

Facilitating Long-term Outback Water Solutions  
(G-FLOWS Stage-1)  
Final Report

Gilfedder M, Munday T

Project Team: Ley-Cooper Y, Davis A, Abdat T, Cahill K, Varma S  
Leaney FW, Jolly ID, Taylor AR, Davies PJ, Smith S  
Sorensen C, Heinson G, Hatch M  
Macdonald JI, McNeil DG  
Bestland E, Craven C, Custance H



Goyder Institute for Water Research  
Technical Report Series No. 13/13



[www.goyderinstitute.org](http://www.goyderinstitute.org)



**Goyder Institute for Water Research Technical Report Series ISSN: 1839-2725**

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. The Institute will enhance the South Australian Government's capacity to develop and deliver science-based policy solutions in water management. It brings together the best scientists and researchers across Australia to provide expert and independent scientific advice to inform good government water policy and identify future threats and opportunities to water security.



Enquires should be addressed to: Goyder Institute for Water Research  
Level 1, Torrens Building  
220 Victoria Square, Adelaide, SA, 5000  
tel: 08-8303 8952  
e-mail: [enquiries@goyderinstitute.org](mailto:enquiries@goyderinstitute.org)

**Citation**

Gilfedder, M, Munday T. (2013) *Facilitating Long-term Outback Water Solutions (G-FLOWS Stage-1) Final Report*. Goyder Institute for Water Research Technical Report Series No. 13/13.

**Copyright**

© 2013 CSIRO To the extent permitted by law, all rights are reserved and no part of this publication covered by copyright may be reproduced or copied in any form or by any means except with the written permission of CSIRO.

**Disclaimer**

The Participants advise that the information contained in this publication comprises general statements based on scientific research and does not warrant or represent the completeness of any information or material in this publication.

## Acknowledgements

This project was funded jointly by the Goyder Institute for Water Research, and its partner organisations, including: Commonwealth Scientific and Industrial Research Organisation (CSIRO) through the Water for a Healthy Country Flagship, the South Australian Research and Development Institute (SARDI), Flinders University of South Australia (FUSA), University of Adelaide (UoA), and the University of South Australia (UniSA). The Project Team is extremely grateful for the support of a wide range of people/organisations/companies/departments who all provided assistance to help undertake and complete this project including Neil Power (DEWNR), Adrian Costar (DEWNR); Miles Davies (DMITRE PACE); Glen Walker (CSIRO), Glenn Harrington (CSIRO). Thank you also to the project team for their hard work undertaking, presenting, and writing up the many aspects of work undertaken in G-FLOWS Stage-1.

## Table of Contents

<b>ACKNOWLEDGEMENTS .....</b>	<b>III</b>
<b>TABLE OF CONTENTS.....</b>	<b>IV</b>
<b>GLOSSARY.....</b>	<b>1</b>
<b>BACKGROUND .....</b>	<b>2</b>
<b>G-FLOWS STAGE-1 OUTCOMES AND RESULTS.....</b>	<b>7</b>
<b>SUMMARY AND CONCLUSIONS .....</b>	<b>15</b>
<b>REFERENCES.....</b>	<b>17</b>
<b>APPENDIX 1 – G-FLOWS STAGE-1 MILESTONES .....</b>	<b>18</b>
<b>APPENDIX 2 – G-FLOWS STAGE-1 TASKS AND DELIVERABLES.....</b>	<b>19</b>

## Glossary

AEM	Airborne Electromagnetic
AHD	Australian Height Datum
APY	Anangu Pitjantjatjara Yankunytjatjara
AW	Alinytjara Wilurara
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)
EM	Electromagnetic
FLAWS	Finding Long-term Outback Water Solutions
FUSA	Flinders University of South Australia
GA	Geoscience Australia
GCMB	Groundwater Chloride Mass Balance
G-FLOWS	Goyder Facilitating Long-Term Outback Water Solutions
LEI	Layered Earth Inversion
MOLR	Method of Last Resort (simple method for estimating groundwater recharge)
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
NT	Northern Territory
NWC	National Water Commission, Canberra
PACE 2020	Plan for accelerating exploration (2010-2014)
PIRSA	Primary Industries and Regions SA (government agency)
QaQc	Quality Assurance and Quality Control
SA	South Australia
SAAL	South Australian Arid Lands
SARDI	South Australian Research and Development Institute
SCI	Spatially Constrained Inversion
SWL	Standing water level
TDEM	Time Domain Electromagnetic
TDS	Total Dissolved Solids
UoA	University of Adelaide
UniSA	University of South Australia

## Background

Water is a critical resource for the growth and sustainability of the resources sector, particularly in outback regions of South Australia. This includes potable and non-potable sources that are used in ore-processing, slurry transport, dust suppression, human water consumption and in the maintenance of environmental and cultural assets. Planned and potential mining and energy development in South Australia's arid zones will require reliable water supplies primarily sourced from groundwater aquifers. Given that the resource sector generates significant economic value to South Australia, industry support remains a priority for the Government. The scale of the planned developments and the potential from current exploration programs facilitated by the South Australian Government through the Plan for accelerating exploration initiative (PACE 2020) will result in a substantial increase in infrastructure requirements. These requirements may include access to water resources and Aboriginal lands for exploration and potential mine developments.

This issue was highlighted in the recommendations from the 2011 Resources and Energy Infrastructure Demand Study (RESIC, 2012) commissioned through the Resources & Energy Sector Infrastructure Council (RESIC). It highlighted future demands on the state's infrastructure presented by mineral and energy projects now and over the next 10 years and beyond. The study noted that a particular concern for industry was the lack of information on the current available capacity and the potential of water source options in arid zones. It also identified that water scarcity and the lack of information created uncertainty for projects with the potential to lead to unsustainable solutions, the selecting of less preferred options, or delays to projects while new sources were sought. Recent studies conducted by RESIC have identified a potential increase in demand for water in the mining and energy sector for potential developments from approximately 40 GL to over 170 GL over the next 10 years. The studies found that water and water infrastructure is the second highest proportion of planned infrastructure capital investment by resource companies.

In response to this increasing demand for information about water source options, the Goyder Institute for Water research (Goyder Institute) developed the Facilitating Long-Term Outback Water Solutions (G-FLOWS) research project. G-FLOWS sought to complement work being undertaken by the Department of Environment, Water and National Resources (DEWNR), by focusing in more detail on previously identified priority areas for resource development (Fig. 1) as defined by the Department for Manufacturing, Innovation, Trade, Resources and Energy (DMITRE). These areas include the Musgrave Province, the north east and north west Gawler Craton, parts of the Frome Embayment in the east, and the northern Eyre Peninsula.



The primary responsibility for securing mine water supplies rests with mine developers. However, it is recognised that this will lead to individual, short-term development of water resources where a more targeted approach could potentially facilitate the development of shared resources, which in turn may increase the viability of mining development in the region.

G-FLOWS Stage-1 has developed and applied techniques to analyse airborne geophysical data to identify groundwater resources. It has then used multiple data sources to bring together a comprehensive current conceptual model of the hydrogeology in the Musgrave Province. This harnessed remotely-sensed datasets, with on-ground and borehole measurements, to provide a much greater sense of the subsurface variability in the area. This will allow finer-scale investigations to be more precisely targeted with respect to likely groundwater resources in this area.

This report forms the Final Report in Stage 1 of G-FLOWS. The report provides a synthesis and summary of key outcomes from the investigations outlined under G-FLOWS Stage-1, explaining the way in which this large project has delivered against its objectives. Details about milestones and deliverables can be found in the two Appendices. The project focused primarily on the Musgrave Province in the north west of South Australia, and the Frome Embayment in the eastern area of the State. This information is backed up by references to published reports and papers from the project, which are also listed in Table 1.

**Table 1 – Publications arising from G-FLOWS Stage-1**

<p><b>Technical Report</b></p> <p>Gilfedder M, Munday T, 2013. <i>Facilitating Long-term Outback Water Solutions (G-FLOWS Stage-1) Final Report</i>. Goyder Institute for Water Research Technical Report Series No. 13/x.</p> <p>Leaney, FW, Taylor, AR, Jolly, ID, Davies, PJ, 2013. <i>Facilitating Long Term Out-Back Water Solutions (G-FLOWS) Task 6: Groundwater recharge characteristics across key priority areas</i>. Goyder Institute for Water Research Technical Report Series No. 13/6.</p> <p>Ley-Cooper, AY, Munday TJ, 2013. <i>Groundwater Assessment and Aquifer Characterization in the Musgrave Province, South Australia: Interpretation and Assessment of SPECTREM Airborne Electromagnetic Data</i>. Goyder Institute for Water Research Technical Report Series No. 13/7.</p> <p>Macdonald, JI, McNeil, DG, 2012. <i>Environmental and cultural values of South Australia’s outback water resources</i>. Goyder Institute for Water Research Technical Report Series No. 12/7.</p> <p>Munday T, Abdat T, Ley-Cooper Y, Gilfedder M, 2013. <i>Facilitating Long-term Outback Water Solutions (G-FLOWS Stage-1): Hydrogeological Framework</i>. Goyder Institute for Water Research Technical Report Series No. 13/x.</p> <p>Varma, S, 2012. <i>Hydrogeological review of the Musgrave Province, South Australia</i>. Goyder Institute for Water Research Technical Report Series No. 12/8.</p>
<p><b>Honours Thesis</b></p> <p>Craven, C, 2012. <i>Sustainability of Regolith Hosted Aquifers in the Musgrave Province: Northern South Australia</i>. Honours Thesis, School of the Environment, Flinders University of South Australia.</p> <p>Custance, H, 2012. <i>Hydrogeochemistry of shallow regolith hosted aquifers in the eastern Musgrave Province of South Australia</i>. Honours Thesis, School of the Environment, Flinders University of South Australia.</p>
<p><b>Conference Paper</b></p> <p>Sorensen C, Munday T, Cherry J, 2013. Fixed wing vs. helicopter airborne EM for mapping fine scale conductivity variations in aquifer systems of the Frome Embayment, South Australia. <i>ASEG-PESA 2013</i>, 11-14 August 2013, Melbourne.</p>
<p><b>Conference Abstract</b></p> <p>Davis A, Macnae J, 2012. Modelling NMR signal for compact sensors, abstract presented at <i>MRS2012, 25-27 September 2012</i>, Hannover, Germany.</p> <p>Ley-Cooper Y, Brodie RC, 2013. Inversion of SPECTREM AEM data for conductivity and system geometry. <i>ASEG-PESA 2013, 11-14 August 2013</i>, Melbourne.</p> <p>Macnae J, Davis A, 2012. Component NMR with NMARMIT sensors. abstract presented at <i>MRS2012, 25-27 September 2012</i>, Hannover, Germany.</p> <p>Sorensen C, Munday T, Cahill K, 2012. Different AEM systems = different results... or should that necessarily be the case? Abstract presented at <i>25th Symposium on the Application of Geophysics to Engineering &amp; Environmental Problems: SAGEEP</i>, Tucson AZ USA March 2012.</p>
<p><b>Conference Poster</b></p> <p>Davis A, Macnae J, 2012. Extending the surface NMR signal model for B-field sensors, POSTER NS41B-1674: <i>AGU Fall Meeting, 3-7 December 2012</i>, San Francisco, USA.</p> <p>Munday T, Ley-Cooper Y.,2012. Assessing different airborne EM systems for delivering information on aquifer geometry and character in remote areas. <i>AGU Fall Meeting</i>, San Francisco Dec 2012.</p>
<p><b>Manuscripts submitted to Journals</b></p> <p>Davis AC, Macnae JC (submitted). Compact receivers for SNMR measurements. (target <i>Geophys. J. Int.</i>)</p> <p>Sorensen, C, Munday, TJ, and Heinson G (submitted) The importance of accurate system characterisation for AEM data inversion – A case study from the Frome Embayment, South Australia (target <i>Exploration Geophysics</i>)</p>

