Project Order

Proforma 2016

1. Short Project Title (less than 15 words)

Impacts of Coal seam gas (CSG) depressurization on the Great Artesian Basin (GAB) flux

Long Project Title	Impacts of CSG depressurization on Great Artesian Basin flux: conceptual model refinement, uncertainty analysis and hypothesis testing
GISERA Project Number	W7
Proposed Start Date	01 July 2016
Proposed End Date	30 June 2018 (PhD student 30th June 2019)
Project Leader	Sreekanth Janardhanan

2. GISERA Region

☐ Queensland ☒ New South Wales ☐ Northern Territory

3. GISERA Research Program

☒ Water Research ☐ GHG Research ☐ Social & Economic Research
☐ Biodiversity Research ☐ Agricultural Land Management Research

4. Research Leader, Title and Organization

Dr. Sreekanth Janardhanan, Research Scientist, CSIRO Land and Water (0.3 FTE)

5. Project Description

The proposal for CSG development in the Pilliga forest in northern NSW has raised a number of water flow questions. The Pilliga forest is the main recharge area for the Pilliga Sandstone aquifer, which is part of the Great Artesian Basin (GAB) aquifer system. There is concern that depressurization of coal seams for producing gas may potentially impact groundwater pressure in the Pilliga Sandstone aquifer and affect the quantity of water recharged into the GAB.

Groundwater flow models are routinely developed to gain better quantitative understanding of the groundwater system changes and impacts caused by external stresses. The conceptual understanding about the groundwater system informed by many different types of groundwater data underpins the reliability of model predictions. Refining the conceptualization of the flow system using new and improved data in an iterative process (Gedeon et al., 2013) is key to minimize uncertainty and improve reliability of and confidence in model predictions. This is important for predicting CSG impacts on flow in the GAB because model predictions inform very important management decisions.

There is very limited amount of data that underpin the conceptualization of interactions between the Surat and Gunnedah basins and the Namoi River alluvial aquifers in the Pilliga area. It is therefore important to integrate the knowledge from multiple lines of evidence and determine the key (conceptual and parameter) uncertainties that have a significant impact on predictions. In this way, research is able to subsequently collect additional data that provides the most accurate information to progressively minimize uncertainty in the prediction of CSG impacts on GAB flow.

Research context

The proposed project aims to assess the probability of extremes around CSG-induced changes to the regional groundwater balance and GAB fluxes. It will build up on the knowledge gained from a number of recently completed and/or ongoing research work including:

1) Great Artesian Basin Water Resources Assessments (Smerdon and Ransley (eds), 2012): this assessment provides a review of the recharge estimates for major recharge areas including the Pilliga Sandstone outcrops. The GABWRA report (Smerdon and Ransley (eds), 2012) highlights existing gaps in the water balance, explaining that "there have been widely disparate estimates of the water balance of the Pilliga Sandstone aquifer system, with estimates of recharge ranging over nearly two orders of magnitude (Habermehl et al., 2009; Wolfgang, 2000)"
2) Hydrochemical and isotopic assessment by Creswell (2014): this study evaluated new measurements from a sampling campaign in 2014 in the proposed project area. It interpreted these data in the context of earlier work from GABWRA (Smerdon and Ransley (eds), 2012) and other studies, and provides an excellent summary of the existing conceptual

understanding. The following knowledge gaps and limitations can be concluded from this study:

- The initial ^{14}C concentration is unknown and needs to be independently verified with tritium and possibly ^{39}Ar measurements on newly collected samples within the recharge areas.
- Existing tritium measurements appear to have detection limits of 0.2-0.5 TU and can therefore indicate only admixtures of larger than 10% recent rain. Today's State-of-the-art detection limits are a factor of 10-100 better, which allows for the detection of 1% of young water or less.
- Radiocarbon values were assessed without knowing the initial ^{14}C in the recharge area or assessed using simple correction models. Similarly, regional ^{36}Cl values have all been interpreted with the same initial $^{36}Cl/Cl$. Recharge $^{36}Cl/Cl$ therefore needs to be verified with combined ^{14}C and ^{36}Cl measurements on the same samples.

