{13}C) and noble gases (^{3}He, ^{4}He, ^{20}Ne, ^{40}Ar, Kr, Xe). More details on the findings of this part of the project are found in Taylor *et al.* (2015a).

2.4 Deliverable 4: Hydraulic characteristics and aquifer connectivity

Cleve Hills

The case study area in the north eastern Eyre Peninsula is geologically complex with a diverse range of hydrogeological settings. Fractured rock aquifers in conjunction with shallow Quaternary units are common features of the Cleve Uplands and Quaternary-Tertiary units of the coastal fringe are typical of many unconfined-confined groundwater settings. Within the complex Uplands areas, aquifer extent is limited by bedrock topography, and no regional scale systems are identifiable. Unlike many other parts of South Australia, no large scale sedimentary aquifer systems exist. Lenses of groundwater commonly exist as smaller scale (<10 km) bodies with flow direction driven by variations in the water table. Surficial sedimentation over geologically very old bedrock is quite variable, with varying weathering depths of sub-surface rocks across the region of about 50 +/– 100 metres. This presents itself as a defining factor in the characterisation of much of the vertical hydrogeology, as confining units appear to be discontinuous.

The study region presents as one of the most complex of hydrogeological settings possible and therefore difficult to characterise. The infrastructure needed to identify the vertical and horizontal extents of aquifers is lacking in this area. This absence of suitable data and useable infrastructure identified in this project is likely to be typical of much of the Eyre Peninsula that is outside the prescribed wells areas. This paucity of information makes it difficult to be specific about the impacts of any future increased development of resource use and its sustainable management.

A methodology combining classical groundwater hydrogeology, environmental tracers, geophysics and analytical modelling has been developed, which has been described in Taylor *et al.* (2015a). Of importance is the development of a detailed groundwater surface (water-table and potentiometric surface) map (Figure 9) that can provide important inferences about the scale, nature and behaviour of the dominant groundwater flow systems in place.

In order to resolve the importance of local versus regional flow systems, the concentration of dissolved solutes and environmental isotopes along four transects were analysed adopting the methodology outlined in Love *et al.* (1993). Sampling regimes were based along three transects in the Cleve Hills region (transects A-A', B-B', and C-C') and one transect on the coastal margin at low elevation (Transect D-D') as shown in Figure 9.

Along the chosen transects in the Cleve Hills setting, the substantial variability and undulation in hydrochemistry suggests that local groundwater flow systems dominate over any regional groundwater flow-paths. There are also likely to be many discharge and recharge points in the landscape, which further complicates the interpretation of flow systems in this region. In the Cleve Hills setting, patterns in the environmental tracers are more consistent with local flow systems rather than regional ones throughout the entire study area. For example, the stable isotopes of water had a clearly visible altitude effect of 0.5‰ $\delta^{18}O$ per 100 m. Had there been only one regional flow system, this altitude effect would not be so pronounced as groundwater recharge at higher elevations would be found in discharge areas. Similarly, ^{14}C activity above background was found across the study area, which suggests that a significant fraction of the groundwater is recharged locally. Otherwise, and due to the low recharge rates, very little ^{14}C would be found in discharge areas. Environmental tracers confirm the notion of dominating local flow systems in the Hills region.

Results from hydrological modelling in the Cleve Hills setting (described in Appendix A of Taylor *et al.* 2015a) are in agreement with the presence of multiple local systems, with no identified flow-paths spanning the entire transect length. The main conclusion from the modelling here suggests that at reasonable depths to an impermeable base of the order of 100 m, the subsurface water flow cannot proceed along the entire transect.

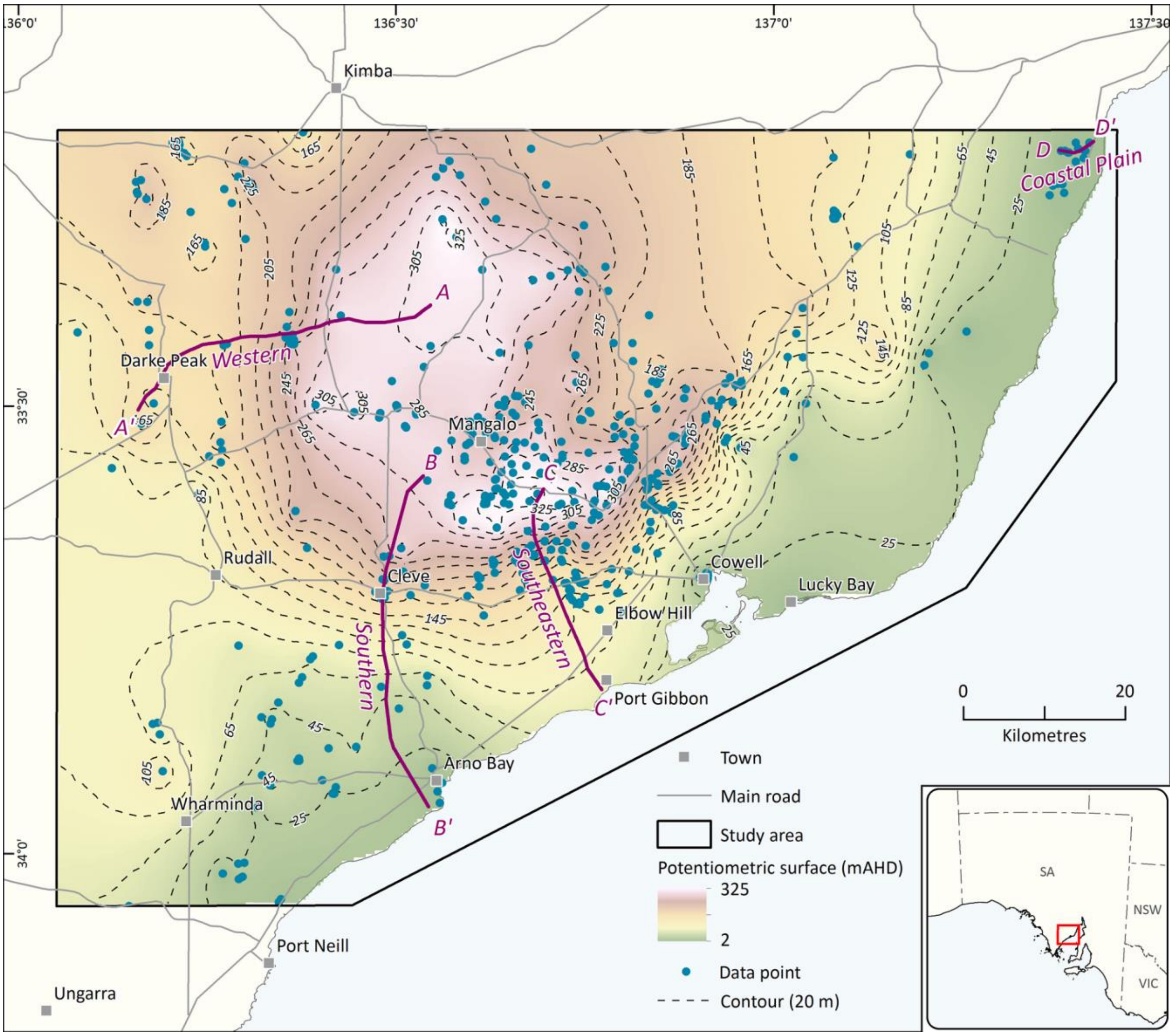

Figure 9 – Potentiometric groundwater surface estimate for north eastern Eyre Peninsula. Tracer analyses are undertaken along transects A-A', B-B', C-C', and D-D'.

Coastal Plain

The coastal plain appears to display groundwater flow characteristics more typical of an unconfined aquifer above a confined aquifer system. Its water table does not show undulations like that of the Cleve Hills, suggesting that regional flow dominates over local flow. The hydraulics of the coastal confined aquifer consist of a component of regional horizontal flow, with a degree of vertical downward inter-aquifer leakage from the quaternary unconfined aquifer. Environmental tracers also provide evidence for vertical inter-aquifer leakage between the confined and unconfined aquifers in the coastal plain, with ^{14}C concentrations in the confined aquifer typical of younger groundwater supporting this conceptualisation.

2.5 Deliverable 5: Interpreted AEM datasets

Local scale AEM data sets have been employed to develop hydrogeological conceptual models to support a regional scale water resources assessment. The work required the reprocessing of multiple historical AEM data sets, including those acquired by several different AEM systems including the TEMPEST (a fixed-wing time domain EM system), HOISTEM, REPTEM and VTEM (helicopter time domain EM systems) systems. This aspect of the project's work is described in Ley-Cooper *et al*. (2015a). It was critical to consider the different AEM system characteristics in order to achieve higher levels of consistency across the study area to provide a regional perspective.

The project has been very successful in gaining access to essentially all of the airborne electromagnetic (AEM) datasets across the northern Eyre Peninsula (Figure 10). The work of CSIRO Mineral Resources is highly regarded with good links to industry, companies and government agencies. The inversion of these data was completed using a common approach with different systems. The project also secured additional DMITRE (now DSD) support for the acquisition of additional AEM data across an area of particular exploration interest in the northern part of the study area (including the Thurgla Palaeochannels and Paris silver deposit). This work was undertaken collaboratively with Investigator Resources, resulting in an Australian Stock Exchange (ASX) announcement recognising the collaboration with the G-FLOWS project.