## G-FLOWS Stage-1 Objectives

The G-FLOWS project is a staged program of research, which aimed to invest in the development of knowledge and information that could be employed to help define an integrated water resource management strategy, thereby facilitating the economic growth potential of priority areas as defined by the South Australian Government. Stage 1 of the project had the following specific objectives:

1. For select resource development priority areas, identify the location and characteristics of aquifers, their capacity, and the quality and variability of the contained groundwater resources. This will build on available data and, through the development and application of procedures and protocols involving the integrated analysis and interpretation of geological and airborne geophysical data, linked to targeted drilling and hydrogeological investigations, it will provide the foundation for extending the comprehensiveness of the study.
2. Undertake a desk top study and review of cultural, ecological and environmental assets that have groundwater dependencies.
3. Develop an understanding of groundwater recharge across the priority areas.
4. Develop information packages that draw on extant databases and information from new and related projects to provide guidance and advice on potential and viable water resources, including GIS compatible mapping products and models for distribution to industry through the relevant State agencies.
5. Develop an informed strategy and Stage-2 proposal for employing regional geophysical data and targeted ground investigations to extend the understanding of aquifer characteristics and groundwater resources in other priority areas earmarked for development, while taking account of ecological and environmental assets.

## G-FLOWS Stage-1 Outcomes and Results

### Delivering against Objectives

G-FLOWS Stage-1 incorporated 10 tasks, and these combine to address the overall Project objectives. In broad terms, the project delivered against the objectives in the following ways:

- 1) Adapt, apply and test methods and techniques for combining topographic and airborne geophysical datasets, leading to the development of a hydrogeological framework for the Musgrave Province.
- 2) A review of key water values in arid zones of South Australia, identify attributes for each value and threats to these attributes. This was expanded through the organisation of a two-day forum and workshop entitled 'Cultural and Environmental Values of Outback Water Resources: Forum and Workshop' which attracted 52 delegates.
- 3) Combination of recharge modelling work across arid Far North South Australia, supported by field trip APY Lands (Musgrave Province) to collect groundwater samples for chemistry and environmental tracer analysis. This allowed groundwater residence times and aquifer properties to be better defined in the area.
- 4) Collation and enhancement of multiple spatial datasets in the Musgrave Province, to provide best available information of groundwater, aquifer characteristics and variability. A methodology has been developed to use these to support the hydrogeological model (Objective 1) and allow targeting of future finer-scale assessments of extensive subsurface drainage features (ancient buried river valleys: aka palaeovalleys)
- 5) Development of a processing and inversion strategy for employing historical and contemporary EM data affected by system uncertainties and errors, to produce calibrated data for hydrogeological assessment. This was undertaken in the Frome Embayment using fixed-wing and helicopter TDEM datasets acquired between 2000 and 2012.
- 6) Development of the Project Plan for G-FLOWS Stage-2 to build on these techniques. Initial stakeholder workshop has endorsed the move to apply these and focus G-FLOWS Stage-2 in the northern Eyre Peninsula region.

### Objective 1: Development of a Physical Hydrogeological Framework

A key output from G-FLOWS Stage-1 is a six-step method that brings together many different data sets and combines them in a structured way (Munday et al. 2013). The method to build a hydrogeological framework is outlined in this section.

The multi-disciplinary nature of the G-FLOWS Stage-1 project has allowed it to encompass results from different data sources, including:

- Geophysics (regional geophysical datasets, magnetic and gravity surveys),
- Local airborne geophysical survey datasets (industry supplied electromagnetic surveys),
- Terrain analysis derived from digital elevation models (DEMs)
- Regolith and geological data (supplied through DMITRE),
- Groundwater and aquifer data (supplied through DEWNR),
- Groundwater chemistry and isotope analysis.

The six-stage method (Fig. 2) has been applied in the Musgrave Province. The method has been used to provide an updated physical hydrogeological framework (Munday et al. 2013), and has several useful purposes:

- Combines and compares multiple sources of regional/local scale geophysical datasets, and existing point/spatial data.
- Can be used to help target locations and appropriate approaches for finer-scale groundwater resource assessments by Government or industry as required.
- Offers a basis for interpreting spatial patterns of groundwater quality and character obtained from individual bores. It helps put these isolated results into a broader perspective.

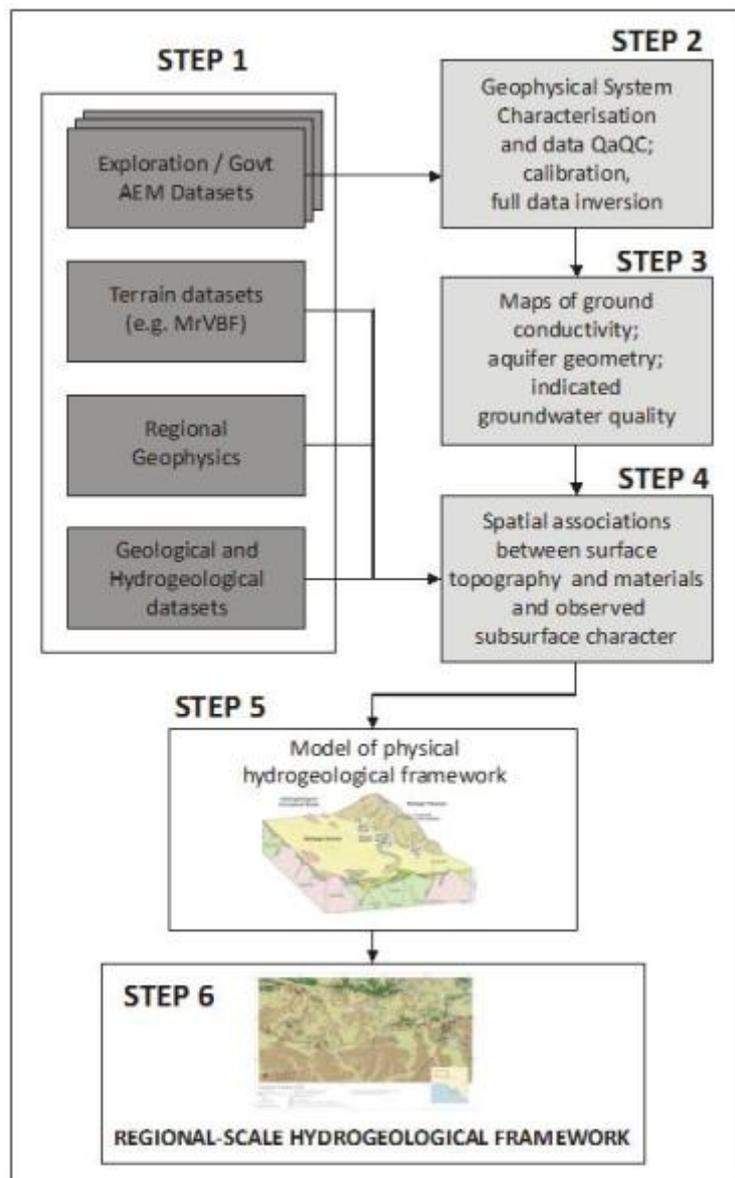


Fig. 2. Method used to develop a regional-scale physical hydrogeological framework.

### Step 1 - Collation of Data Sets

G-FLOWS Stage-1 has collated regional and local, prospect scale, geophysical data sets, through engagement with State agencies (DMITRE) and exploration companies who may commonly acquire high resolution airborne data sets for targeting mineralisation. The latter are a valuable resource, particularly airborne electromagnetic (AEM) data, as these offer insights into the subsurface character of aquifer systems.

### Step 2 - Geophysical data and interpretation

Once acquired, the AEM data are then checked for their quality, and for the availability of detailed information about the system characteristics and any processing steps undertaken by the contractors who acquired the data. This information is a critical step in interpretation of the data to obtain meaningful results/interpretation from a groundwater/hydrogeology perspective.

G-FLOWS Stage-1 has applied and compared different methodologies for interpreting the raw data to make best use of it for characterising aquifers. This is known as “data inversion” and involves interpreting the raw signal collected, and constraining this in terms of the likely structure beneath the ground. The project has documented methods for improving the comparison between different AEM systems, and provides guidance on issues around the amount of data required to pick out sub-surface drainage lines and aquifer characteristics.

### Step 3 - Producing maps of conductivity; aquifer geometry; indicated groundwater quality

The process of data inversion G-FLOWS Stage-1 has undertaken yields a set of maps showing patterns of ground conductivity and how this varies with depth below the surface. This can have several meanings, which include the geology, mineralogy, water quality etc. Fig. 3 shows maps of ground conductivity for an interval ~60 m below the ground surface, shown on a map of surface topography (DEM) for an area in the north west part of the Musgrave Province. This reveals the ancient buried valley drainage lines. These palaeovalleys appear on the maps like a grey pitchfork in the top right of Fig. 3), underneath what appears from the surface as an essentially flat dune-field.

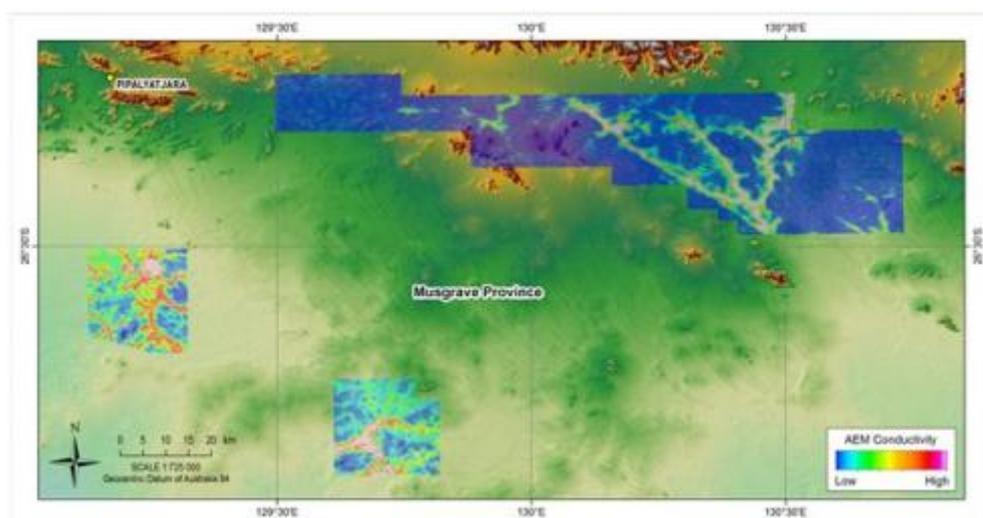


Fig. 3. Map of Musgrave Province showing current land surface elevation, together with the results from 3 AEM surveys. These show conductivity for a slice ~60 m below the land surface and highlight the old drainage lines.