  Creswell (2014) indicate that there is no evidence for upward cross-formational GW movement based on an assessment of hydrochemistry. However, the detection limit of hydrochemical indicators towards influx of groundwater from deeper formations via fractures and faults or aquitard leakage is in the range of 5-10% admixture of deep water (e.g. fluoride concentration in the Maules Creek Formation is 6-12 mg/L and 0-1.5 mg/L in the Pilliga Sandstone). In contrast, helium can indicate admixtures in the per mil range because deeper aquifers (e.g. Black Jack Group or Maules Creek Group) – if indeed containing much older groundwater – contain up to a factor of 1000 higher helium concentrations than the shallower aquifers (e.g. Pilliga Sandstone). Helium therefore is a much more sensitive parameter for upward flowing groundwater and will provide more robust indications of cross formational flow.

A detailed assessment of existing hydrochemical and isotopic data is provided in an appendix.

3) Ongoing groundwater modelling and uncertainty analysis for the Namoi region in the Bioregional Assessment (BA) Programme: Groundwater modelling undertaken in BA focus on predicting changes in groundwater pressure/ water level at specified receptors (e.g. irrigation bores) caused by the cumulative effects of CSG and coal mining developments. Quantification of the probability extremes around changes in the GAB flux caused by CSG development in the Pilliga Sandstone are not a focus of the BA study. Also, the modelling method used in BA is not directly suitable for quantifying the probability extremes around GAB flux changes. However, the numerical modelling framework using the state-of-the-art MODFLOW USG and representation of the diffuse and river recharge processes used in the development of the BA model can be easily and effectively adapted in the modelling task of the proposed project. It is also notable that no new data collection including that of environmental tracers is undertaken as part of Bioregional Assessments. The collection of new environmental tracer and hydroochemical data in task 4 of the proposed project will

help to constrain the conceptual understanding of the system which in turn will lead to a reduction of the model prediction uncertainty.

4) Groundwater modelling undertaken in the CSIRO Faults and Aquitards project: on the other has an improved representation of the aquitards in between the Surat and Gunnedah Basins in a modified version of the Santos EIS groundwater model (CH2M Hill, 2014). Groundwater modelling in the proposed study will use the improved knowledge on aquifer-aquitard connectivity emerging from Faults and Aquitards project. While the groundwater models used in the BA and Faults and Aquitard projects are not independently suitable for the proposed study, integration of useful knowledge from these models in task 5 will provide useful information for minimizing the uncertainty around potential impacts of the CSG development in the Pilliga forest on the GAB fluxes.

5) University of New South Wales (UNSW) research: UNSW has conducted extensive research in the Namoi region (e.g. McLean, 2003; Kelly et al., 2014). However, a preliminary literature review and discussions with UNSW researchers confirmed that most of UNSW's research in the Namoi River catchment focussed on the hydrodynamics of the alluvial aquifers and alluvium-bedrock interaction.

The knowledge emerging from this high volume of previous and ongoing work will be used to the full extent to inform the proposed study. This improved conceptualization and representation of faults and aquitards in regional groundwater models and the extensive work that Santos is undertaking in the assessment and monitoring of groundwater across the Pilliga region, university research (UNSW), and studies conducted by other agencies including the government of NSW. The project team members' direct involvement in ongoing studies enables leveraging the knowledge from these studies to provide quick preliminary estimates of water balance and uncertainty in CSG-induced GAB flux changes within a period of 6 months. This will allow to build a staircase of confidence based on a stepwise reduction of conceptual and parameter uncertainties.

6. Budget Summary

Expenditure	2015/16	2016/17	2017/18	2018/19	Total
Labour	0	188,504	144,783	0	333,287
Operating	0	60,000	40,000	10,000	110,000
Subcontractors	0	3,000	7,000	0	10,000
Total Expenditure	**0**	**251,504**	**191,783**	**10,000**	**453,287**

Expenditure per Task	2015/16	2016/17	2017/18	2018/19	Total
Task 1	0	52,402	11,304	0	63,706
Task 2	0	13,451	17,763	0	31,214
Task 3	0	101,142	49,229	0	150,371
Task 4	0	80,609	24,257	0	104,866
Task 5	0	23,900	69,229	10,000	103,129
Total Expenditure	**0**	**271,504**	**171,782**	**10,000**	**453,287**