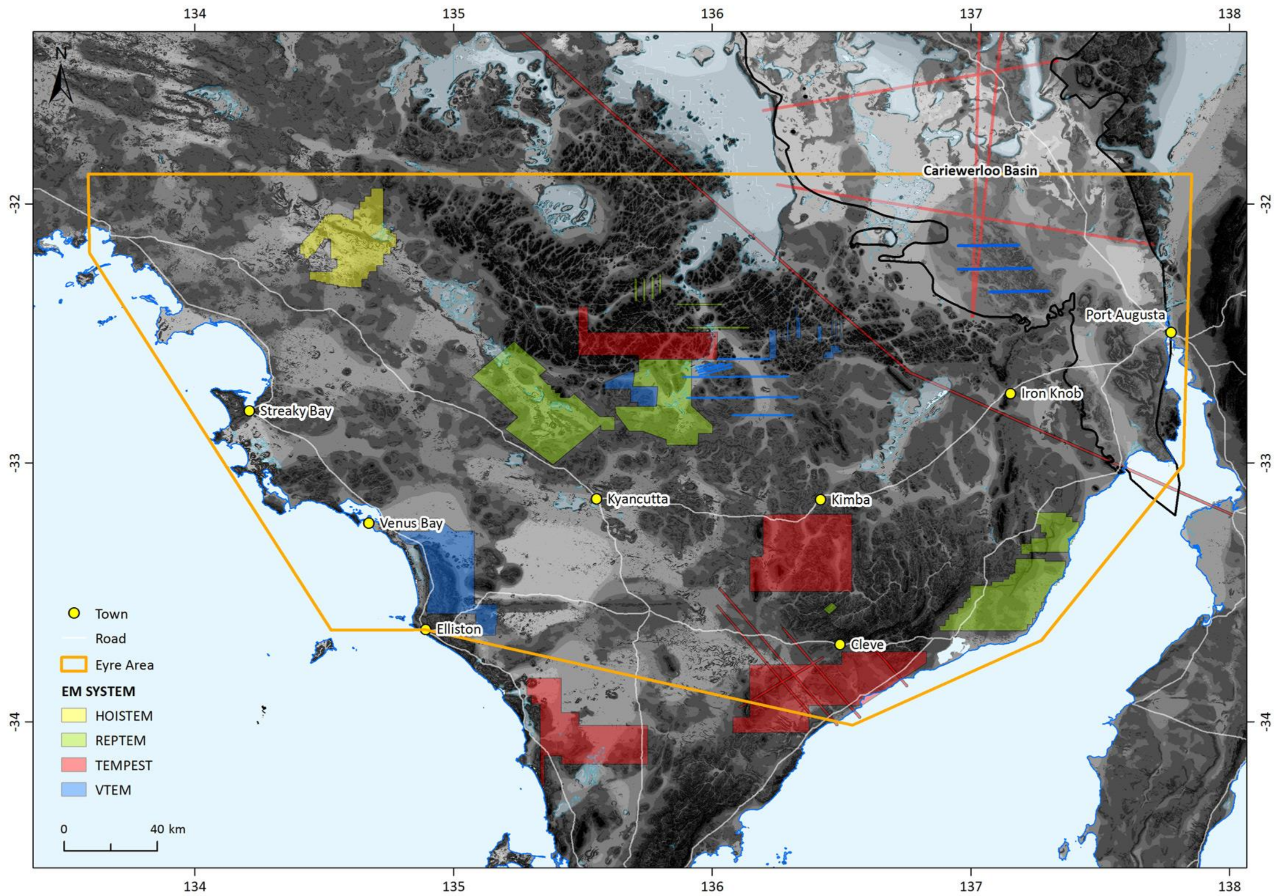

Figure 10 - Coloured areas and lines indicate the location and extent of airborne electromagnetic (AEM) survey data which has been brought together and used by the G-FLOWS Stage-2 project. Grey-scale background is a surface topography product (MrVBF) showing low flat areas as pale grey

Figure 11 illustrates the derived electrical conductivity models for the AEM coverage areas – which are shown in bright rainbow colours. In the example in Figure 11, the AEM conductivity models are for a depth interval of 20 metres below the ground surface. Higher conductivities are noted to largely coincide with low parts of the contemporary landscape. This includes: 1) valleys that contain a conductive fill (typically fine textured material such as clays), and 2) effect of coastal seawater (e.g. Pirie Basin sediments on the east coast shows a red fringe).

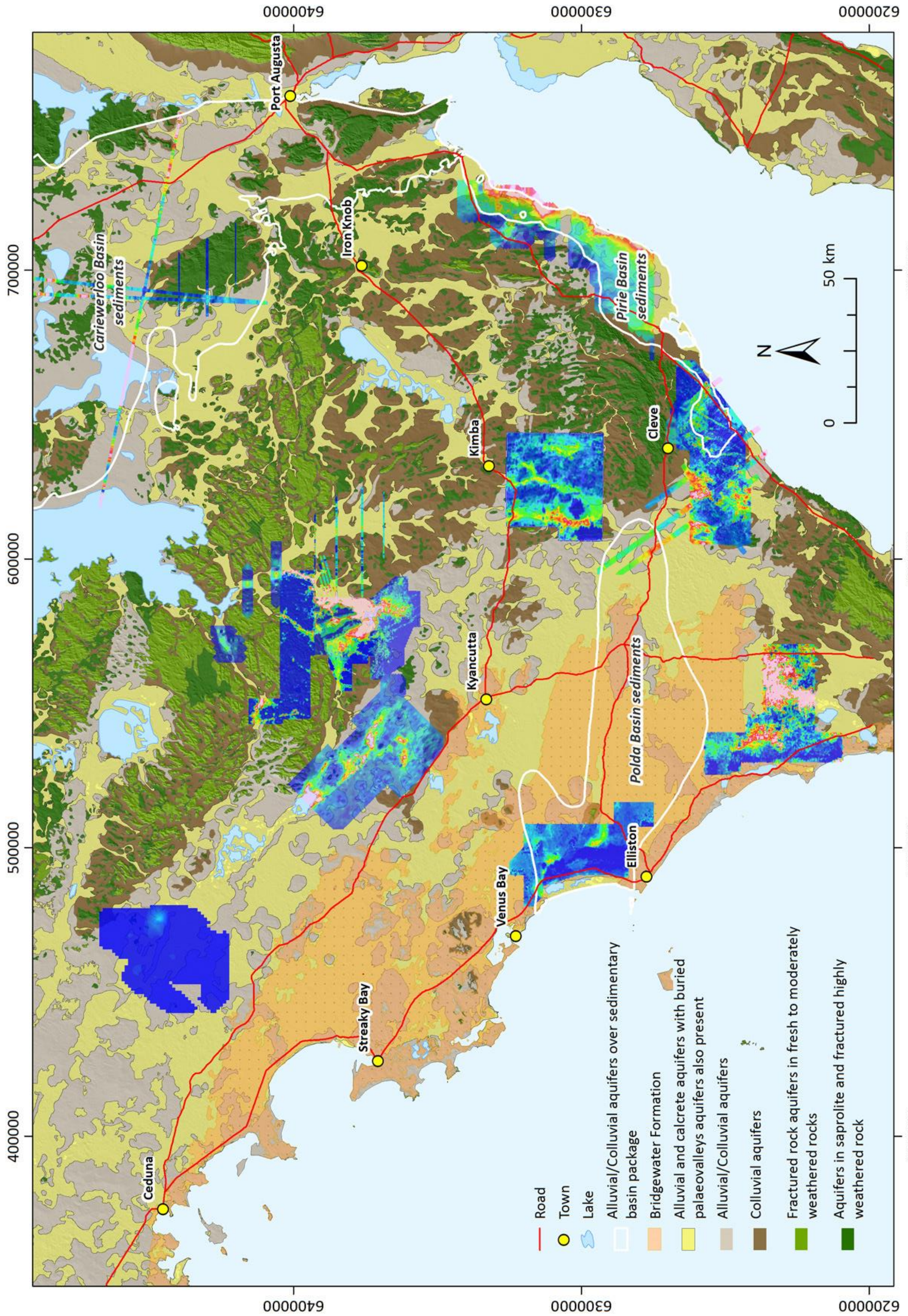

Figure 11 - Sliced layers showing the inverted AEM data for the northern Eyre Peninsula. The background is the hydrogeological framework as informed by surface topography analysis. The AEM areas are on a rainbow colour scale from lower-conductivity (violet/blue) up to higher conductivity (red/pink)

In parts of the Eyre Peninsula, palaeovalleys have groundwater resource potential. The AEM coverage in the NW Cleve Hills area (see “A” in Figure 12) reveals strong north-south pattern in the electrical conductivity. This reflects the orientation of the basement geology and shows the spatial extent of electrically conductive palaeovalleys (green to orange/red areas near “A” in Figure 12) that contrasts with the blue areas (subcropping and outcropping of the basement rock). The AEM coverage in the east part of the area (see “B” in Figure 12) shows the high electrical conductivity (pink-red) zone showing coastal influence from seawater.