#### Step 4 - Comparing current land topography and materials with Geophysics results

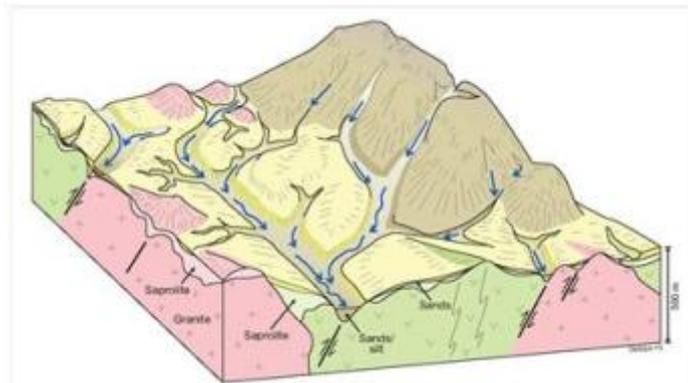
G-FLOWS Stage-1 derived maps and sections of ground conductivity for areas in the Musgrave Province, and then compared these with other regional geophysical data sets. This provided additional information and insight to understand geological/hydrogeological processes.

G-FLOWS Stage-1 then investigated whether the mapped palaeovalleys were coincident with subtle broad lows that characterise the contemporary landscape. G-FLOWS Stage-1 used the MrVBF terrain index (Gallant and Dowling 2003) to identify these from current land surface topography. The position of the broad low valley systems appears to be a useful starting point for locating the position of the deeper portions of the older valley system. The inference is that the contemporary valleys, or landscape lows, represent areas most likely to contain buried sequences of thick alluvial sediments, and by association alluvial aquifers.

#### Step 5 - Model of physical hydrogeological framework

The combined interpretation of the local scale AEM data, the regional magnetic and current land surface topography has contributed to the development by G-FLOWS Stage-1 of an updated hydrogeological conceptual model (Fig. 4) and a framework for groundwater resource assessment. This model indicates the relative extent and significance of the sediments that fill the palaeovalleys in the Musgrave Province. Limited drilling has confirmed that these sediments contain a significant groundwater resource. However, their full extent and geometry remains largely hidden from view and at present, largely untested.

##### ANCIENT LANDSCAPE (Pre-Pliocene)



##### CURRENT LANDSCAPE

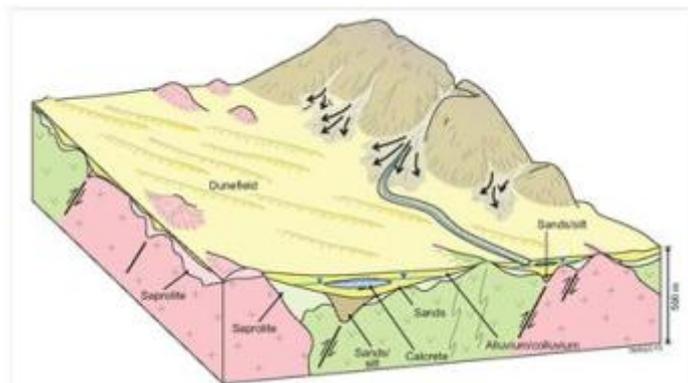


Fig. 4. Hydrogeological conceptual model for the north west and Central Musgrave Province developed by G-FLOWS Stage-1. Diagram at the top shows a conceptual model for an ancient (pre-Pliocene) landscape. The block diagram at the bottom shows the current landscape where the palaeovalleys have been filled with sediment.

## Step 6 - Upscaling the physical hydrogeological framework

The final step has been for G-FLOWS Stage-1 to take these local scale relationships, and to employ regional scale data sets and produce a physical hydrogeological framework for the larger region.

G-FLOWS Stage-1 used current land surface topography, AEM results, and existing geological and regolith information to define a set of aquifer units. Upscaling the physical hydrogeology to the rest of the Musgrave Province was then completed. The resulting map with available AEM data sets employed in this exercise is shown in Fig. 5. The regional distribution of aquifer systems is presented in Fig. 6.

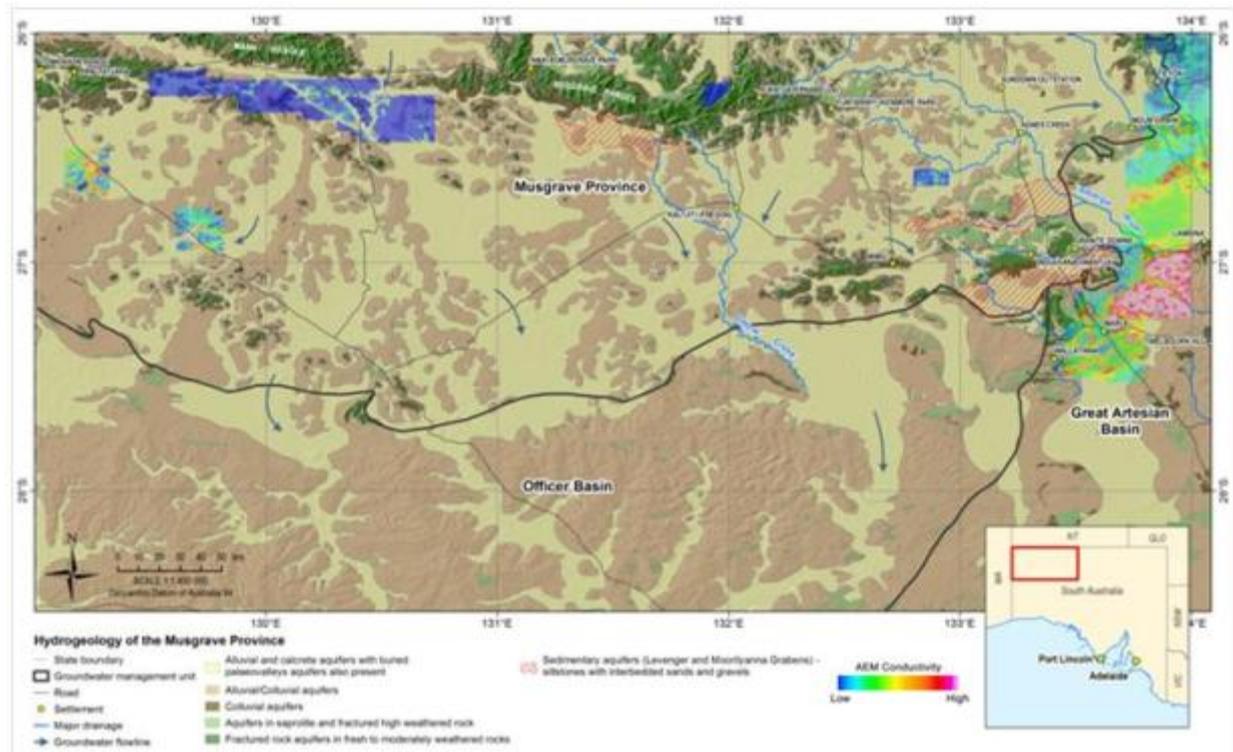


Fig. 5. Hydrogeological framework map of the Musgrave Province showing the distribution of AEM data sets which were employed in this upscaling exercise.

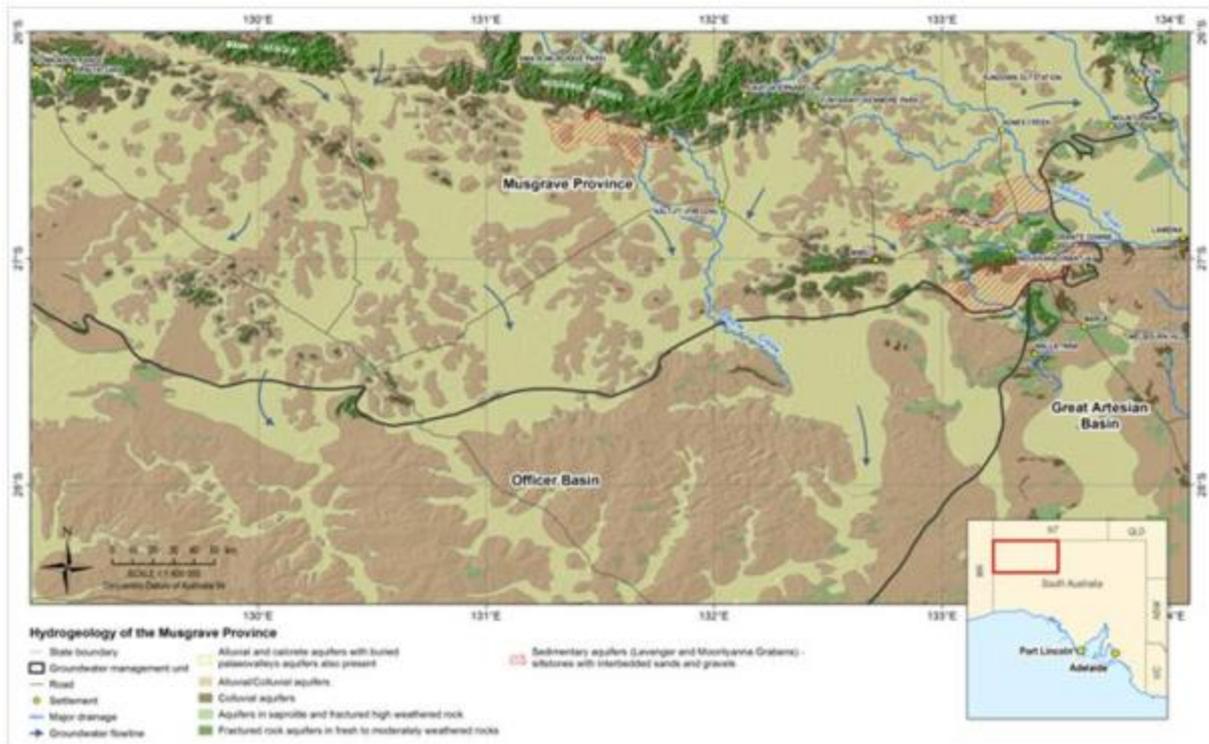


Fig. 6. Regional scale hydrogeological framework map of the Musgrave Province.

## Objective 2: Key water values in arid zones of South Australia

G-FLOWS Stage-1 helped identify and discuss environmental and cultural values of water and water dependent ecosystems across South Australia's arid zones, including the priority areas specified above, in addition to regions administered by the South Australian Arid Lands (SAAL) Natural Resource Management Board. G-FLOWS Stage-1 primarily focused on South Australian resources, its findings also included relevant contributions from arid zones in other States.