Source of Cash Contributions	2015/16	2016/17	2017/18	2018/19	Total
GISERA Industry Partners (25%)	0	62,876	47,946	2,500	113,322
- Santos (12.5%)	0	31,438	23,973	1,250	56,661
- AGL (12.5%)	0	31,438	23,973	1,250	56,661
NSW Government (25%)	0	62,876	47,946	2,500	113,322
Federal Government (25%)	0	62,876	47,946	2,500	113,322
Total Cash Contributions	**0**	**188,628**	**143,838**	**7,500**	**339,966**

In-Kind Contribution from Partners	2015/16	2016/17	2017/18	2018/19	Total
CSIRO (25%)	0	62,876	47,946	2,500	113,322
Total In-Kind Contribution from Partners	**0**	**62,876**	**47,946**	**2,500**	**113,322**

	Total funding over all years	Percentage of Total Budget
GISERA Investment	113,322	25%
NSW Government Investment	113,322	25%
Federal Government Investment	113,322	25%
CSIRO Investment	113,322	25%
Total Other Investment		
TOTAL	**453,288**	

Task	Milestone Number	Milestone Description	Funded by	Start Date (mm-yy)	Delivery Date (mm-yy)	Fiscal Year	Fiscal Quarter	Payment $
Task 1	1.1	Stakeholder workshop	GISERA	Aug-2016	Aug-2016	16/17	1	47,780
Task 2	2.1	Preliminary modelling and water balance report (task3 +4)	GISERA	Jan 2017	Jan-2017	16/17	3-4	23,411
Task 3	3.1	Water balance analysis report (task 3 + 4)	GISERA	Jul 2016	Jan 2017	16/17	1-2	112,778
Task 4	4.1	Conceptual modelling report	GISERA	Jul 2016	Jul-2017	16/17	1-4	78,650
Task 5	5.1	Uncertainty analysis and hypothesis testing report	GISERA	Jul-2017	Jun-2018	17/18	1-4	77,347

7. Other Researchers (include organisations)

Researcher	Time Commitment (project as a whole)	Principle area of expertise	Years of experience	Organisation
Tao Cui	0.2FTE	Groundwater modelling and uncertainty analysis	6	CSIRO
Matthias Raiber	0.3FTE	3D geological modelling and hydrochemistry	11	CSIRO
Axel Suckow	0.1 FTE	Multiple environmental tracer measurement & interpretation	25	CSIRO
Andrew Taylor	0.05FTE	Environmental Tracer Sampling, organization of field trip	13	CSIRO
Mat Gilfedder	0.15 FTE	Hydrology / project management	22	CSIRO
Sreekanth Janardhanan	0.3FTE	Groundwater modelling and uncertainty analysis	9	CSIRO
Trevor Pickett	0.1FTE	Software development	12	CSIRO
Luk Peeters	0.1 FTE	Uncertainty analysis and groundwater modelling	12	CSIRO
Kate Holland	0.1FTE	Ecohydrology/Groundwater Dependent Ecosystems	17	CSIRO
PhD student	3FTE	Conceptual/numerical modelling		CSIRO/UQ

8. Subcontractors

Subcontractors (clause 9.5(a)(i))	**Subcontractor**	**Role**
	Catherine Moore, GNS New Zealand	Consultant (advisory role)

9. Project Objectives and Outputs

The work proposed in this study aims to integrate multiple lines of evidence and refine the groundwater system conceptualization specifically focusing on CSG induced GAB flux changes and will apply and extend novel methods for the assessment and communication of probability extremes around GAB flux predictions underpinning management decisions. The proven and tested methods that have already been successfully applied to similar case studies in the CSG context in GISERA QLD (Sreekanth and Moore, 2015, Suckow et al., 2016) will be applied to test and accept/reject hypotheses about changes in GAB fluxes. For example, effective recharge can be better quantified from tracer measurements and hypotheses such as “CSG depressurization will result in a decrease in the Pilliga Sandstone fluxes to the broader GAB by 2%” can be explored and accepted/rejected at a high confidence level.