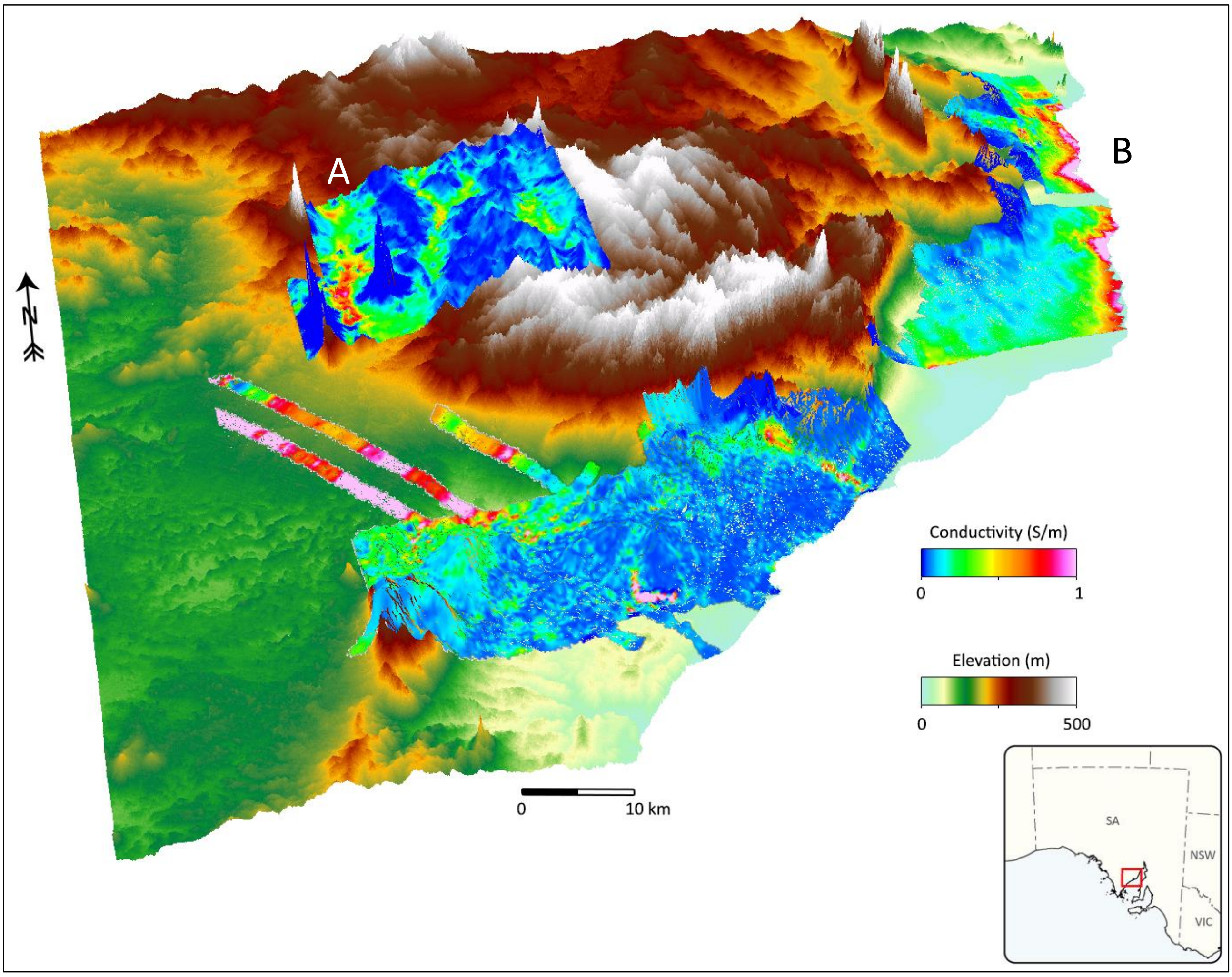

Figure 12 - Depth slice (at 20 m below ground surface) of areas of inverted AEM in the Cleve Hills case study area superimposed onto land surface topography. Note A: north west Cleve Hills AEM, B: seawater impact near coast.

2.6 Deliverable 6: Final Report

This report is the final deliverable:

- Gilfedder M, Munday T, Bestland E, Cahill K, Davies PJ, Davis A, Heinson G, Ibrahimi T, Lamontagne S, Ley-Cooper Y, Love A, Olifent V, Pichler M, Robinson N, Smith S, Sørensen C, Suckow A, Taylor AR, Thompson J, Annetts D (2015) *Facilitating Long-term Outback Water Solutions (G-FLOWS Stage-2) Final Report*. Goyder Institute for Water Research Technical Report Series No. 15/49, Adelaide.

3 Summary & Conclusions

The G-FLOWS Stage-2 Project has achieved its objectives. The project focused on areas of the northern Eyre Peninsula in South Australia, and made scientific advances using a range of methods to enhance the understanding of water resources in the arid zones of South Australia. Key aspects of the work undertaken in G-FLOWS Stage-2 include:

- Application to the northern Eyre Peninsula of the hydrogeological framework developed as part of G-FLOWS Stage-1 (Munday *et al*. 2013), which combines and interprets multiple datasets from industry and government to help target finer-scale assessment of groundwater resources (see Figure 2);
- Application and further development of a range of approaches and techniques for interpretation and use of airborne geophysics to provide information on hydrogeology and groundwater:
    - Hydrogeophysical (AEM, NMR) (e.g. Davis *et al*. 2015, Ley-Cooper *et al*. 2015c, Sørensen *et al.* 2014 online);
    - Groundwater conceptual understanding through use of isotopes/tracers (groundwater age and chemistry measurements) in the Cleve Hills part of the northern Eyre Peninsula (Taylor *et al.* 2015a, 2015c, Olifent 2014, Thompson 2014), which highlights the complexity of this area and suggests that local groundwater flow system processes are dominant in the region.
    - Successful application and further development of the processing and inversion strategy (Ley-Cooper *et al.* 2015a, 2015b) for employing overlapping historical and contemporary EM data affected by system uncertainties and errors.
- Extensive communication of scientific results to a wide range of stakeholders and audiences, which included:
    - Many presentations and posters at industry workshops, scientific conferences, meetings of professional associations, and at universities.
    - Publications in international journals, trade journal, science magazine
- Close collaboration and goodwill with data exchange between mineral companies and stakeholders, including government agencies.

4 Recommendations

The work undertaken in the northern Eyre Peninsula as part of G-FLOWS Stage-2, could be built on in the following ways with future efforts:

1) Examine potential of combined regional geophysical (AEM) and surface (regolith) datasets as a means of up-scaling spatial patterns of groundwater recharge, which includes on-ground follow up to improve and validate the hydrogeological framework.

2) Continued verification of AEM data through comparison with multiple lines-of-evidence, including :
    a. Ground-based geophysical data at representative locations
    b. Groundwater salinity data compared with AEM-derived conductivity patterns

3) Undertake additional work to apply the piloted Markov chain Monte Carlo (McMC) analysis of AEM data to inform hydrogeological modelling. This could include the following:
    a. Use McMC to identify different sources of uncertainty (e.g. conceptual model uncertainty, parameter uncertainty, etc.).
    b. Develop a program of work to systematically reduce key sources of uncertainty.
    c. Develop McMC version for parallel computing to better address computational limitations

4) Work towards using inverted AEM datasets to provide detailed 3D geometry as part of geological and groundwater model development.

5) Link spatial understanding of hydraulic parameter variation (from remotely sensed techniques such as NMR) to inform hydrogeological modelling.

6) Extend and link existing recharge investigations across the Eyre Peninsula to assess geographic influence, as well as undertake finer-scale groundwater investigations in priority areas for exploration and potential mine development, combining local scale recharge studies linked to finer scale, targeted geophysical data acquisition (air and ground), groundwater model development and groundwater resource estimation.

5 Publications from G-FLOWS during Stage-2

G-FLOWS has published and presented the results of its research to a wide variety of audiences. Table 1 summarises the output from the project to-date.

Table 1 – Publications arising from G-FLOWS during Stage-2 of the project

Journal Paper

Davis AC, Dlugosch R, Quietsch M, Macnae JC, Stolz R, Müeller-Petke M (2014) First evidence of detecting surface nuclear magnetic resonance signals using a compact B-field sensor. *Geophysical Research Letters* 41(12): 4222-4229.

Ley-Cooper AY, Viezzoli A, Guillemoteau J, Vignoli G, Macnae J, Cox L, Munday T (2015c) Airborne electromagnetic modelling options and their consequences in target definition. *Exploration Geophysics* 46:74-84. doi:10.1071/EG14045

Sørensen CC, Munday T, Heinson G (online early – Dec 2014) Integrated interpretation of overlapping AEM datasets achieved through standardisation. *Exploration Geophysics* online early. DOI: http://dx.doi.org/10.1071/EG14066

Trade Journal

Munday T, Gilfedder M, Taylor AR, Ibrahimi T, Ley-Cooper Y, Cahill K, Smith S, Costar A (2015a) The role of airborne geophysics in facilitating long-term outback water solutions to support mining in South Australia. *Water* 42(2), 138-141.