The work in G-FLOWS Stage-1 reported by Macdonald and McNeil (2012) provides a review of existing knowledge to capture key water values in arid zones of South Australia, identify attributes for each value and threats to these attributes. Information and data were collection from many sources.

G-FLOWS Stage-1 also organised a two-day forum and workshop attended by 52 delegates, entitled 'Cultural and Environmental Values of Outback Water Resources: Forum and Workshop' which was held at SARDI in May 2012, and is reported on in Macdonald and McNeil (2012). This brought together a diverse group of scientists, managers, community members, tourism operators, landowners and other stakeholders to discuss key environmental and cultural values of water resources in central Australia.

### **Objective 3: Recharge modelling and groundwater chemistry**

The Musgrave Province / Anangu Pitjantjatjara Yankunytjatjara (APY) Lands was the focus of field investigations for this task. The Project Team worked diligently to gain access to this remote area, with help of the community and State Agency staff (DMITRE/PACE, DEWNR, AW NRM Board and APY Executive). The field trip was undertaken from 2-12 Oct 2012, and successfully sampled 21 groundwater bores, with a good spread across the APY Lands. This amount of sampling exceeded expectations due to the remoteness of the area and the unknown condition of historical bores and whether their infrastructure still existed. The results are described in detail in Leaney et al. (2013).

Analysis of groundwater samples reported in Leaney et al. (2013) provide estimates of groundwater “age” from bores in the valleys of the Musgrave Range using CFC dating, which suggest an age of around 20 years old. Results from  $^{14}\text{C}$  analyses (and the temporal changes in the  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  compositions of the groundwater in the recharge valleys for the Musgrave Ranges) suggest groundwater younger than 50 years. These modern fresh groundwater reserves likely result from recharge during large episodic rainfall events where the monthly rainfall exceeds 80 mm/month. The rainfall needs to be sufficient to cause overland flow to the rivers and valleys in these areas for significant recharge to occur.

Further away south from the ranges, the salinity of the groundwater generally increases. In this area of shallow poorly consolidated sediments, diffuse recharge of saline water tends to dominate. Leaney et al. (2013) report recharge rates of <1 mm/yr across most of northern arid South Australia using the Method of Last Resort (MOLR).

### **Objective 4: Collation of Multiple Data-sets**

As part of Objective 1, G-FLOWS Stage-1 has produced/applied/used/derived many different point and spatial data sources to support the testing of a methodology (and its application) to support and build a hydrogeological framework for the Musgrave Province. These data-sets have been compiled and are being transferred to State Agencies for broader distribution.

### **Objective 5: Plans for G-FLOWS Stage-2**

Over the last 12 months, G-FLOWS Stage-1 has organised and facilitated several meetings to build a useful, sensible and achievable plan for a proposed second stage (G-FLOWS Stage-2).

The study area for Stage-2 was selected as the northern Eyre Peninsula, after much discussion at a project meeting (early November 2012). This is an area of active exploration and mining, with considerable water availability issues. Stakeholder needs and wishes (industry and government) were clarified at a well-attended workshop (late January 2013). This has helped define and refine the science direction and workplan for G-FLOWS Stage-2.

The current G-FLOWS Stage-2 Project Plan represents an opportunity to apply G-FLOWS Stage-1 methodology for creating a hydrogeological framework in a new investigation area (northern Eyre Peninsula). G-FLOWS Stage-2 will aim to develop a more detailed understanding not only of recharge processes, but of groundwater stores, movements and connections between aquifers. The Frome Embayment PhD work will continue to be supported.

## Hydrogeological Framework – using multiple data sets

An innovative method for developing a hydrogeological framework has been defined. This draws on the combined interpretation of multiple data sets. The project has collated and transformed local scale AEM data sets, hydrochemical information, regional scale magnetic and terrain data, coupled with existing geological and regolith information to provide a holistic interpretation of regional hydrogeology. This has been demonstrated in the Musgrave Province. The approach is directly applicable to other arid zones of South Australia, including the SAAL NRM region, parts of the AW NRM region outside of the Musgrave Province, and the northern Eyre Peninsula.

A key step in the framework process was the accurate processing and re-interpretation and processing of the local scale AEM data sets, the concepts of which can be applied more extensively across this region and other areas of the State. The derived physical framework provides a basis for interpreting existing hydrogeological data and would serve to assist industry in determining the available water resources for mine, infrastructure and community developments.

The G-FLOWS Stage-1 project work has developed methods and protocols to further expand understanding of different inversion methods for handling historical minerals exploration AEM data sets from a hydrogeological perspective. In doing so it has established effective and appropriate methods and protocols that can be employed in other arid zones. The Project's activity in this area is an international "first" and is attracting interest from other national agencies (e.g. USGS: USA) where exploration data sets may be a significant but undervalued resource for groundwater assessment purposes. Methodologies developed from this investigation have established effective and appropriate procedures and protocols that can be applied to future AEM surveys to provide a dual purpose; mineral exploration combined with groundwater resource identification. These methodologies are currently being adopted by PACE 2020 for its AEM programs.

The derived physical framework provides a basis for interpreting existing hydrogeological data and would serve to assist industry in determining the available water resources for mine, infrastructure and community developments. The Musgrave Province case-study indicates that a substantial reserve of groundwater may exist in deep sedimentary aquifers that occupy an extensive, but buried network of palaeovalleys. However, scrutiny of existing available hydrogeological data is poor (especially for deep groundwater systems), and this potential remains to be fully determined.

## Summary and Conclusions

The G-FLOWS Stage-1 Project has delivered on its objectives. The Project focused on data-poor areas of Far North South Australia, and made advances using a range of scientific methods to increase the understanding on the water resources in arid zones of South Australia. Key aspects of the work in G-FLOWS Stage-1 include:

1. Development of new hydrogeological framework for the Musgrave Province that combines and interprets multiple datasets from industry and government to help target finer-scale assessment of groundwater resources (Munday et al. 2013). The framework provides the basis for planning follow-up groundwater investigations whether it is undertaken by government agencies or industry. In the Musgrave Province, the targeting of groundwater for industrial development would be best focussed on the alluvial aquifers where palaeovalley fill may provide a significant resource. In these areas, additional geophysics (ground or airborne) would help define the thicker alluvial sequences;
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:
  - a. Hydrogeophysical (AEM, NMR) (e.g. Ley-Cooper & Munday 2013, Davis & Macnae 2012, Davis & Macnae 2013, Macnae & Davis 2013, Sorensen et al. 2013);
  - b. Recharge understanding through use of isotopes/tracers (groundwater age and chemistry measurements) (Leaney et al. 2013, Craven 2012, Custance 2012);
  - c. Hydrogeological conceptual models collation and summary (Varma 2012);
  - d. Development of a processing and inversion strategy for employing overlapping historical and contemporary EM data affected by system uncertainties and errors.
3. Summary of existing and ongoing social/cultural/ecological research relating to water in arid-zone of Australia (Macdonald & McNeil 2012);
4. Extensive communication of scientific results to a wide range of stakeholders and audiences both within Australia and Internationally;
5. Close collaboration and goodwill with data exchange between mineral companies and stakeholders.

## Recommendations & opportunities

1. South Australian Government agencies could consider the acquisition of targeted lines (transects) of AEM data on the back of local surveys undertaken for mineral exploration purposes. This would provide the State with an opportunity to supplement its knowledge about aquifer systems in the State's arid regions, focusing on data poor areas, at relatively low cost (an example would be the acquisition of 10 km of EM data at ~ \$1500-2000, including interpretation).

One approach would be to have DMITRE act as a liaison agency between industry and the State Government to acquire select lines of data as and when the opportunity arose. This would be an alternative to the Government acquiring their own complete data sets with all the associated costs including mobilisation. A trial of this approach might be considered in the context of G-FLOWS Stage-2.

2. A major gap in understanding the available groundwater resource in the Musgrave Province is information on the hydrogeology of the valley fill sequences associated with the buried palaeovalleys that dissect the region. Recent drilling in the north west of the Musgrave Province, which targeted a valley fill sequence, indicated that in places these valleys contain a significant, potable resource.

## References

- Craven, C, 2012. *Sustainability of Regolith Hosted Aquifers in the Musgrave Province: Northern South Australia*. Honours Thesis, School of the Environment, Flinders University of South Australia.
- Custance, H, 2012. *Hydrogeochemistry of shallow regolith hosted aquifers in the eastern Musgrave Province of South Australia*. Honours Thesis, School of the Environment, Flinders University of South Australia.
- Davis A, Macnae J, 2012. *Modelling NMR signal for compact sensors*, abstract presented at MRS2012, 25-27 September 2012, Hannover, Germany.
- 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.
- Leaney, FW, Taylor, AR, Jolly, ID, Davies, PJ, 2013. *Facilitating Long Term Out-Back Water Solutions (G-FLOWS) Task 6: Groundwater recharge characteristics across key priority areas*. Goyder Institute for Water Research Technical Report Series No. 13/6.
- Ley-Cooper, AY, Munday TJ, 2013. *Groundwater Assessment and Aquifer Characterization in the Musgrave Province, South Australia: Interpretation and Assessment of SPECTREM Airborne Electromagnetic Data*. Goyder Institute for Water Research Technical Report Series No. 13/7.
- Macdonald, JI, McNeil, DG, 2012. *Environmental and cultural values of South Australia's outback water resources*. Goyder Institute for Water Research Technical Report Series No. 12/7.
- Macnae J, Davis A, 2012. *Component NMR with NMARMIT sensors*. abstract presented at MRS2012, 25-27 September 2012, Hannover, Germany.
- 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.
- 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](http://www.pir.sa.gov.au/__data/assets/pdf_file/0011/167465/TED286_Resic_Consultation_Paper_FA.pdf)]
- Sorensen C, Munday T, Cherry J, 2013. Fixed wing vs. helicopter airborne EM for mapping fine scale conductivity variations in aquifer systems of the Frome Embayment, South Australia. *ASEG-PESA 2013*, 11-14 August 2013, Melbourne.
- Sorensen C, Munday T, Cahill K, 2012. Different AEM systems = different results... or should that necessarily be the case? Abstract presented at *25th Symposium on the Application of Geophysics to Engineering & Environmental Problems: SAGEEP*, Tucson AZ USA March 2012.
- Varma, S, 2012. *Hydrogeological review of the Musgrave Province, South Australia*. Goyder Institute for Water Research Technical Report Series No. 12/8.

## Appendix 1 – G-FLOWS Stage-1 Milestones

Table A1: List of milestones for each task in G-FLOWS Stage-1.