The objective of this project is to:

1) <u>Improve the conceptual understanding of GAB flux in the Pilliga region</u>: this includes integrating information from existing conceptual and numerical models (e.g. aquifer geometry, internal aquifer architecture and geological structure), hydrochemical data and environmental tracer data. This will help to minimise uncertainty in the conceptualization of the hydrodynamics and water balance of the Pilliga Sandstone, its interaction with recharge flux from south-eastern outcrops of the Pilliga Sandstone and its hydraulic connection with the underlying Gunnedah Basin. The assessment of existing data will be supplemented by collection of samples for environmental tracers from new groundwater observation bores installed in the areas of interest in the Pilliga Sandstone and the underlying Gunnedah Basin by NSW DPI Water.
2) <u>Assess the probability of extremes around CSG induced GAB groundwater head and flux changes</u> using state-of-the-art uncertainty analysis and modelling techniques for its assessment and communication. Novel methods based on Pareto-front concept (Moore *et al*., 2009; Sreekanth *et al*., 2016) will be applied to explore the trade-off between a hypothesised extreme prediction and its likelihood.

10. GISERA Objectives Addressed

Carrying out of research and improving and extending knowledge of social and environmental impacts and opportunities of unconventional gas projects for the benefit of the Gas Industry, the relevant community and the broader public.

Informing government, regulators and policy-makers on key issues regarding policy and legislative framework for the Gas Industry.

11. Project Development (1 page max.)

The project was developed in consultation with a number of stakeholders including the industry (Santos), University researchers (UNSW, UQ) and government agencies (DPI, NSW). Review of literature and personal communications with University researchers confirmed that while a lot of data collection and analysis have been conducted in the Namoi catchment and alluvial aquifers to study alluvial hydrodynamics and alluvium-bedrock interaction (e.g. McLean, 2003; Kelly et al., 2014; Lamontagne et al., 2015), there is only very limited quantification of the recharge in to the deeper GAB aquifers. Therefore there is no quantification of probable extreme changes in GAB fluxes caused by CSG development and its likelihood. This has led to widespread speculations on potential impacts of CSG on GAB fluxes ranging from one extreme of ‘no impacts’ (ABC News, 2015) to another extreme of ‘widespread impacts” (Stop Pilliga Coal Seam Gas, 2015). Current public discussion centers on the remaining uncertainty in groundwater impact predictions which result from the inevitably incomplete knowledge about the underground geology and insufficient quantification of deeper recharge. It is of key importance to demonstrate, which risks can be confidently excluded because of physical laws, which risks are possible but have a low probability and which risks are likely. Based on this knowledge, adaptive management strategies can be developed.

The proposed method can test hypotheses around these extremes and put likelihood measures around these hypothesised impacts. Quantification of prediction extremes of the flux changes can also inform management decisions such as necessity of mitigation measures and licensing changes to allocations. Among the stakeholders there is recognition of the value and necessity of an integrated approach that considers multiple lines of evidence (tracers, hydrochemistry and modelling) for the understanding of the Pilliga Sandstone. Although considerable previous research has been conducted on the Namoi River alluvium and its interaction with the sedimentary bedrock, substantial uncertainties exist on the hydrodynamics of the Pilliga Sandstone and its interactions with the underlying Gunnedah Basin, and the estimates of flux from the south-eastern outcrops of the Pilliga Sandstone to the broader GAB are absent or not reliable. Although groundwater models have been developed in previous studies, none of these models independently incorporates all the knowledge/data on the geological and hydrogeological conceptualization that is currently available for an uncertainty-based quantification of CSG-induced changes in the GAB flux. Hypothesis testing to minimise uncertainty of extreme predictions of changes in GAB flux estimated in this study will integrate the relevant knowledge captured in existing groundwater models and improved conceptualization of GAB flux underpinned by existing and new data. Furthermore, state-of-the-science methodologies successfully developed and tested in GISERA QLD, will also form a strong basis for developing new and improved methods to better answer the question on CSG-induced GAB flux changes and increase confidence in the model predictions.

Stakeholders and CSG industry will benefit from the new conceptual and quantified understanding of the CSG-induced flux changes from the Pilliga Sandstone to the south-eastern part of the GAB. Quantification of prediction extremes of the flux changes can inform management decisions such as the necessity of mitigation measures and licensing changes to allocations. The study will also inform investment priorities for future data collection based on data-worth analysis.