Honours Thesis

Olifent V (2014) *Salinity sources and recharge processes in the Cleve Uplands groundwater system, Eyre Peninsula, South Australia*. BSc (Hons) unpublished thesis. School of the Environment (Faculty of Science and Engineering), Flinders University of South Australia.

Thompson J (2014) *Hydrogeological characterisation of sedimentary and fractured rock groundwater in the eastern Eyre Peninsula, South Australia*. BSc (Hons) unpublished thesis. School of the Environment (Faculty of Science and Engineering), Flinders University of South Australia.

Technical Report

Gilfedder M, Munday T, Bestland E, Cahill K, Davies PJ, Davis A, Heinson G, Ibrahimi T, Lamontagne S, Ley-Cooper Y, Love A, Olifent V, Pichler M, Robinson N, Smith S, Sørensen C, Suckow A, Taylor AR, Thompson J, Annetts D (2015) *Facilitating Long-term Outback Water Solutions (G-FLOWS Stage-2) Final Report*. Goyder Institute for Water Research Technical Report Series No. 15/49, Adelaide, South Australia.

Ley-Cooper AY, Munday T, Gilfedder M, Ibrahimi T, Annetts D, Cahill K (2015a) *Inversion of legacy airborne electromagnetic datasets to inform the hydrogeological understanding of the northern Eyre Peninsula, South Australia*. Goyder Institute for Water Research Technical Report Series No. 15/x, Adelaide, South Australia.

Taylor AR, Pichler MM, Olifent V, Thompson J, Bestland E, Davies PJ, Lamontagne S, Suckow A, Robinson N, Love A, Munday T (2015a) *Groundwater Flow Systems of North-eastern Eyre Peninsula (G-FLOWS Stage-2): Hydrogeology, geophysics and environmental tracers*. Goyder Institute for Water Research Technical Report Series No. 15/37, Adelaide, South Australia.

Conference Abstract/Presentation

Davis A (2015a) Surface NMR Processing and Inversion – I: Noise Cancellation. In *proceedings of MRS 2015, 6th International Workshop on Magnetic Resonance*, Aarhus, Denmark, 8-10 June 2015.pp4.

Davis A (2015b) Surface NMR Processing and Inversion – II: Data Fitting. In *proceedings of MRS 2015, 6th International Workshop on Magnetic Resonance*, Aarhus, Denmark, 8-10 June 2015. pp2.

Davis A (2015c) Surface NMR Processing and Inversion – III: Inversion. In *proceedings of MRS 2015, 6th International Workshop on Magnetic Resonance*, Aarhus, Denmark, 8-10 June 2015. pp3.

Davis AC, Müeller-Petke M, Dlugosch R, Quietsch M , Macnae J, Stolz R (2015a) First evidence ofT2* in SNMR measurements with SQUID sensors. *ASEG Extended Abstracts 2015*, 1–3.

http://dx.doi.org/10.1071/ASEG2015ab239

Ley-Cooper AY, Salama W, Munday T, Anand R, González Alvarez I, Spinks S, Gilfedder M (2015b) Advances in Electromagnetic (EM) interpretation. In *proceedings of SAGA-2015, 14th Biennial Geophysical Conference*, 6–9 September 2015, Drakensberg, South Africa. pp4. **[KEYNOTE PRESENTATION]**

Munday T (2015) Cover, water and exploration in the Musgrave Province, South Australia. *Unlocking South Australia's Mineral Wealth Technical Forum 2015, South Australian Resources and Energy Investment Conference (SAREIC)*, 15 April 2015, Adelaide

Munday T, Gilfedder M (2013) Facilitating long-term outback water solutions to support mining in South Australia – The Goyder Institute's FLOWS Project. *7th Annual Mining South Australia*, 26-27 November 2013, Whyalla, SA.

Munday T, Gilfedder M (2015) Geophysical investigations and information available for both exploration and hydrogeology; Examples from the Eyre Peninsula and Musgrave Province, SA. *Hydrogeology in Mining Conference*, May 1 2015, North Adelaide: SA Branch of Australian Institute of Geoscientists.

Munday T, Gilfedder M, Taylor AR, Ibrahimi T, Ley-Cooper Y, Cahill K, Smith S, Costar A (presented by Neil Power) (2015b) Finding Long-term Outback Water Solutions (G-FLOWS). Presentation at *Goyder Institute Annual Conference* 17-18 Feb 2015.

Olifent V, Bestland E, Taylor AR, Pichler M, Love A (2015) Flowpaths, salinity sources and recharge processes in the Cleve Uplands groundwater system, Eyre Peninsula, South Australia. Presentation at *Goyder Institute Annual Conference* 17-18 Feb 2015.

Taylor AR, Leaney FW, Harrington GA, Jolly ID, Davies PJ, Munday T, Gilfedder M (2015b) Environmental tracers: useful indicators of recharge processes in a remote arid region – Musgrave Province South Australia. *Hydrogeology in Mining Conference*, May 1 2015, North Adelaide: SA Branch of Australian Institute of Geoscientists.

Davis A, Munday T, Parsekian A, Grombacher D, Cahill K, Flinchum B (2015b) Combining geophysical datasets for determining groundwater resource potential linked to remote communities in the APY lands, SA. Abstract, *Australian Groundwater Conference 2015*, 3-5 November 2015, Canberra.

Taylor AR, Pichler MM, Olifent V, Davies PJ, Suckow A, Lamontagne S, Love A (2015c) A multi-disciplinary approach to characterising groundwater flow systems in the Cleve Hills: Eyre Peninsula, South Australia. Abstract, *Australian Groundwater Conference 2015*, 3-5 November 2015, Canberra.

Munday T, Gilfedder M, Taylor A, Ley-Cooper Y, Ibrahimi T, Love A, Bestland E (2015c) Working with the minerals industry in facilitating outback water solutions for remote parts of South Australia: The Goyder Facilitating Long-Term Outback Water Solutions (GFLOWS) Projects. Abstract *Australian Groundwater Conference 2015*, 3-5 November 2015, Canberra. **[KEYNOTE PRESENTATION]**

Munday TJ, Davis AC, Gilfedder M, and Annetts D (2015d) Regional scale groundwater resource assessment in the Australian outback - Geophysics is the only way. Invited presentation at AGU Fall Meeting, December 2015, San Francisco USA.

Conference Poster

Davis AC, Müeller-Petke M, Dlugosch R, Quietsch M , Macnae J, Stolz R (2015) First evidence ofT2 SNMR measurements with SQUID sensors. *Poster Session F01. MRS 2015, 6th International Workshop on Magnetic Resonance*, Aarhus, Denmark, 8-10 June 2015.

Taylor AR, Leaney FW, Harrington GA, Jolly ID, Davies PJ, Munday T, Gilfedder M (2014) Environmental tracers: useful indicators of recharge processes in a remote arid region – Musgrave Province South Australia. *Proceedings of the Waite Campus Conference & Exhibition*; 22 August 2014; Waite Campus, Urrbrae: CSIRO.

Magazine Article

Williams T (2015) Outback water: in search of underground oases. *Ecos Magazine* 211, September 2015. Available from: https://blogs.csiro.au/ecos/outback-water-in-search-of-underground-oases/

SUBMITTED Journal Manuscript

Sørensen et al. (submitted) Optimising inversion parameters for resolving fine scale conductivity variations in AEM data. For consideration by the Journal of Applied Geophysics.

Sørensen et al. (submitted) Standardisation of a prospect scale AEM dataset using wide line spaced regional AEM data. For consideration by Near Surface Geophysics.

Ley-Cooper AY, Salama W, Munday T, Anand R, González Alvarez I, Anand R, Gilfedder M (submitted) Advances in interpretation of airborne electromagnetics. For consideration by Exploration Geophysics.

Appendix A G-FLOWS Stage-2 Milestones

Apx Table A.1 - List of milestones for each task in G-FLOWS Stage-2.