<b>TASK 1: MILESTONES</b>	<b>START</b>	<b>DUE</b>
Coordinate and participate in regular meetings with Stakeholders	1/1/2011	30/6/2012
Establish Project Steering Committee and conduct first Quarterly meeting	1/1/2011	20/2/2011
Provide Interim Project Progress Reports – to Goyder RAC & stakeholders	1/1/2011	30/6/2012
Final Stage 1 Summary Report submitted	1/5/2012	30/6/2012
<b>TASK 2: MILESTONES</b>	<b>START</b>	<b>DUE</b>
MOU with DfW and PIRSA for access to data	1/1/2011	15/2/2011
Data mining activity initiated– Interim report tabled to steering group	1/1/2011	20/6/2011
Project GIS defined for key areas, GIS populated Summary report on data gaps	1/1/2011	30/6/2011
GIS Update #1 complete and distributed	1/7/2011	30/11/2011
Final Project GIS delivered to State Agencies	1/12/2011	30/6/2012
<b>TASK 3: MILESTONES</b>	<b>START</b>	<b>DUE</b>
Review of existing Industry and government geophysical data sets	1/1/2011	31/5/2011
Forward Modelling study and test line assessment form an aquifer characterisation perspective.	1/3/2011	30/6/2011
Definition of regional survey characteristics – orientation, system, line spacing etc.	1/9/2011	30/3/2012
Report of strategies for regional groundwater assessment across priority areas using airborne geophysics methods	1/2/2012	30/6/2012
<b>TASK 4: MILESTONES</b>	<b>START</b>	<b>DUE</b>
Review of available/appropriate inversion procedures given system and data types	1/1/2011	30/4/2011
Review and documentation of “Calibration methods”. Report on Cross calibration methods	1/1/2011	30/6/2011
Trial of calibration procedures and delivery of re-processed, interpreted data	1/4/2011	1/12/2011
Integration with regional hydrogeological data and generation derived products including groundwater quality maps	1/7/2011	30/3/2012
<b>TASK 5: MILESTONES</b>	<b>START</b>	<b>DUE</b>
Acquisition of field data and calibration and interpretation of data from Gawler and GAB Margins	1/4/2011	30/6/2011
Extension of methods to other data form priority areas and population of GIS with derived products from Interpreted geophysical surveys	1/6/2011	30/10/2011
Case study reports on methods developed and results	1/7/2011	30/10/2011
<b>TASK 6: MILESTONES</b>	<b>START</b>	<b>DUE</b>
Complete review of available and accessible bores	1/3/2011	30/6/2011
Sampling and analysis of select bores initiated	30/3/2011	30/5/2011
Targeted drilling and sampling	1/6/2011	30/10/2011
Determination of regional groundwater ages	1/6/2011	30/10/2011
Report detailing groundwater recharge processes and ages across the priority areas	1/6/2011	30/10/2011
<b>TASK 7: MILESTONES</b>	<b>START</b>	<b>DUE</b>
Desktop review complete	1/1/2011	30/6/2011
Workshop held with key stakeholders	20/6/2011	30/9/2011
Final project Report	20/5/2011	30/9/2011
<b>TASK 8: MILESTONES</b>	<b>START</b>	<b>DUE</b>
Collation of data on critical and key aquifers in priority areas	1/3/2011	30/5/2011
Hydrogeological interpretation of data	1/4/2011	30/6/2011
Maps (GIS compatible) on groundwater levels, and water quality	1/7/2011	30/3/2012
Report on the hydrogeology of key priority areas and definition of GMU’s	1/2/2012	30/3/2012
<b>TASK 9: MILESTONES</b>	<b>START</b>	<b>DUE</b>
Preliminary outcomes from early tasks documented	1/4/2011	30/6/2011
Draft Final report circulated to Stakeholders	1/4/2012	31/5/2012
Final Stage 1 report delivered	1/6/2012	30/6/2012
<i>ADDED TASK: CONTRACT VARIATION IN 2013</i>		
<b>TASK 10: MILESTONES</b>	<b>START</b>	<b>DUE</b>
CSIRO work on Industry Workshop & Outcomes	1/1/2013	1/2/2013
C Sorensen PhD extended .27 FTE	1/1/2013	28/2/2013

## Appendix 2 – G-FLOWS Stage-1 Tasks and Deliverables

Appendix 2 presents the objectives, milestones and deliverables for each of the tasks in G-FLOWS Stage-1, to provide an overview of the project.

### Task 1: Project Management

#### Objectives

Due to the large number of stakeholders and widely spread project team located in various cities around Australia, it was necessary to implement a high level of overall project management and coordination within the G-FLOWS Stage-1 Project Team, as well as to Goyder Institute and other stakeholders.

1. Define, develop and coordinate effective communication between the Project Team and key stakeholders
2. Establish a Project Steering Committee and coordinate quarterly meetings
3. Ensure all reporting requirements are met and reports are reviewed and delivered in a timely manner

#### Milestones

<b>TASK 1: MILESTONES</b>	<b>SUB-LEADER</b>	<b>START DATE</b>	<b>DUE DATE</b>
• Coordinate and participate in regular meetings with Stakeholders	Tim Munday	1/1/2011	30/6/2012
• Establish Project Steering Committee and conduct first Quarterly meeting	Tim Munday	1/1/2011	20/2/2011
• Provide Interim Project Progress Reports – to Goyder RAC & stakeholders	Tim Munday+ Task leaders	1/1/2011	30/6/2012
• Final Stage 1 Summary Report submitted	Tim Munday	1/5/2012	30/6/2012

#### Deliverables/Outputs

1. Conduct of regular (monthly) meetings with the Task Leaders to review and monitor project progress
2. Establishment of Project Steering Committee
3. Final reports delivered to high quality on time.

#### Summary

Regular meetings were held with the various stakeholders and Project Team members. There is good rapport between the Project Team and the various stakeholders, which is a strength of the project.

A Project Steering Committee (PSC) was not defined. This was substituted with 1:1 meetings with key stakeholders. In hindsight a PSC would have been advantageous.

This project supplied the Goyder Office with quarterly update reports, and regular updates on progress via draft reports, meetings with State government to update them on project results at an early stage.

#### Recommendations

It is recommended that G-FLOWS Stage-2 establish a Project Steering Committee (PSC) to provide a structured governance arrangement to oversee the delivery and reporting from the project.

## Task 2: Collate extant geological, geophysical and hydrogeological information (including industry data) on groundwater and aquifers in agreed priority areas.

### Objectives

1. Collate existing Government (State and Federal) and industry data sets pertaining to the geology, geophysical and hydrogeological data of priority areas for industry development in northern South Australia. Project emphasis on collating data for non-prescribed wells areas.
2. Develop Project GIS for the Priority areas, including a dedicated groundwater information database of all existing bores in the study area with information on groundwater levels, chemistry and bore depth and construction details for each site.
3. Identify information knowledge gaps and define key areas for further ground investigation, including geophysical, and hydrogeochemical and isotopic investigations.

### Milestones

<b>TASK 2: MILESTONES</b>	<b>SUB-LEADER</b>	<b>START DATE</b>	<b>DUE DATE</b>
1. MOU with DfW and PIRSA for access to data	Tim Munday	1/1/2011	15/2/2011
2. Data mining activity initiated– Interim report tabled to steering group	Tim Munday	1/1/2011	20/6/2011
3. Project GIS defined for key areas, GIS populated Summary report on data gaps	Tim Munday+ Task leaders	1/1/2011	30/6/2011
4. GIS Update #1 complete and distributed	Tim Munday	1/7/2011	30/11/2011
5. Final Project GIS delivered to State Agencies	Tim Munday	1/12/2011	30/6/2012

### Deliverables/Outputs

1. GIS compatible data for distribution through key State agency partners for Industry Priority areas.
2. Report on data acquired and their review.

### Technical Report

- 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.

### Summary

This task was finalised through a workshop on “AEM interpretation – The Musgrave Province” which was held at the DMITRE in Feb 2013. This workshop presented the project’s techniques and results, with presentations by Tim Munday and Yusen Ley-Cooper. Transfer of project data to DMITRE was also initiated at the workshop. The agenda for the workshop was:

1. A comparative look at a hydrogeophysical investigation of the SPECTREM, VTEM, TEMPEST and SkyTEM data sets in the Musgrave Province.
2. Inversion vs fast approximate transforms for mapping regolith variability.
3. New results from inverting SPECTREM data – A first for this system.
4. Comparative results from a conductive target mapping exercise – VTEM vs SkyTEM 508.
5. Revisiting historical EM data –extracting good regolith information – Frome Embayment.
6. Palaeo-channel Uranium in the Callabonna sub-basin – revisiting the geophysical story.

## Task 3: Forward modelling study to review and assess quality assurance and quality control of available geophysical data sets in priority areas in consultation with DMITRE/PACE, GA and industry

### Objectives

1. A review of all geophysical data sets provided to the project for the priority areas, from the perspective of their quality and their relevance to groundwater and aquifer characterisation. Key issues to be investigated and documented are:
  - a) The system/techniques employed and their limitations from the perspective of resolution and characterisation (physical properties measured/detected).
  - b) Whether the data are calibrated and of an acceptable quality for further processing and interpretation. Appropriate system characterisation is critical for the further inversion and analysis of data.
2. Undertake a forward modelling study of key areas and aquifer systems in the priority regions to determine the type of AEM system that might be needed to resolve, depth of penetration, critical aquifer systems and variability that might be resolved. We advocate the acquisition of test lines using one, or two AEM systems, to determine their effectiveness at targeting key aquifer elements and groundwater quality.
3. Consideration and investigation of regional geophysics, magnetics, gravity and seismics from the perspective of defining the geometry and extent of deep aquifer systems in priority areas for industrial development.

### Milestones

<b>TASK 3: MILESTONES</b>	<b>SUB-LEADER</b>	<b>START DATE</b>	<b>DUE DATE</b>
1. Review of existing Industry and government geophysical data sets	Andrew Fitzpatrick	1/1/2011	31st May 2011
2. Forward Modelling study and test line assessment from an aquifer characterisation perspective.	Andrew Fitzpatrick	1/3/2011	30/6/2011
3. Definition of regional survey characteristics – orientation, system, line spacing etc.	Andrew Fitzpatrick	1/9/2011	30/3/2012
4. Report of strategies for regional groundwater assessment across priority areas using airborne geophysics methods	Andrew Fitzpatrick	1/2/2012	30/6/2012

Work undertaken in this task supported the development of new hydrogeological framework for the Musgrave Province (Munday et al. 2013) using 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 DMITRE) and South Australian hydrogeological data (through DEWNR).

Milestone 2 involved an assessment of data from several AEM systems across the Musgrave Province and in the Frome Embayment. These included a range of fixed-wing and helicopter time domain EM systems (e.g. TEMPEST, SPECTREM, VTEM, HOISTEM, REPTM and SkyTEM). Systems characteristics were documented, with this information incorporated into forward modelling and inversion approaches. The intent was to define conductivity-depth models that could be compared across different areas. This work is summarised in Munday and Cooper (2012), Munday et al. (2013; Fig. 5), and Sorensen et al (2012).