12. Project Plan

The research is designed to proceed in two stages. The first stage will be completed in the first 6 months and will include a stakeholder consultation workshop, the preliminary modelling and water balance analysis and a preliminary review of existing hydrochemical and isotopic data. Tasks 2, 3 and part of task 4 will be undertaken in a parallel fashion following completion of task 1.

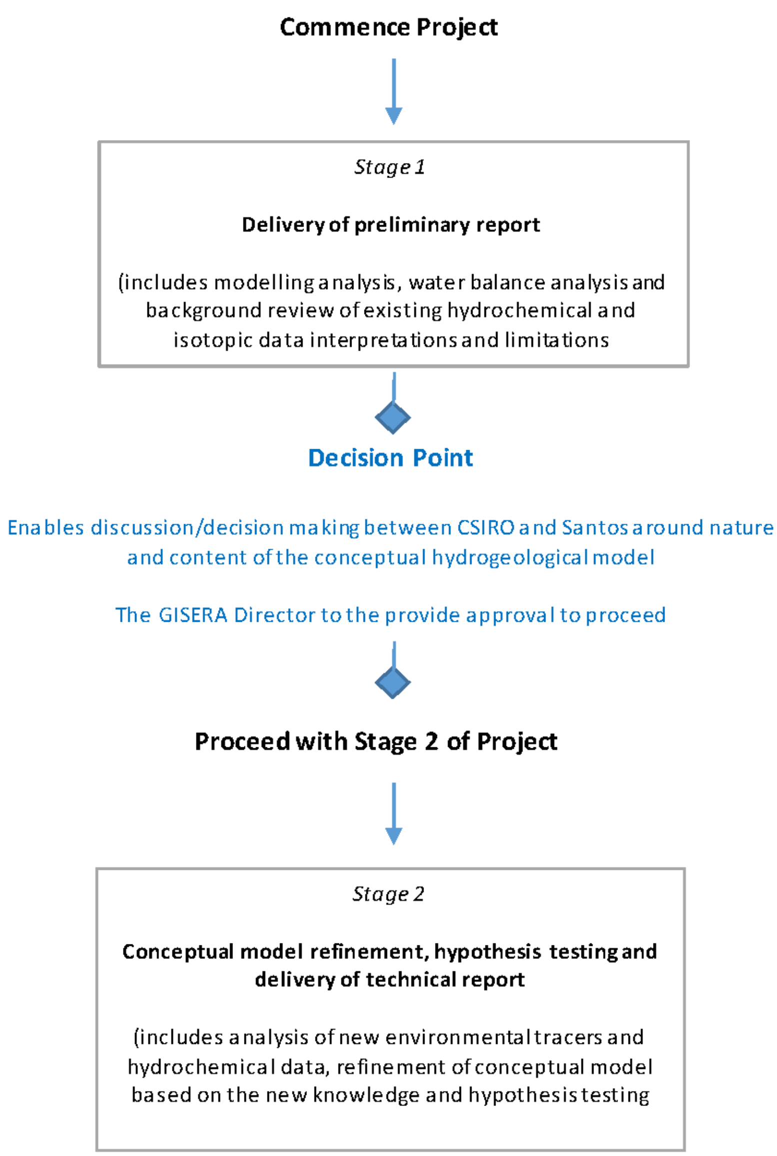
A preliminary report will be delivered following completion of stage 1.

The decision point between stage 1 and 2 will occur in January 2017 and is designed to:

i) ensure CSIRO researchers consult with Santos groundwater specialists to ensure the work contains the relevant information.

ii) enable shared negotiation/decision making occurs between CSIRO and Santos around the nature and content of the conceptual hydrogeological model of the Pilliga Sandstone.

Following the approval of the GISERA Director, the project can progress to Stage 2.