Milestone Number	Milestone Description	Participant	Start Date	Delivery Date
Task 1 - Data mining, collation and dissemination				
1.1.C	Data mining and collation	CSIRO	Nov 13	Mar 14
1.2.C	Data derived and disseminated	CSIRO	Apr 14	May 15
Task 2 – Groundwater flow systems analysis				
2.1.C	Review and case study identified	CSIRO	Nov 13	Nov 13
2.2.C	Field sampling	CSIRO	Dec 13	Jul 14
2.3.C	Analysis of samples	CSIRO	Aug 14	Sep 14
2.4.C	Task 2 Report Groundwater recharge sections	CSIRO	Oct 14	Apr 15
2.1.F	Review and case study identified	Flinders	Nov 13	Nov 13
2.2.F	Mapping and Field Trip	Flinders	Dec 13	Jul 14
2.3.F	Develop conceptual model	Flinders	Aug 14	Sep 14
2.4.F	Task 2 Report Evaluation of GFS	Flinders	Oct 14	Apr 15
Task 3 - Hydrogeophysical data processing and interpretation				
3.1.C	Review and case study identified	CSIRO	Nov 13	Nov 13
3.2.C	FLOWS 1 Inversion	CSIRO	Dec 13	Apr 14
3.3.C	Bayesian Inversion	CSIRO	May 14	Jul 14
3.4.C	Conceptual model development	CSIRO	Aug 14	Apr 15
Task 4 - Hydrogeophysical technique development				
4.1.C	TEM & NMR technique	CSIRO	Nov 13	Jul 14
4.2.C	Statistical AEM Technique	CSIRO	Aug 14	Apr 15
4.1.UA	Statistical AEM Technique	Uni of Adelaide	Nov 13	Jul 14
4.2.UA	Journal paper	Uni of Adelaide	Aug 14	Sep 14
Task 5 - Improved groundwater understanding & project management				
5.1.C	Startup	CSIRO	Nov 13	Dec 13
5.2.C	Closure Report	CSIRO	Jan 14	May 15

Appendix B G-FLOWS Stage-2 Tasks and Deliverables

Appendix B presents the objectives, milestones and deliverables for each of the five tasks in G-FLOWS Stage-2, to provide an overview of the project.

B.1 Task 1: Data mining, collation and dissemination

TASK LEADER: Tania Ibrahimi (CSIRO)

B.1.1 OBJECTIVES

1.1 Identify key industries involved in activities in the study area and work with G-FLOWS Stage-2 Task Leaders to secure a range of relevant geophysical, geological and hydrogeological data pertinent to the goals of the G-FLOWS Stage-2 Project. Develop appropriate non-disclosure agreements with industry Stakeholders as required. This will involve liaison with DMITRE.
1.2 Liaise with Government agencies and access/licence key datasets.
1.3 Collate data from disparate sources into a project GIS/database and circulate to Task Leaders and DEWNR (subject to any confidentiality arrangements).
1.4 Collate derived data and information as the project progresses (links to Tasks 2, 3, and 4 in particular). Ensure appropriate metadata is supplied with all collated and derived data sets developed during the project.
1.5 Liaise with State Government agencies and supply derived project outputs/data in an appropriate form.
1.6 Liaise with Stakeholders and supply derived products consistent with non-disclosure agreements.

B.1.2 MILESTONES

Milestone Number	Milestone Description	Participant	Start Date	Delivery Date
Task 1 - Data mining, collation and dissemination				
1.1.C	Data mining and collation	CSIRO	Nov 13	Mar 14
1.2.C	Data derived and disseminated	CSIRO	Apr 14	May 15

B.1.3 DELIVERABLES/OUTPUTS

1.1, 1.2, 1.3	Geophysical and related hydrogeological data collated
1.4	Ongoing derived data storage, and archiving with appropriate state agencies as per agreements
1.5, 1.6	Distribution of derived products through Tasks and with State Agencies as per agreements

1.1, 1.2, 1.3	YES – Figure 10 shows areas/lines
1.4	YES - the derived data has been sent to DSD
1.5, 1.6	YES - the derived products have been distributed and presented

B.1.4 SUMMARY

- The project has been very successful in gaining access to essentially all of the airborne electromagnetic (AEM) datasets across the northern Eyre Peninsula (see Figure 10).
- The inversion of these data was completed using a common approach with different systems. [Objectives 1.1, 1.2, 1.3].
- The inverted data from the northern Eyre Peninsula Area has been provided to DSD (Geological Survey of South Australia). DSD is in the process of assessing the data against confidentiality requirements, following that, may make it publically available in the SARIG database in due course. [Objectives 1.4, 1.5]
- The project's work in this area has been communicated to Stakeholders and State Government Agencies through presentations at Technical Forums and Mining Conferences (e.g. SAREIC 2015, Mining SA 2013, Hydrology in Mining Conference 2015, etc.) as well as a final project agency briefing workshop at DSD (August 6 2015, Adelaide) [Objectives 1.5, 1.6].

B.2 Task 2: Groundwater flow systems analysis

TASK LEADER: Andy Love (Flinders)

B.2.1 OBJECTIVES

2.1 Review background geologic and available hydrogeologic data from publically available data sources and industry Stakeholders to determine potential locations for groundwater sampling to characterise recharge/discharge processes. Complete an inspection of potential groundwater sampling locations in a reconnaissance field trip. Prepare and present justification for case-study selection (with Task 3.1) to project steering committee in early December 2013.

2.2 Groundwater sampling field trips. Based on findings of the reconnaissance field trip, researchers would revise the scope of field sampling. Arrange landowner access in collaboration with DEWNR and industry Stakeholders. Liaise with DEWNRs sampling program to achieve a more comprehensive dataset for the EPNRM Region.

2.3 Groundwater-flow-system (GFS) mapping, including analysis of water level and salinity data from the groundwater observation network and other sources. Develop conceptualisations of groundwater flow system connectivity. This mapping exercise will cover all focused sites.

2.4 Analyse and interpret sample results (groundwater chemistry and isotopes) in conjunction with information on the geological setting and geophysical data (Tasks 3 and 4) to determine spatially distributed groundwater recharge/discharge and infer groundwater fluxes from environmental (age) tracers. Contribute to the development of a hydrogeological conceptual model for the study area with Task 3.

B.2.2 MILESTONES

Milestone Number	Milestone Description	Participant	Start Date	Delivery Date
Task 2 – Groundwater flow systems analysis				
2.1.C	Review and case study identified	CSIRO	Nov 13	Nov 13
2.2.C	Field sampling	CSIRO	Dec 13	Jul 14
2.3.C	Analysis of samples	CSIRO	Aug 14	Sep 14
2.4.C	Task 2 Report Groundwater recharge sections	CSIRO	Oct 14	Apr 15
2.1.F	Review and case study identified	Flinders	Nov 13	Nov 13
2.2.F	Mapping and Field Trip	Flinders	Dec 13	Jul 14
2.3.F	Develop conceptual model	Flinders	Aug 14	Sep 14
2.4.F	Task 2 Report Evaluation of GFS	Flinders	Oct 14	Apr 15

B.2.3 DELIVERABLES/OUTPUTS

2.1 CASE STUDY AREAS IDENTIFIED. Case study areas identified, and draft report sections written to outline background literature, maps, and sampling procedure. Justification of the selection process, stakeholder feedback, geophysical data availability, presentation and sign-off from Project Steering Committee required (in conjunction with Task 3.1). [early Dec 2013]

2.2 FIELD TRIP PLAN: documented outcome of reconnaissance trip incorporated into briefing that outlines the specific transects of wells/bores to be sampled and expected outcome from analysis of tracers and other groundwater data (i.e. the rationale for sampling). Methodology developed for mapping recharge and discharge zones based on hydraulic head data and naturally occurring hydrogeological features.

2.3 GROUNDWATER FLOW SYSTEM CONCEPTUALISATION: developed from background literature and analysis of groundwater data, which will provide an interpretation of the degree of groundwater recharge, depth of circulation, aquifer connectivity and groundwater flow rates. Links to Task 3 with interpretation of results from aquifer characterisation information from AEM.

2.4 TASK REPORT and Draft RESEARCH PAPER: Samples analysed and results obtained:
- TASK REPORT completed with results, implications, and conclusions (FUSA/CSIRO).
- FINAL REPORT sections as required to contribute to project delivery.
- Draft Research paper: Bestland et al. Groundwater flow paths in the Gawler Ranges determined from strontium isotopes and other environmental Tracers;

2.1 CASE STUDY AREAS IDENTIFIED. YES – sign off in January 2014

2.2 FIELD TRIP PLAN: YES – multiple field trips planned and conducted safely and successfully

2.3 GROUNDWATER FLOW SYSTEM CONCEPTUALISATION: YES – Taylor *et al.* (2015a) Task 2 report.

2.4 TASK REPORT and Draft RESEARCH PAPER:
- YES – Taylor *et al.* (2015a) Task 2 report
- YES – Gilfedder *et al.* (2015) Final Report
- YES – Work has been presented at Australian Groundwater Conference (Taylor *et al.* 2015c), and journal papers are planned

B.2.4 SUMMARY

Objective 2.1 - Case study selection

Case study selection was approved by the Project Steering Committee and focuses on two areas in the north eastern part of the Eyre Peninsula (see Figure 4), as well as the broader region (part of Task 3.1):

1. Cleve Hills - Investigated localised aquifer connectivity and recharge with a study along a regional transects. The Task sampled bores along a broad litho-structurally controlled drainage line which heads south and east out of the Kimba/Cleve region, using existing AEM/magnetics (industry and State) coverages, and bore sampling.

2. Coastal Aquifer - This study used the recently constructed piezometer network on the coastal plain near Whyalla, and investigated the connection between coastal aquifer and the hinterland fractured rock.

Objective 2.2 - Field Work

An initial Task 2 field trip was affected by heavy prolonged rain (March/April) but provided opportunities to build links with Uranium SA, and landholders. The field component of the project was then rescheduled into three separate trips (July, August, September). This allowed more time to both negotiate access to more landholder properties, to and better review existing information.