In consultation with DMITRE, several scenarios for a regional AEM survey covering the Musgrave Province were considered and costed. The most suitable geophysical systems were deemed to be fixed-wing TDEM systems. Options concerning suitable line spacings were examined, and results of these considerations are shown in Fig. 4 (Munday et al. 2013). One recommendation to emerge from this work was to consider the acquisition of targeted lines of data, funded by the State, linked to the acquisition of AEM data undertaken by Exploration companies. The costs for data acquisition would be limited to ~\$ 100-200/line km including interpretation. Linking data acquisition for groundwater and aquifer characterisation to surveys being undertaken for exploration would be of the order of ~\$2000 for 10 km of data. This would represent a considerable cost saving to the State compared with those required for independent surveys.

## Deliverables/Outputs

### Technical Reports:

- A Yusen Ley-Cooper and Tim J. Munday, 2013. *Groundwater Assessment and Aquifer Characterization in the Musgrave Province, South Australia: Interpretation and Assessment of SPECTREM Airborne Electromagnetic Data*. Goyder Institute for Water Research Technical Report Series No. 13/7.
- 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.

### Conference abstracts

- Y.Ley-Cooper and R C Brodie. (2013) Inversion of SPECTREM AEM data for conductivity and system geometry. *ASEG-PESA 2013*, 11-14 August 2013, Melbourne.
- Sorensen C, Munday T, Cahill K, 2012. Different AEM systems = different results... or should that necessarily be the case? Abstract presented at *25th Symposium on the Application of Geophysics to Engineering & Environmental Problems: SAGEEP*, Tucson AZ USA March 2012.

### Conference poster

- T Munday, Y.Ley-Cooper (2012) Assessing different airborne EM systems for delivering information on aquifer geometry and character in remote areas. *AGU Fall Meeting*, San Francisco Dec 2012.

## Summary

The work in this Task was the first attempt at using a common processing and inversion ("calibration") framework for combining historical AEM data acquired from different systems over different dates. The evaluation of the use of the data from a SPECTREM<sub>2000</sub> airborne electromagnetic (AEM) survey flown in April 2012 to assess groundwater and aquifers in the Musgrave Province of South Australia is presented in Ley-Cooper and Munday (2013).

# Assessing different airborne EM systems for delivering information on aquifer geometry and character in remote areas

A case study from the Musgrave Province, South Australia

For Munday and Aaron Ley-Cooper

CSIRO EARTH SCIENCE AND RESOURCE ENGINEERING/WATER FOR A HEALTHY COUNTRY

INVESTIGATION REPORT

CSIRO

In the Musgrave Province of South Australia, local scale AEM data sets are being employed to develop hydrogeological conceptual models in support of a regional scale water resources assessment. The work has required the re-processing of historical AEM data sets, including those acquired by TEMPESE, HOISTEM and SYSTEM AEM systems. Co-incident data from several new AEM systems, including the new SkyTEM<sup>TM</sup> (a helicopter TDEM system) and the SPECTREM<sub>2000</sub> (a fixed wing TDEM system) have also been acquired to inform systems for the further pre-competitive AEM data collection, supporting mineral exploration and groundwater resource assessment in the region.

### Study Area and Hydrogeology

The Musgrave Province, located in the hills of South Australia, is a region of isolated basement consisting mainly of the amphibolite and granitic belts gneisses intruded by mafic to granitic dykes and granitoids, and areas of volcanic rocks. While extensive outcrops of isolated hills and ridges north of it is covered by regolith, groundwater occurs in the unweathered and fractured sections of the basement, alluvial fans, alluvium and the surface sediments consisting of silt, sand, mud and organic deposits. Recharge is very low (between 1mm/yr and 5mm/yr). The geotectonic system is complex and extensive and includes the Musgrave Province. The geotectonic system is complex and extensive and includes the Musgrave Province. The geotectonic system is complex and extensive and includes the Musgrave Province.



The geotectonic system is complex and extensive and includes the Musgrave Province. The geotectonic system is complex and extensive and includes the Musgrave Province. The geotectonic system is complex and extensive and includes the Musgrave Province.

### System Comparison

To inform options for the further pre-competitive AEM data acquisition over the region, we have acquired, processed and inverted consistent AEM data from a range of systems. Results from a comparison of these systems is shown in Figure 1. Comparison was facilitated by using the same model parameterisation and a common inversion scheme, specifically the G4-C with the data inverted using common parameters, and a robust 3D inversion.

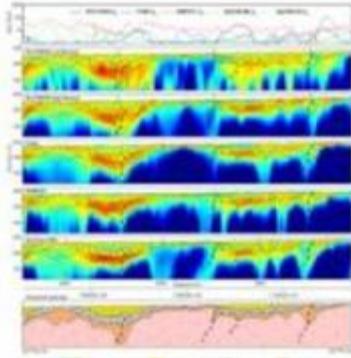


Figure 1 shows a comparison of AEM data from different systems. The figure consists of several panels showing cross-sections of the subsurface. The top panel shows the raw data, and the subsequent panels show the inverted data for different systems. The data is color-coded to represent different geological features and aquifer characteristics.

### Discussion

An evaluation of historical AEM data sets over the Musgrave Province reveals a complex, extensive and complex geotectonic system which contains groundwater of variable quality (2000 - 3000 mg/l TDS). Mineral resources were to be developed in this area, these systems could represent the best option for water supply. Review of available and recently acquired AEM data sets indicates that more consistently available TDEM systems would effectively map the distribution of these parameters, although some would be better at defining variability associated with the heterogeneity of the system. The consistent interpretation of the AEM and regional magnetic data has contributed to the development of an initial hydrogeological conceptual model (Figure 2) and a platform for groundwater resource assessment.



Figure 2 shows a 3D model of the Musgrave Province. The model illustrates the complex geotectonic system and the distribution of groundwater. The model is color-coded to represent different geological features and aquifer characteristics.

### Conclusions

Using "consistent" AEM data sets identify an extensive and complex geotectonic system. These systems, located along basement, faults and dykes which are well defined in the regional magnetic, contain a varied B<sub>1</sub> and conduct to saline groundwater. They could be mapped effectively with a range of consistently available airborne TDEM systems, the most important objective being to map the larger systems and their thickness. If regional acquisition was to be considered, survey the spacing of 10-20 km would be optimal.

## Task 4: Develop procedures and protocols for processing historical geophysical data and generating maps of groundwater and aquifer characteristics

### Objectives

The objectives of Task 4 were:

1. Review of methods for the accurate inversion of all geophysical data sets provided to the project, considering systems and data types.
2. Develop and document procedures and protocols for “correcting” or calibrating historical data sets. Potentially this would then allow them to be re-processed with a view to generating seamless coverages (when linked to more regional data sets), or maps of ground conductivity, from which groundwater and aquifer characteristics can be determined through reference to available bore and related analytical data.

### Milestones

<i>TASK 4: MILESTONES</i>	<i>SUB-LEADER</i>	<i>START DATE</i>	<i>DUE DATE</i>
1. Review of available/appropriate inversion procedures given system and data types	Tim Munday	1/1/2011	30/4/2011
2. Review and documentation of “Calibration methods”. Report on Cross calibration methods	Tim Munday	1/1/2011	30/6/2011
3. Trial of calibration procedures and delivery of re-processed, interpreted data	Tim Munday	1/4/2011	1/12/2011
4. Integration with regional hydrogeological data and generation derived products including groundwater quality maps	Tim Munday	1/7/2011	30/3/2012

This task addressed and examined commonly accepted approaches to the calibration of AEM data sets from different systems. Consideration of different methods formed part of the Frome study and inversion (e.g. Sorensen et al., submitted). A common requirement is an accurate system parameter description in order to invert the data and obtain an accurate resistivity-depth structure of the ground. The value in accurate system characterization and the recording and preserving of system information and survey characteristics has been highlighted. When revisiting historical data, sometimes some of this crucial information is missing. When reprocessing and re-inverting, it can be necessary to make assumptions about system geometry and acquisition parameters, with the result that inaccurate resistivity-depth models may be determined. In some cases this information was never recorded, so assumptions based on the best available evidence must be made. Seamless maps of ground conductivity are unlikely when employing data from different systems regardless of how well calibration and characterisation is done, primarily because of the differences in system resolution and depth of investigation.

This task also considered the value and relevance of employing ground-based hydrogeophysical methods in combination with AEM data sets to derive information (and maps) on groundwater and aquifer characteristics. One approach considered was the use of surface nuclear magnetic resonance (sNMR) coupled with ground EM data. The biggest limitation identified for remote area investigations using ground methods was the time it took to acquire NMR data. Alternative approaches to speed up data acquisition, and to extend coverage in local areas was considered (Davis and Macnae 2012). The work of Macnae and Davis (2012) undertook the first tests of these new NMARMIT sensors in Australia, which have a low-amplitude pulsed waveform transmitter have shown that they may be capable of detecting nuclear magnetic resonance (NMR) signals associated

with near surface water, and could map 2D changes around the edge of a dam surrounded by a transmitter. Further tests with more powerful NMR transmitters are planned in Task 4 of the proposed G-FLOWS Stage-2.

Work undertaken in this task also supported the development of new hydrogeological framework for the Musgrave province (Munday et al. 2013) using 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 DMITRE) and South Australian hydrogeological data (through DEWNR).

### Deliverables/Outputs

1. Report on data processing methods, their effectiveness and protocols for re-processing and merging of historical data.
2. Re-processed data and derived products from the integrated analysis and interpretation with regional hydrogeological data.

#### Submitted to Journal

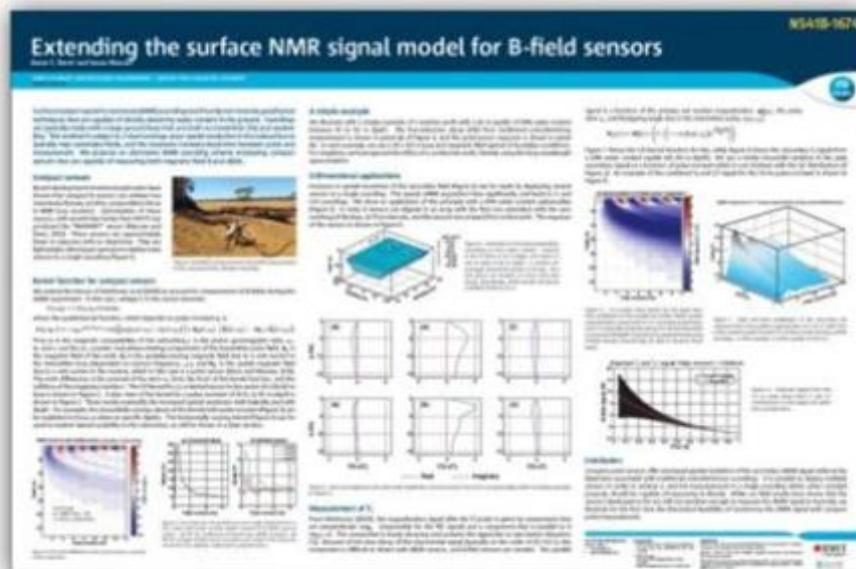
- Davis AC, Macnae JC (submitted). Compact receivers for SNMR measurements. Submitted to *Geophys. J. Int.* (submitted in May 2013)
- Sorensen, C, Munday, TJ, and Heinson G (submitted June 2013) The importance of accurate system characterisation for AEM data inversion – A case study from the Frome Embayment, South Australia (target journal Exploration Geophysics).