12.1 Project Schedule

ID	Task Title	Task Leader	Scheduled Start	Scheduled Finish	Predecessor
Task 1	Stakeholder workshop	Matthias Raiber/Mat Gilfedder	August 2016	August 2016	
Task 2	Preliminary modelling analysis	Sreekanth Janardhanan	August 2016	Jan 2017	Task 1
Task 3	Water balance analysis	Tao Cui	Jul 2016	Jan 2017	Task 2
Task 4	Conceptual model refinement	Matthias Raiber	July 2016	July 2017	Task 1 and 2
Task 5	Hypothesis testing	Sreekanth Janardhanan	Jul 2017	Jun 2018	Task 4

Task 1

TASK NAME: Stakeholder consultation workshop

TASK LEADER: Matthias Raiber/Mat Gilfedder

OVERALL TIMEFRAME: August 2016

BACKGROUND: The proposed project strongly builds on existing data (Santos, government) and models such as the models developed and used in the CSIRO projects (BA, OWS). To allow an effective integration of these data and models into the proposed work a workshop will be held at the start of the project. The workshop will provide a communication platform between the project team and key stakeholders such as, Santos, government and CSIRO researchers.

TASK OBJECTIVE: The main objectives of the workshop are;

- to ascertain that all existing data, models and knowledge is adequately incorporated into the project and that key stakeholders have the opportunity to provide additional feedback on the data collection strategy and the modelling approach.
- to review and ascertain the opportunities for new data collection in the existing wells of NSW government and Santos
- to establish a longer-term connection between the researchers of this new project and the stakeholders and to coordinate interactions and a communication platform that will ascertain close interactions throughout the remainder of the project.

TASK OUTPUTS: Refined work plan for the project

SPECIFIC DELIVERABLES: 1-day workshop

Task 2

TASK NAME: Preliminary modelling analysis

TASK LEADER: Sreekanth Janardhanan

OVERALL TIMEFRAME: Jul 2016 – Jan 2017

BACKGROUND: This task will leverage and benefit from the ongoing CSIRO groundwater modelling and uncertainty analysis undertaken in the current modelling work for the Namoi subregion. Based on the given conceptualization of the groundwater system in the latest model available, this exercise will give a preliminary estimate of the predictive uncertainty in CSG-induced GAB flux changes. The uncertainty analysis undertaken in this exercise also informs the relative worth of different data types and hydraulic properties in reducing the prediction uncertainty in GAB fluxes.

TASK OBJECTIVE: The main objective of this task is to undertake a preliminary uncertainty and data-worth analysis using the pre-existing groundwater model for the Namoi region for CSG-induced change in GAB flux.

TASK OUTPUTS: Preliminary estimate of the change in GAB flux caused by CSG development and the associated uncertainty.

SPECIFIC DELIVERABLES: Technical report on preliminary groundwater modelling and uncertainty analysis (shared with task 3).

Task 3

TASK NAME: Water balance analysis

TASK LEADER: Tao Cui

OVERALL TIMEFRAME: Jul 2016 – Jan 2017

BACKGROUND: Most of the components of groundwater balance such as the diffuse recharge from rainfall, the amount of storage and the discharge through rivers can be estimated independently. For example, long-term mean recharge can be derived from a Chloride mass balance analysis. The independent water budget estimates forms a key component of a conceptual model and provides context for groundwater modelling.

TASK OBJECTIVE: The specific objective of this task is to conduct independent groundwater budget analysis to provide constraints for any subsequent work as it estimates the magnitude of current fluxes. In addition, insights of the water balance can inform and improve the conceptual understanding of the Pilliga Sandstone aquifer groundwater dynamics undertaken in task 4. All existing estimates of the water balance components will be collated and reviewed. The independently estimated water balance components will be integrated in a mass balance calculation, either directly or via a numerical model. The water balance analysis also help identify important components, processes and stresses of the Namoi groundwater system.

TASK OUTPUTS: A tabulation of estimates of water balance components with associated uncertainties for the chosen water balance area that encompasses the Narrabri Gas Project.

SPECIFIC DELIVERABLES:

1) Technical report on preliminary groundwater modelling and uncertainty analysis (shared with task 2) Fact sheet on the GAB focusing on the Pilliga Sandstone (within 3 months of the start of the project)

Task 4

TASK NAME: Conceptual model refinement

TASK LEADER: Matthias Raiber, Axel Suckow

OVERALL TIMEFRAME: Jul 2016 – Dec 2017

BACKGROUND: Following the preliminary modelling analysis and water balance assessment, the fourth task of this project aims to improve the conceptual hydrogeological model of the Pilliga Sandstone (GAB). Conceptual hydrogeological models, which provide the understanding of how different components of hydrogeological systems operate and interact, are generally subjected to considerable uncertainties and are often developed to describe specific processes and/or are based on subsets of data (e.g. due to the focus on answering specific questions or due to data availability limitations).