The first two field trips involved sampling the Uranium SA site on the coastal plain near Whyalla, and in the Kimba/Darke Peak/Cleve Hills area (and adjacent palaeovalleys) (see Figure 4 for location). Regional scale work involved sampling in and amongst the Kimba/Cleve hills and the adjacent palaeovalleys (see Figure 8). The Project sampled wells along the northern transect from the Cleve hills east towards the Uranium SA site at the coast, and along the southern transect from the Hills through the palaeovalleys south towards Arno Bay.

During the final field trip in September the team was successful in sampling four more sites within the AEM survey around Kimba/Darke Peak, including a site adjacent the palaeovalley next to Carappee Hill, a site in the palaeovalley on the eastern side of the AEM survey and one of the water supply wells of Archer Exploration. In addition, a few more samples were collected at Uranium SA from aquifers adjacent the Kanaka Bed Sands to help with the interpretation of connectivity between aquifers, and a shallow sample from the Quaternary formation as well as a seawater sample to help interpret the location of the groundwater/seawater interface.

Objective 2.3-2.4

This work is described in detail in the technical report:

- Taylor AR, Pichler MM, Olifent V, Thompson J, Bestland E, Davies PJ, Lamontagne S, Suckow A, Robinson N, Love A, Munday T (2015a) *Groundwater Flow Systems of North-eastern Eyre Peninsula (G-FLOWS Stage-2): Hydrogeology, geophysics and environmental tracers*. Technical Report Series No. 15/37, Goyder Institute for Water Research, Adelaide.

Outputs from Task 2

Technical Reports:

- Taylor AR, Pichler MM, Olifent V, Thompson J, Bestland E, Davies PJ, Lamontagne S, Suckow A, Robinson N, Love A, Munday T (2015a) *Groundwater Flow Systems of North-eastern Eyre Peninsula (G-FLOWS Stage-2): Hydrogeology, geophysics and environmental tracers*. Technical Report Series No. 15/37, Goyder Institute for Water Research, Adelaide.

Conference presentations

- Taylor AR, Leaney FW, Harrington GA, Jolly ID, Davies PJ, Munday T, Gilfedder M (2015b) Environmental tracers: useful indicators of recharge processes in a remote arid region – Musgrave Province South Australia. *Hydrogeology in Mining Conference*, May 1 2015, North Adelaide: SA Branch of Australian Institute of Geoscientists.
- Olifent V, Bestland E, Taylor AR, Pichler M, Love A (2015) Flowpaths, salinity sources and recharge processes in the Cleve Uplands groundwater system, Eyre Peninsula, South Australia. Presentation at *Goyder Institute Annual Conference* 17-18 Feb 2015.

Conference poster

- Taylor AR, Leaney FW, Harrington GA, Jolly ID, Davies PJ, Munday T, Gilfedder M (2014) Environmental tracers: useful indicators of recharge processes in a remote arid region – Musgrave Province South Australia. *Proceedings of the Waite Campus Conference & Exhibition*; 22 August 2014; Waite Campus, Urrbrae: CSIRO.

Conference abstract accepted

- Taylor AR, Pichler MM, Olifent V, Davies PJ, Suckow A, Lamontagne S, Love, A (2015c) A multi-disciplinary approach to characterising groundwater flow systems in the Cleve Hills: Eyre Peninsula, South Australia. ABSTRACT. *Australian Groundwater Conference 2015*, 3-5 November 2015, Canberra.

Honours Theses

The project also provided excellent opportunity for student Honours project work. Both Vanessa Olifent and Jessica Thompson have been exemplary assistants in the field, providing great support and significant input to discussions surrounding sampling methods and uses of tracers in groundwater research. Each student has a defined area within the total G-FLOWS Stage-2 project from which to complete their characterisation, with one having focus on a coastal sedimentary setting and the other working on what is essentially a fractured rock system.

- Olifent V (2014) Salinity sources and recharge processes in the Cleve Uplands groundwater system, Eyre Peninsula, South Australia. BSc (Hons) unpublished thesis Supervisors Erick Bestland and Andrew Love School of the Environment (Faculty of Science and Engineering), Flinders University of South Australia.
- Thompson J (2014) Hydrogeological characterisation of sedimentary and fractured rock groundwater in the eastern Eyre Peninsula, South Australia. BSc (Hons) unpublished thesis Supervisor: Assoc. Prof. Erick Bestland and Assoc Prof Andrew Love, School of the Environment (Faculty of Science and Engineering), Flinders University of South Australia.

B.3 Task 3: Hydrogeophysical data processing and interpretation

TASK LEADER: Tim Munday (CSIRO)

B.3.1 OBJECTIVES

3.1 Review of existing geophysical data and assessment of data distribution for case study site selection. Prepare and present justification for selection to project steering committee (with Task 2.1) [early December 2013].

3.2 Application of methods developed in FLOWS-1, including the inversion and interpretation version of historical AEM data sets taking account of accurate system characterisation to enable their quantitative analysis, to develop conceptual hydrogeological models.

3.3 Trial and application of a stochastic approach to the 1D inversion of time-domain AEM data that provides not only a best fit model, but also information about the uncertainty and non-uniqueness using a Markov chain Monte Carlo method to perform Bayesian inference. The method may provide improved characterisation of aquifer systems and their variability. We would examine this in the context of aquifers that were well characterised and then extend the approach to other areas where information about aquifer character was less well understood.

3.4 Combined approach linking environmental tracer data and hydrogeophysics, in conceptual model development at an appropriate scale. This would require close interaction with Task 2. We seek to identify key areas for linked airborne, surface and sub-surface data analysis with other Task leaders. Attention will be paid to key geologic structures such as fracture trends, faults, and geologic discontinuities (identified from both magnetics and AEM), as potential areas where lateral and vertical connectivity may occur.

B.3.2 MILESTONES

Milestone Number	Milestone Description	Participant	Start Date	Delivery Date
Task 3 - Hydrogeophysical data processing and interpretation				
3.1.C	Review and case study identified	CSIRO	Nov 13	Nov 13
3.2.C	FLOWS 1 Inversion	CSIRO	Dec 13	Apr 14
3.3.C	Bayesian Inversion	CSIRO	May 14	Jul 14
3.4.C	Conceptual model development	CSIRO	Aug 14	Apr 15

B.3.3 DELIVERABLES/OUTPUTS

3.1 REPORT SECTIONS reviewing inversion procedures and inversion approach, including system descriptions, the latter determined by the data sets available in selected case study areas chosen.
3.2 REPORT SECTIONS describing results from application of FLOWS 1 methodology in developing physical hydrogeological models
3.3 PAPER describing Bayesian approach to inversion of AEM for aquifer characterisation
3.4 REPORT SECTIONS to support work in Task 2, and FINAL REPORT sections to support project delivery.

3.1 REPORT SECTIONS – YES – Section 7 in Taylor *et al.* 2015a (Task 2 Report),
- YES - Ley-Cooper *et al.* 2015a (Inversion report under review)
- YES - Ley-Cooper *et al*. 2015c (journal)

3.2 REPORT SECTIONS - YES – Section 7 in Taylor *et al.* 2015a (Task 2 Report),
YES –Munday & Gilfedder (2015) presentation abstract

3.3 PAPER – (Currently as REPORT) - Ley-Cooper *et al.* 2015a (Inversion report under review)
3.4 REPORT SECTIONS – YES – Section 7 in Taylor *et al.* 2015a (Task 2 Report),
- YES – Material in Gilfedder *et al.* 2015 (Final report)

Journal Papers

- Ley-Cooper AY, Viezzoli A, Guillemoteau J, Vignoli G, Macnae J, Cox L, Munday T (2015c) Airborne electromagnetic modelling options and their consequences in target definition. *Exploration Geophysics* 46:74-84. doi:10.1071/EG14045 [Deliverable 3.1]

Technical Reports

- Ley-Cooper AY, Munday T, Gilfedder M, Ibrahimi T, Annetts D, Cahill K (2015) *Inversion of legacy airborne electromagnetic datasets to inform the hydrogeological understanding of the northern Eyre Peninsula, South Australia*. Goyder Institute for Water Research Technical Report Series No. 15/50, Adelaide. [Deliverable 3.1, Deliverable 3.3 (report)]
- Contribution to Task 2 Technical Report (Taylor AR, Pichler MM, Olifent V, Thompson J, Bestland E, Davies PJ, Lamontagne S, Suckow A, Robinson N, Love A, Munday T (2015a) *Groundwater Flow Systems of North-eastern Eyre Peninsula (G-FLOWS Stage-2): Hydrogeology, geophysics and environmental tracers*. Technical Report Series No. 15/37, Goyder Institute for Water Research, Adelaide.) [Deliverable 3.1, 3.2, 3.4]

Conference presentations

- Munday T, Gilfedder M (2015) Geophysical investigations and information available for both exploration and hydrogeology; Examples from the Eyre Peninsula and Musgrave Province, SA. *Hydrogeology in Mining Conference*, May 1 2015, North Adelaide: SA Branch of Australian Institute of Geoscientists.
- Ley-Cooper AY, Salama W, Munday T, Anand R, González Alvarez I, Spinks S, Gilfedder M (2015b) Advances in Electromagnetic (EM) interpretation. *Proceedings of SAGA-2015, 14th Biennial Geophysical Conference*, 6–9 September 2015, Drakensberg, South Africa. ***[KEYNOTE PRESENTATION]***

B.3.4 SUMMARY

This task used a common processing and inversion (“calibration”) framework (developed in G-FLOWS Stage-1) for combining historical AEM data acquired from different systems over different dates in the northern Eyre Peninsula. The locations of the datasets are shown in Figure 11, and the hydrogeological framework developed is shown Figure 2.