#### Conference Abstracts

- Davis A, Macnae J (2012). Modelling NMR signal for compact sensors, abstract presented at MRS2012, 25-27 September 2012, Hannover, Germany.
- Macnae J, Davis A, (2012) component NMR with NMARMIT sensors, abstract presented at MRS2012, 25-27 September 2012, Hannover, Germany.

#### Poster

- Davis A, Macnae J (2012). Extending the surface NMR signal model for B-field sensors, POSTER NS41B-1674: AGU Fall Meeting, 3-7 December 2012, San Francisco, USA.



## Task 5: Case studies on the integration of regional and local scale geoscience data for groundwater and aquifer characterisation in key areas targeted for industry development.

### Objectives

This task developed case studies to demonstrate the value and relevance of employing both regional and local scale geophysical and related geoscience data in defining groundwater resources and aquifer characteristics across priority areas of the State. Specifically it used the regional TEMPEST data that has been acquired by Geoscience Australia (GA) and DMITRE for the Gawler Craton and the Frome Embayment and combined those data with local scale, industry surveys in a demonstration of procedures and methods developed in this project. It also demonstrated the appropriateness of technologies and data sets used.

Specifically, an accurate quasi-3D inversion (spatially constrained Inversion (SCI)) procedure was employed to derive models of ground conductivity. The SCI is a method based on a 1D forward response, with 3D spatial constraints. The spatial constraints allow prior information (e.g. the expected geological variability of the area, or the down-hole conductivity) to migrate across the entire dataset. The output models balance the information that is present locally within the individual TEM soundings with the ones carried by the constraints. The SCI has a demonstrated applicability in semi-layered environment. The models of ground conductivity were then linked with available groundwater information and derived products of groundwater quality were generated. The derived products have been incorporated into a 3D geological understanding of aquifers and aquifer characteristics where that information existed.

### Milestones

<b>TASK 5: MILESTONES</b>	<b>SUB-LEADER</b>	<b>START DATE</b>	<b>DUE DATE</b>
• Acquisition of field data and calibration and interpretation of data from Gawler and GAB Margins	Tim Munday	1/4/2011	30/6/2011
• Extension of methods to other data from priority areas and population of GIS with derived products from Interpreted geophysical surveys	Tim Munday	1/6/2011	30/10/2011
• Case study reports on methods developed and results	Tim Munday	1 <sup>st</sup> July 2011	30/10/2011

Work undertaken in this task supported the development of new hydrogeological framework for the Musgrave province (Munday et al. 2013) using 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 DMITRE) and South Australian hydrogeological data (through DEWNR).

## Deliverables/Outputs

### Case Study (Musgraves and GAB margin)

- 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.

### Case Study (Frome) - Journal paper manuscript

- Sorensen, C, Munday, TJ, and Heinson G (submitted June 2013) The importance of accurate system characterisation for AEM data inversion – A case study from the Frome Embayment, South Australia (target journal Exploration Geophysics).

### Conference paper:

- Sorensen C, Munday T, Cherry J (2013) *Fixed wing vs. helicopter airborne EM for mapping fine scale conductivity variations in aquifer systems of the Frome Embayment, South Australia*. ASEG-PESA 2013, 11-14 August 2013, Melbourne.

## Summary

This PhD work on the Frome Embayment is ongoing and additional PhD field work component to the Frome Embayment occurred in early November 2012 to support this work. This is in the process of being written up through the PhD process, due for completion mid 2014. The notion of the conjunctive use of industry exploration data sets to supplement other hydrogeological data in groundwater resource assessment is increasingly being recognised by industry through their willingness to part with data. Recently Uranium One signed over a significant tranche of historical AEM data for use in the project covering the Frome Embayment. These data are being investigated by Camilla Sorensen as part of her PhD through the University of Adelaide, which is expected to be completed in July 2014.

## Task 6: Groundwater recharge characteristics across key priority areas.

### Objectives

Task 6 had the following specific objectives:

1. A review of accessible groundwater bores in key areas in order to establish reliable sampling points (i.e. bores with known construction and geology logs). This process will also assist in identifying regions of data paucity that may be targeted in a drilling program.
2. Collection and analysis of groundwater samples for physical parameters, major ion chemistry and selected environmental tracers.
3. Sampling of key bores for regional estimation of groundwater age relationships.
4. Conduct isotope analysis of selected water samples to define groundwater residence times and hydraulic properties.
5. Definition of key groundwater recharge and discharge processes and rates across key priority areas for industrial development in the arid zones of northern South Australia. This task will also involve the identification of parameters associated with climate, soils, regolith, near-surface geology, landforms and vegetation that collectively influence recharge and discharge rates across the priority areas.
6. Develop a spatial understanding of groundwater ages across targeted aquifers in the priority areas and more generally across the arid north of the State.

These objectives were largely addressed through delivery of a single technical report (Leaney et al. 2013). Section 2 of the report delivers on Objectives 1, 2, 3, 4 through an on-ground field-sampling program conducted in the Musgrave Province/APY Lands in north western South Australia. Objectives 5 and 6 are addressed in Section 1 of that report and focus on the entire Far North of the State.

### Milestones

<b>TASK 6: MILESTONES</b>	<b>SUB-LEADER</b>	<b>START DATE</b>	<b>DUE DATE</b>
1. Complete review of available and accessible bores	Fred Leaney	1/3/2011	30/6/2011
2. Sampling and analysis of select bores initiated	Fred Leaney	30/3/2011	30/5/2011
3. Targeted drilling and sampling	Fred Leaney	1/6/2011	30/10/2011
4. Determination of regional groundwater ages	Fred Leaney	1/6/2011	30/10/2011
5. Report detailing groundwater recharge processes and ages across the priority areas	Fred Leaney	1/6/2011	30/10/2011

## Deliverables/Output

The main deliverable from this task is a Technical Report:

- Leaney, FW, Taylor, AR, Jolly, ID, and Davies PJ (2013) *Facilitating Long Term Out-Back Water Solutions (G-FLOWS) Task 6: Groundwater recharge characteristics across key priority areas*. Goyder Institute for Water Research Technical Report Series No. 13/6.

A second set of deliverables are two Honours Theses (Flinders University) on recharge processes, and hydrogeochemistry in the Musgrave Province:

- Craven, C (2012) *Sustainability of Regolith Hosted Aquifers in the Musgrave Province: Northern South Australia*. Honours Thesis, School of the Environment, Flinders University of South Australia.
- Custance, H (2012) *Hydrogeochemistry of shallow regolith hosted aquifers in the eastern Musgrave Province of South Australia*. Honours Thesis, School of the Environment, Flinders University of South Australia.

## Summary

The Musgrave Province/Anangu Pitjantjatjara Yankunytjatjara (APY) Lands was the focus of field investigations for this task. The Project Team worked diligently to gain access to this remote area, with help of the community and State Agency staff (DMITRE/PACE, DEWNR, AW NRM Board and APY Executive). The field trip was undertaken from 2-12 Oct 2012, and successfully sampled 21 groundwater bores, with a good spread across the APY Lands. This amount of sampling exceeded expectations due to the remoteness of the area and the unknown condition of historical bores and whether their infrastructure still existed. The results are described in detail in Leaney et al. (2013).

## Task 7: Desktop study on groundwater dependent ecosystems, linked cultural flows and ecological and environmental assets in priority areas.

### Objectives

The overarching objective of Task 7 was to identify the environmental and cultural values of water and water dependent ecosystems across South Australia's arid zones, including the priority areas described earlier, in addition to regions administered by the South Australian Arid Lands (SAAL) Natural Resource Management (NRM) Board (i.e. South Australian portion of the Lake Eyre Basin and the Far North Prescribed Wells Area) and the Alinytjara Wilurara (AW) Natural Resource Management (NRM) Board, namely the Anangu Pitjantjatjara Yankunytjatjara (APY) Lands, the Maralinga Tjarutja (MT) Lands, Yalata Indigenous Protected Area, and adjoining conservation zones, reserves and National Parks. Whilst the project was primarily focussed on South Australian resources, its findings also encompassed, and have relevance to arid zones in other Australian states. Specifically, Task 7 aimed to:

- Capture and document present knowledge on values of groundwater dependent ecosystems (GDEs) and surface water dependent ecosystems in the South Australian arid zone;
- Identify attributes for each value, and current and perceived threats to these attributes;
- Provide recommendations on future opportunities for research investment and collaboration, and develop a research prospectus that could be fully realised in the next phase of G-FLOWS (Stage-2).

### Milestones

<b>TASK 7: MILESTONES</b>	<b>SUB-LEADER</b>	<b>START DATE</b>	<b>DUE DATE</b>
• Desktop review complete	Dale McNeil	1/1/2011	30/6/2011
• Workshop held with key stakeholders	Dale McNeil	20/6/2011	30/9/2011
• Final project Report	Dale McNeil	20/5/2011	30/9/2011

### Deliverables/Outputs

The output from this task is documented in a technical report. This report encompasses Milestone 1: Desktop Review, and Milestone 2: Stakeholder Workshop.

- Macdonald JI and McNeil DG (2012) *Environmental and cultural values of South Australia's outback water resources*. Goyder Institute for Water Research Technical Report Series No. 12/7.

### Summary

Milestone 1 involved a review of existing knowledge to capture key water values in arid zones of South Australia, identify attributes for each value and threats to these attributes. Information and data were collected from several sources. The review also aided in selecting delegates from around the country to attend the Forum and Workshop (see Milestone 2).

Milestone 2 centred on a two-day forum and workshop entitled 'Cultural and Environmental Values of Outback Water Resources: Forum and Workshop' held at SARDI 10-11 May 2012. The overarching aim of this event was to bring together a diverse group of scientists, managers, community members, tourism operators, landowners and other stakeholders to discuss key environmental and cultural values of water resources in central Australia. 52 delegates attended the event, reflecting the multidisciplinary and multicultural demographic that has experience of working and living within, studying and managing arid zone environments.

## Task 8: Detailed documentation of aquifer systems, their extent and variability, and groundwater characteristics in priority areas.

### Objectives

Knowledge of groundwater resources in the Musgrave Province and the Anangu Pitjantjatjara Yankunytjatjara (APY) Lands in the Far North of South Australia is very limited. The objective of this task was to review and collate existing information on the character and variability of groundwater resources, the sustainability of this resource, and its relationship to environmental and cultural assets where possible.

### Milestones

<b>TASK 8: MILESTONES</b>	<b>SUB-LEADER</b>	<b>START DATE</b>	<b>DUE DATE</b>
1. Collation of data on critical and key aquifers in priority areas	Sunil Varma	1/3/2011	30/5/2011
2. Hydrogeological interpretation of data	Sunil Varma	1/4/2011	30/6/2011
3. Maps (GIS compatible) on groundwater levels, and water quality	Sunil Varma	1/7/2011	30/3/2012
4. Report on the hydrogeology of key priority areas and definition of GMU's	Sunil Varma	1/2/2012	30/3/2012

### Deliverables/Output

Work undertaken in this task supported the development of new hydrogeological framework for the Musgrave Province using 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 DMITRE) and South Australian hydrogeological data (through DEWNR).