TASK OBJECTIVE: The specific objective of this task is to test and improve the conceptual understanding of GAB flux in the Pilliga region: this includes integrating information from existing conceptual and numerical models (e.g. aquifer geometry, internal aquifer architecture and geological structure), hydrochemical data and environmental tracer data. This will help to minimise uncertainty in the conceptualization of the hydrodynamics and water balance of the Pilliga Sandstone (a GAB hydrostratigraphic unit), its interaction with recharge flux from south-eastern outcrops of the Pilliga Sandstone and its hydraulic connection with the underlying Gunnedah Basin.

Existing knowledge and data from previous projects (e.g. studies conducted by Santos as part of the Environmental Impact Statement Process, Office of Water Sciences Faults and Aquitards projects, NSW government, Bioregional Assessment and the University of New South Wales, Cresswell, 2014) will be compiled and reviewed. This will be further supplemented by collection and analysis of hydrochemical and selected environmental tracer samples (e.g. ^{2}H, ^{18}O,, ^{3}H, ^{14}C, ^{36}Cl, helium, ^{85}Kr, ^{39}Ar, ^{81}Kr, noble gases) from new groundwater monitoring bores installed in the Pilliga Sandstone (GAB) and the underlying Gunnedah Basin hydrostratigraphic units by NSW DPI Water and from existing Santos monitoring bores.

The preliminary assessment of existing hydrochemical and isotopic data (Cresswell, 2014) showed that there is a particular need to independently verify previous ^{36}Cl measurements with ^{14}C and ^{81}Kr (the latter is not influenced by geochemical processes and will not be impacted by dead chloride). Furthermore, the collection of samples from multi-level observation bores will help to determine a depth profile of environmental tracers at one location. This will enable direct comparison of tracer concentration depth profiles with conceptual models. The current conceptual model which suggests that there is no evidence for upward cross-formational groundwater movement (Cresswell, 2014) is based primarily on hydrochemical data. However, the analysis of helium proposed in this study is a much more sensitive parameter than hydrochemistry to determine upward flowing groundwater and will provide more robust indications of cross formational flow.

Overall, the integrated assessment of hydrochemical and isotopic patterns within the Pilliga Sandstone and the underlying Gunnedah Basin will form an independent line of evidence to test existing conceptual models of recharge mechanisms and connection between the GAB and Gunnedah Basin. Environmental tracer data will add the critical component on temporal aspects of groundwater flow, resulting in an improved understanding of flow velocities and the timing and quantification of effective recharge to the deeper parts of the GAB aquifers.

This integrated assessment of geology (e.g. aquifer geometry, internal aquifer architecture and geological structure), groundwater recharge estimates, aquifer hydraulic properties and hydrochemical (e.g. from NSW groundwater database or from the Santos groundwater database) and isotopic data in close consultation with key stakeholders will help to improve the conceptual model of this multi-aquifer system. It will also allow identification of knowledge gaps and weaknesses or inconsistencies in the existing conceptual hydrogeological models.

The improved hydrogeological conceptualisation developed in this task has been identified as a knowledge gap in the classification of water dependent assets and receptors that was undertaken in the Bioregional Assessment for the Namoi subregion. In contrast to the Namoi subregion, the landscape classification for the Maranoa-Balonne-Condamine subregion includes data that describes the hydrogeological connection of GDEs in the subregion, which is consistent with the National GDE atlas. Improved conceptual and spatial understanding of the hydrogeological connections of GDEs will inform hypothesis testing and analysis of the potential impacts of the CSG development to groundwater-dependent assets in the Namoi region.

TASK OUTPUTS: An improved conceptual hydrogeological model based on all available data, providing an increased confidence in the understanding of hydrogeological flow regimes of the Pillaga Sandstone and its connectivity with the underlying Gunnedah Basin. Identify methods and spatial datasets to improve the conceptualisation of the hydrogeological connection of GDEs in the Namoi region in consultation with NSW Office of Water and MDBA.