This task also investigated alternative options for improving the process of inverting legacy AEM datasets, and this is reported in Ley-Cooper *et al*. (2015c). Some of this work is the process of being considered for publication in journals. In particular, note these two abstracts for Journal Papers that have been submitted:

Optimising inversion parameters for resolving fine scale conductivity variations in AEM data
Camilla Sørensen & Timothy Munday

Inversion of airborne electromagnetic (AEM) data is non-unique, and model outcomes are highly dependent on the approach taken. In this paper differences resulting from varying regularization parameters, and specifically the constraint on vertical conductivity profiles, are examined to define the impact it has on how well the subsurface structure can be resolved.

Data examples are from the Frome Embayment of South Australia, where transported sediments are host to sedimentary uranium mineralisation. In this area, subtle variations in ground conductivity linked to changes in the character of regolith cover have significance for a variety of reasons. These include the definition of layers or boundaries that could be employed in geochemical sampling as part of an exploration programme, and for defining groundwater quality in aquifers.

Individual soundings of TEMPEST data have been inverted with different vertical constraint and resulting conductivity models compared against borehole conductivity logs to establish appropriate inversion settings for the data. Borehole lithological logs have been used to verify that the optimisation of the vertical constraints resulted in improved conductivity-depth sections for TEMPEST AEM data acquired for both fine and regional-scale studies. This study confirms the importance of carefully considering the optimisation of inversion parameters for a particular survey.

Standardisation of a prospect scale AEM dataset using wide line spaced regional AEM data
Camilla Sørensen, Timothy Munday, Graham Heinson

A regional, fixed-wing time domain airborne electromagnetic (AEM) survey data set that overlaps a tenement scale helicopter time domain electromagnetic data set acquired at a finer scale (closer line spacing) has been used as a basis for standardizing the two data sets. The objective is to achieve spatially coherent, common conductivity-depth model, which might be used for improved hydrogeological mapping and groundwater quality definition.

Eleven lines of the regional (2.5km line spacing) Frome TEMPEST dataset, acquired by Geoscience Australia in 2010, form the basis for the standardisation of a 2007 tenement scale (1km line spacing) REPTEM dataset. Resistivity-depth models obtained from the full non-linear inversion of each TEMPEST sounding were forward modelled using the REPTEM system specifications to generate synthetic REPTEM model responses. A scaling factor necessary to bring the synthetic and measured REPTEM responses into agreement with the TEMPEST data was found for each REPTEM sounding on each of the eleven lines, and a mean scaling factor was derived.

The reinverted standardised REPTEM data provides resistivity-depth models which show good agreement with the TEMPEST models, particularly for the near surface, when compared to the non-standardised REPTEM models. The approach of using large pre-competitive AEM dataset already available in the public domain to standardise other AEM surveys has the logistical advantage of not needing to acquire new data for the standardisation. Furthermore it provides the possibility to increase knowledge of how the standardised datasets fit into a more regional picture.

B.4 Task 4: Hydrogeophysical technique development

TASK LEADER: Yusen Ley / Tim Munday (CSIRO)

B.4.1 OBJECTIVES

4.1 Develop and apply a statistically-based approach to EM system calibration employing limited field data. This sub-task will consider the value of ground geophysical time domain EM (TDEM) data for improving model resolution by comparing the AEM inversion models to models obtained from ground-based EM data.

4.2 Development and assessment of joint transient electromagnetic (TEM) and surface NMR methods for aquifer and groundwater characterisation in South Australian aquifer systems. This sub-task also affords the opportunity to examine new approaches to surface NMR data inversion using stochastic inversion methods. Comparison of surface and borehole NMR results to pump tests (primarily from industry) to calibrate NMR for soundings in production bore fields linked to a proposed mine would provide an ideal test site for the proposed work. Available data obtained from the hydraulic testing of aquifer systems can be directly compared to airborne EM and NMR data taken in the area. The definition of an empirical geostatistical relationship between AEM, NMR and hydraulic test data could then be applied to infer hydraulic properties of aquifers, which are outside the immediate area of existing drilling.

B.4.2 MILESTONES

Milestone Number	Milestone Description	Participant	Start Date	Delivery Date
Task 4 - Hydrogeophysical technique development				
4.1.C	TEM & NMR technique	CSIRO	Nov 13	Jul 14
4.2.C	Statistical AEM Technique	CSIRO	Aug 14	Apr 15
4.1.UA	Statistical AEM Technique	Uni of Adelaide	Nov 13	Jul 14
4.2.UA	Journal paper	Uni of Adelaide	Aug 14	Sep 14
Task 5 - Improved groundwater understanding & project management				
5.1.C	Startup	CSIRO	Nov 13	Dec 13
5.2.C	Closure Report	CSIRO	Jan 14	May 15

B.4.3 DELIVERABLES/OUTPUTS

4.1	PAPER describing statistical method for calibration of AEM data
4.2	PAPER describing stochastic inversion of NMR and TEM data linked to AEM investigations.

4.1	PAPER	- YES – Sørensen *et al.* (2014) PAPER
		- YES – components of Ley-Cooper *et al. (*2015a) (inversion report)
4.2	PAPER	- YES – Davis *et al*. (2014) Journal
		- YES – Davis (2015a,b,c) conference extended abstracts

B.4.4 SUMMARY

Journal Papers

- Davis AC, Dlugosch R, Queitsch M, Macnae JC, Stolz R, Muller-Petke M (2014) First evidence of detecting surface nuclear magnetic resonance signals using a compact B-field sensor. *Geophysical Research Letters* 41(12): 4222-4229. [Deliverable 4.2]
- Sørensen CC, Munday T, Heinson G (online early - Dec 2014) Integrated interpretation of overlapping AEM datasets achieved through standardisation. Exploration Geophysics online early. DOI: http://dx.doi.org/10.1071/EG14066 [Deliverable 4.1]

Conference Abstracts [all Deliverable 4.2]

- Davis A (2015a) Surface NMR Processing and Inversion – I: Noise Cancellation. In *proceedings MRS 2015, 6th Int. Workshop on Magnetic Resonance*, Aarhus, Denmark, 8-10 June. 4p.
- Davis A (2015b) Surface NMR Processing and Inversion – II: Data Fitting. In *proceedings MRS 2015, 6th Int. Workshop on Magnetic Resonance*, Aarhus, Denmark, 8-10 June. 2p.
- Davis A (2015c) Surface NMR Processing and Inversion – III: Inversion. In *proceedings MRS 2015, 6th Int. Workshop on Magnetic Resonance*, Aarhus, Denmark, 8-10 2015. 3p.
- Davis AC, Müeller-Petke M, Dlugosch R, Quietsch M , Macnae J, Stolz R (2015) First evidence ofT2* in SNMR measurements with SQUID sensors. *ASEG Extended Abstracts 2015*, 3p. http://dx.doi.org/10.1071/ASEG2015ab239

B.5 Task 5: Enhanced groundwater understanding for industry, community and environment

TASK LEADER: Mat Gilfedder (CSIRO) + Tim Munday (CSIRO)

B.5.1 OBJECTIVES

This is the core project management task. It will report on integration of information/data within Tasks 1-4 via the Final Report, which will document the overall hydrogeological conceptual model across the case study area that could inform government policy and support industry, community and environment. This task provides a home for the overall reporting and presentation of summary information from the project, and forms the main project delivery and communication mechanism.

5.1 Coordinate and participate in regular meetings with Stakeholders
5.2 Provide Interim Project Progress Reports to Goyder Institute Director for provision to DEWNR, DMITRE and key stakeholders
5.3 Project leadership and management (reporting, budgeting, review process, communication)
5.4 Final Report and workshop for Goyder FLOWS Stage-2 Project delivered

B.5.2 MILESTONES

Milestone Number	Milestone Description	Participant	Start Date	Delivery Date
Task 5 - Improved groundwater understanding & project management				
5.1.C	Startup	CSIRO	Nov 13	Dec 13
5.2.C	Closure Report	CSIRO	Jan 14	May 15

B.5.3 DELIVERABLES/OUTPUTS

5.4	FINAL PROJECT REPORT detailing hydrogeological conceptual model of northern Eyre Peninsula and ground water resource assessment.
5.4	FINAL WORKSHOP with industry and other stakeholders to present findings from G-FLOWS Stage-2.