This task delivered a holistic review of the hydrogeology and groundwater prospects of the Musgrave Province. The output from this task is documented in a technical report:

- Varma, S., 2012, *Hydrogeological review of the Musgrave Province, South Australia*, Goyder Institute for Water Research Technical Report Series No. 12/8.

Milestone 8.3 consists of two maps that are part of the Varma (2012) report, and are replicated here.

The groundwater flow pattern in the Musgrave Province has been studied from the limited available data (see Fig. A1 [Fig. 10 in Varma 2012]). A hydraulic gradient of about 0.0015 has been estimated for the eastern part of the Musgrave Province since sufficient water level data exist to construct watertable elevation contours.

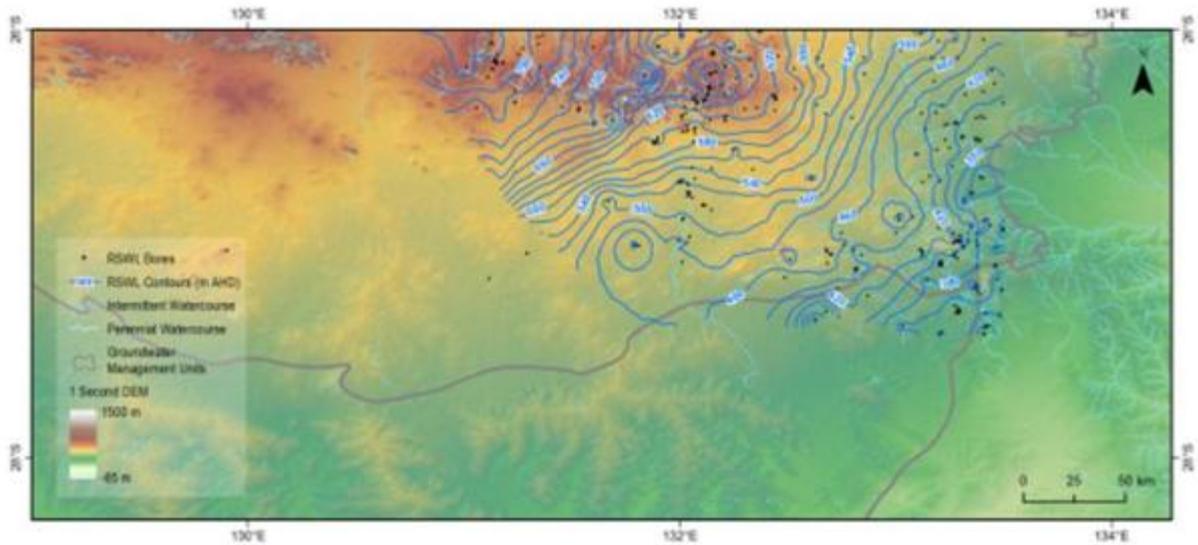


Fig. A1. Regional watertable (RSWL) contours (m AHD) for the eastern Musgrave Province. Data density is shown as black dots. There is a lack of watertable elevation data in the western part. Groundwater flow is perpendicular to the contours. A watertable may not exist where basement outcrops occur unless they have laterally and vertically connected fractures that are saturated with groundwater.

A salinity distribution map (Fig. A2 here [Fig. 11 in Varma 2012]) has been prepared and colour coded for the aquifer intersected in the various bores for the Musgrave Province. Groundwater is either fresh or marginally brackish with lower salinity groundwater occurring near the granite and gneiss outcrops due to recharge from the concentration of runoff over the rocky outcrops. The median salinities of the groundwater in the different aquifers are generally less than 1500 mg/L (Table 1). Groundwater salinity in the palaeovalleys varies from 500 to >10,000 mg/L.

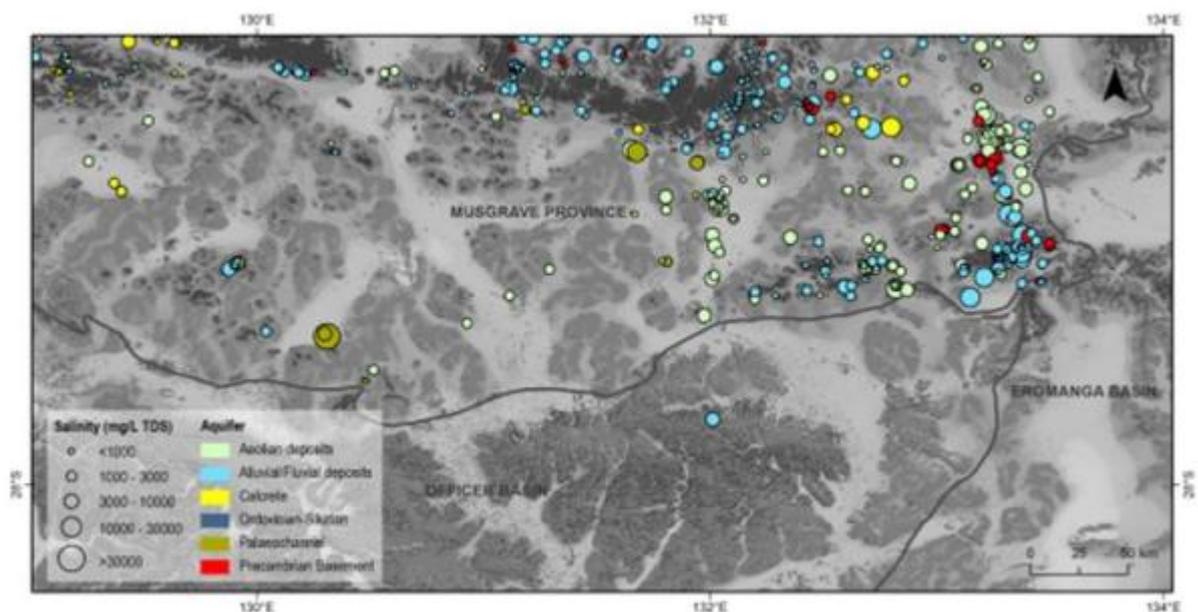


Fig. A2. Groundwater salinity in the Musgrave Province, colour coded with respect to the aquifer intersected. The background map shows the surface of valley bottoms based on their topographic signature as flat low-lying areas based on MrVBF algorithm (Gallant and Dowling, 2003).

## Task 9: Final report for Stage 1

### Objectives

This task will deliver a final summary report for G-FLOWS Project (Stage-1) and provide recommendations for follow-up studies in other priority areas.

### Milestones

<b>TASK 9: MILESTONES</b>	<b>SUB-LEADER</b>	<b>START DATE</b>	<b>DUE DATE</b>
• Preliminary outcomes from early tasks documented	Tim Munday	1/4/2011	30/6/2011
• Draft Final report circulated to Stakeholders	Tim Munday	1/4/2012	31/5/2012
• Final Stage 1 report delivered	Tim Munday	1/6/2012	30/6/2012

### Deliverables/Outputs

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

- Gilfedder, M, Munday, T (2013) *Facilitating Long-term Outback Water Solutions (G-FLOWS Stage-1) Final Report*. Goyder Institute for Water Research Technical Report Series No. 13/x.

### Summary

Preliminary draft report circulated to Goyder Office in April 2013.

Draft report circulated to Goyder Office May 2013, and submitted for internal review.

## Task 10: Industry Workshop

### Objectives

To undertake a stakeholder workshop to define and refine the science direction and case study area for the G-FLOWS Stage-2 project in the northern Eyre Peninsula region. It also provides two months bridging funds to ensure continuation of PhD funding to University of Adelaide.

This task was added through a Contract Variation signed on March 19 2013.

### Milestones

<i>ADDED TASK: CONTRACT VARIATION IN 2013</i> <b>TASK 10: MILESTONES</b>	<b>SUB-LEADER</b>	<b>START DATE</b>	<b>DUE DATE</b>
• CSIRO work on Industry Workshop & Outcomes	Tim Munday	1/1/2013	1/2/2013
• C Sorensen PhD extended .27 FTE	Tim Munday	1/1/2013	28/2/2013

### Deliverables/Outputs

This task delivered a successful and well-attended workshop on 31/1/2013. This workshop involved staff from Goyder Institute, G-FLOWS Stage-1 Project Team (CSIRO, FUSA, UoA), Government Agencies (DEWNR, DMITRE/PACE), and representatives from twelve mineral exploration companies/consultants.

### Summary

The final study area was decided at a project meeting (5/11/2012) and identified as the northern Eyre Peninsula. This is an area of active exploration and mining, with considerable water availability issues. Stakeholder needs and wishes (industry and government) were clarified at a well-attended workshop (31/1/2013). This has helped define and refine the science direction and workplan for G-FLOWS Stage-2.

The agenda for the meeting included:

- DEWNR FLOWS Initiative background/DEWNR activities (including the non-prescribed groundwater assessments currently being conducted in the Eyre peninsula) (5 mins Adrian C)
- G-FLOWS Stage-2 project framework/background/general goals (10 mins Mat G)
- Goyder Institute background (15 mins Neil P)
- G-FLOWS Stage-1 Project – (20 mins Tim M)
- Define study area (northern Eyre Peninsula) with a map (Mat G and Adrian C) and touch on DEWNR activities to date
- Areas of interest for PACE and discuss existing geophysical (extent of AEM) and other regional datasets (if any) available to DMITRE and G-FLOWS Stage-2 project (Miles D)
- Roundtable discussion with industry stakeholders to discuss:
  - Current water requirements and water use (i.e. where is water currently sourced from)
  - Area of interest (if not sensitive)
  - Experiences with drilling and presence of groundwater
  - Canvass views of Industry et al on what is known and what, in their view is lacking

## Recommendations from Task 10

The outcomes from the stakeholder workshop are summarised here:

### Study Area

- Refined study area to include:
  - a. Kimba area and northwards to edge of volcanics (and possibly further north if impacts on rest of area)
  - b. Largely north of the line between the towns of Lock and Cleve

### Key Issues / Gaps

- Aquifer characterisation, water quality, and storativity
- Groundwater age, recharge and discharge
- Lateral connectivity of aquifer systems
- Vertical connection between fractured rock aquifers and overlying regolith/alluvial aquifers
- Regionality of flow systems – local vs regional connectivity (scales)
- Fine scale studies using geophysics to better understand fractured rock systems – structural controls and scaling, modelling and uncertainty.
- Social science component – community concerns and links to water quality- Links
- Groundwater Dependent Ecosystems (GDEs) – definitions and localities – e.g. Lake Gilles
- Connection to Poldas Basin.

### Project

- Good initial support for data sharing
- Collaborative approach to maximise benefit to all
- Key contacts defined and stakeholders advised
- Geophysical data availability
- Existing hydrogeological knowledge
- Likely community response tied to land use
- Need to understand the nature and extent of ongoing DEWNR work in Eyre Peninsula



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.