5.4	FINAL PROJECT REPORT	– YES – Gilfedder *et al.* 2015 (this report).
5.4	FINAL WORKSHOP	– YES – Workshop held with DSD and DEWNR – August 6 2015

B.5.4 SUMMARY

A deliverable for this task is a Final Report on Stage-1 activity, summarising key outcomes and identifying knowledge gaps and providing recommendations.

- Gilfedder M, Munday T, Bestland E, Cahill K, Davies PJ, Davis A, Heinson G, Ibrahimi T, Lamontagne S, Ley-Cooper Y, Love A, Olifent V, Pichler M, Robinson N, Smith S, Sørensen C, Suckow A, Taylor AR, Thompson J, Annetts D (2015) *Facilitating Long-term Outback Water Solutions (G-FLOWS Stage-2) Final Report*. Technical Report Series No. 15/49, Goyder Institute for Water Research, Adelaide.

Communication with stakeholders, including industry and government agencies was undertaken throughout the life of the project. Presentations were made at several industry workshops/conferences to raise awareness of the project and its aims/outcomes. These meetings included the following presentations:

- Munday T, Gilfedder M (2013) Facilitating long-term outback water solutions to support mining in South Australia – The Goyder Institute's FLOWS Project*. 7th Annual Mining South Australia, 26-27 November 2013*, Whyalla, SA.
- Munday T (2015). Cover, water and exploration in the Musgrave Province, South Australia. Unlocking South Australia's Mineral Wealth Technical Forum 2015*, South Australian Resources and Energy Investment Conference (SAREIC), 15 April 2015*, Adelaide
- Munday T, Gilfedder M (2015) Geophysical investigations and information available for both exploration and hydrogeology; Examples from the Eyre Peninsula and Musgrave Province, SA. *Hydrogeology in Mining Conference, May 1 2015*, North Adelaide: SA Branch of Australian Institute of Geoscientists.
- Taylor AR, Leaney FW, Harrington GA, Jolly ID, Davies PJ, Munday T, Gilfedder M (2015b) Environmental tracers: useful indicators of recharge processes in a remote arid region – Musgrave Province South Australia*. Hydrogeology in Mining Conference, May 1 2015*, North Adelaide: SA Branch of Australian Institute of Geoscientists.
- Munday T, Gilfedder M, Taylor AR, Ibrahimi T, Ley-Cooper Y, Cahill K, Smith S, Costar A (presented by Neil Power) (2015b) Finding Long-term Outback Water Solutions (G-FLOWS). Presentation at *Goyder Institute Annual Conference* 17-18 Feb 2015.

The project has published results from G-FLOWS Stage-1 in an industry trade journal:

- Munday T, Gilfedder M, Taylor AR, Ibrahimi T, Ley-Cooper Y, Cahill K, Smith S, Costar A (2015a) The role of airborne geophysics in facilitating long-term outback water solutions to support mining in South Australia. *Water* 42(2), 138-141.

The project has published a magazine article intended for a broad audience based on G-FLOWS Stage-1 work in the Musgrave Ranges.

- Williams T (2015) Outback water: in search of underground oases. *Ecos Magazine* 211, September 2015. Available from: https://blogs.csiro.au/ecos/outback-water-in-search-of-underground-oases/

G-FLOWS Stage-1 was a finalist in the 11th Annual Australian Mining Prospect Awards (October 24 2014)

A workshop was held on August 6 2015 to brief DEWNR and DSD agency staff on the findings from the project as well as the type of data products that have been sent for possible uploading into government databases.

Glossary

AEM	Airborne Electromagnetic
ASX	Australian Stock Exchange
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEM	Digital Elevation Model (gridded map of land surface elevation)
DEWNR	Department of Environment, Water and Natural Resources (SA)
DMITRE	Department for Manufacturing, Innovation, Trade, Resources and Energy (SA)
DSD	Department for State Development
EM	Electromagnetic
FLOWS	Finding Long-term Outback Water Solutions
FUSA	Flinders University of South Australia
GA	Geoscience Australia
G-FLOWS	Goyder Facilitating Long-Term Outback Water Solutions
MrVBF	Multi-resolution Valley bottom floor: A technique for mapping low flat parts of the landscape (i.e. valley floors) [Gallant and Dowling 2003]
NMR	Nuclear Magnetic Resonance
PACE 2020	Plan for accelerating exploration (2010-2014)
RESIC	Resources & Energy Sector Infrastructure Council
SA	South Australia
TDEM	Time Domain Electromagnetic
TDS	Total Dissolved Solids
UoA	University of Adelaide

References

Berens V, Alcoe DW, Watt EL (2011) Non-prescribed groundwater resources assessment – Eyre Peninsula Natural Resources Management Region. Phase 1 - Literature and Data Review. DFW Technical Report 2011/16, Government of South Australia, through Department for Water, Adelaide. Available from: http://www.waterconnect.sa.gov.au/TechnicalPublications/Pages/default.aspx

Davis AC, Dlugosch R, Queitsch M, Macnae JC, Stolz R, Muller-Petke M (2014) First evidence of detecting surface nuclear magnetic resonance signals using a compact B-field sensor. Geophysical Research Letters 41(12): 4222-4229.

Eriksson E, Khunakasem V (1969) Chloride concentration in groundwater, recharge rate and rate of deposition of chloride in the Israel Coastal Plain. Journal of Hydrology 7 (12), 178-197, doi:10.1016/0022-1694(69)90055-9

Gallant, JC, Dowling, TI (2003) A multiresolution index of valley bottom flatness for mapping depositional areas. Water Resources Research 39 (12), 1347, doi:10.1029/2002WR001426

Harding A, Henschke C, Ciganovic P, Dooley T (2002) Eastern Cleve Hills Salinity Management Plan. Rural Solutions SA, Government of South Australia, 58pp.

Ley-Cooper AY, Munday T, Gilfedder M, Ibrahimi T, Annetts D, Cahill K (2015a) Inversion of legacy airborne electromagnetic datasets to inform the hydrogeological understanding of the northern Eyre Peninsula, South Australia. Technical Report Series No. 15/50, Goyder Institute for Water Research, Adelaide.

Ley-Cooper AY, Salama W, Munday T, Anand R, González Alvarez I, Spinks S, Gilfedder M (2015b) Advances in Electromagnetic (EM) interpretation. In proceedings of SAGA-2015, 14th Biennial Geophysical Conference, 6–9 September 2015, Drakensberg, South Africa. pp4.

Ley-Cooper AY, Viezzoli A, Guillemoteau J, Vignoli G, Macnae J, Cox L, Munday T (2015c) Airborne electromagnetic modelling options and their consequences in target definition. Exploration Geophysics 46:74-84. doi:10.1071/EG14045

Love AJ, Herczeg AL, Armstrong D, Stadter F, Mazor E (1993) Groundwater flow regime within the Gambier Embayment of the Otway Basin, Australia: evidence from hydraulics and hydrochemistry. Journal of Hydrology 143 (3-4), 297-338. doi:10.1016/0022-1694(93)90197-H

Munday T, Abdat T, Ley-Cooper Y, Gilfedder M (2013) Facilitating Long-term Outback Water Solutions (G-FLOWS Stage-1): Hydrogeological Framework. Goyder Institute for Water Research Technical Report Series No. 13/12.

Olifent V (2014) Salinity sources and recharge processes in the Cleve Uplands groundwater system, Eyre Peninsula, South Australia. BSc (Hons) unpublished thesis. School of the Environment (Faculty of Science and Engineering), Flinders University of South Australia.

RESIC (2012) Consultation Paper – RESIC recommendations to the South Australian Government, DMITRE, South Australia. http://www.pir.sa.gov.au/__data/assets/pdf_file/0011/167465/TED286_Resic_Consultation_Paper_FA.pdf

Risby L, Harrington G (2014). Non-prescribed groundwater resources assessment – Eyre Peninsula Natural Resources Management Region, Phase 2 – Hydrogeochemistry. DEWNR Technical Report 2014/10, Government of South Australia, through Department of Environment, Water and Natural Resources, Adelaide.

Sørensen CC, Munday T, Heinson G (online early – Dec 2014) Integrated interpretation of overlapping AEM datasets achieved through standardisation. Exploration Geophysics online early. doi:10.1071/EG14066

Taylor AR, Pichler MM, Olifent V, Thompson J, Bestland E, Davies PJ, Lamontagne S, Suckow A, Robinson N, Love A, Munday T (2015a) Groundwater Flow Systems of North-eastern Eyre Peninsula (G-FLOWS Stage-2): Hydrogeology, geophysics and environmental tracers. Technical Report Series No. 15/37, Goyder Institute for Water Research, Adelaide.

Thompson J (2014). Hydrogeological characterisation of sedimentary and fractured rock groundwater in the eastern Eyre Peninsula, South Australia. BSc (Hons) unpublished thesis. School of the Environment (Faculty of Science and Engineering), Flinders University of South Australia.

The Goyder Institute for Water Research is a partnership between the South Australian Government through the Department of Environment, Water and Natural Resources, CSIRO, Flinders University, the University of Adelaide and the University of South Australia.