SPECIFIC DELIVERABLES: Technical report and journal papers on the conceptual model development and method to improve the understanding of the hydrogeological connection of GDEs in the Namoi region. A preliminary background review of existing hydrochemical and isotopic data interpretations and limitations will be provided by Jan 2017 (included in Task 3 technical report).

Task 5

TASK NAME: Hypothesis testing

TASK LEADER: Sreekanth Janardhanan

OVERALL TIMEFRAME: Jul 2017 – Jun 2018

BACKGROUND: A numerical groundwater flow model underpinned by the improved conceptual hydrogeological model and constrained by different types of existing and new groundwater observations obtained from Task 4 will be used for hypothesis testing. Groundwater modelling undertaken in this task will use the state-of-the-science modelling platform MODFLOW USG package (Unstructured grid package) that offers the most promising features in terms of relevance to the CSG context. MODFLOW USG offers many of the advantages of finite element packages, potentially without some of the drawbacks e.g. long model run times, compromised ability to interrogate flux terms etc. MODFLOW USG also supports the conduit package which will be important for analyzing the impacts of fault representations within the Surat/Gunnedah basins. The flexibility offered by unstructured grids permit better representation of preferential flow pathways in the numerical model.

The specific hypothesis testing method used implements a 'Pareto-front' approach. This method is suitable for testing probability extremes in groundwater model predictions. The Pareto-front approach provides a trade-off between a hypothesised extreme prediction and its likelihood. The Pareto-front approach can thus explore the combinations of model parameterization for which the hypothesised extreme prediction can occur. If the parameter combinations obtained are not feasible to occur while honouring the measurements and knowledge underpinning the model, the hypothesis can be rejected with a reasonable level of confidence.

Using this methodology we can assess the probability of CSG induced groundwater impacts.

Hypotheses on GAB flux and groundwater head changes to be tested will be selected at the time this task is undertaken based on the results from previous tasks and stakeholder inputs. Using the proposed methodology these hypotheses can be tested and accepted/rejected with high confidence level (e.g. 95%).

TASK OBJECTIVE: Assess the probability of extremes around CSG induced GAB flux and head changes using state-of-the-art uncertainty analysis and modelling techniques for its assessment and communication. Novel methods based on Pareto-front concept (Moore *et al.*, 2009; Sreekanth *et al.*, 2016) will be applied to explore the trade-off between a hypothesised extreme prediction and its likelihood. In summary the work aims for:

- Quantification of the risk of hypothesized impacts occurring. These risks will relate to the five key predictive simulations of regional groundwater flux and head changes around risk receptors including chosen farmers bores and key ecological assets in the GAB. These will be selected based on improved knowledge of the geometries of geological strata, spatial distribution of hydraulic parameters, risk receptor locations and CSG development scenarios.
- Specification of confidence intervals of the predictions (e.g. 95%, 99,9%).

TASK OUTPUTS: Prediction of GAB flux changes and confidence levels.

SPECIFIC DELIVERABLES: Technical report, progress presentation at project workshops and submission of paper demonstrating the methodology and application.

Gas Industry Social & Environmental Research Alliance

13. References

ABC News, 2015 Hydrogeologist Dr Richard Cresswell says Santos CSG operation wont impact on water resource in Pilliga. Webpage archived on April 14 2016 at: http://web.archive.org/web/20160119082707/http://www.abc.net.au/news/2015-07-15/pilliga-csg-no-threat-to-water/6620952

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GISERA Gas Industry Social & Environmental Research Alliance

14. Communications Plan

The following communication strategy is envisaged:

1) A factsheet about Great Artesian Basin focusing on the Pilliga will be produced within the first 3 months of commencement of the project
2) The interim and final reports will be published on the GISERA website after necessary approval process.
3) A symposium/knowledge transfer session will be organized within the first 18 months of the project to synthesize and communicate the major results emerging from the research project and evaluate any potential policy implications of the findings. The target audience for the symposium include NSW government (DPI Water), gas industry representatives (Santos, other gas companies), University researchers (UNSW) and other stakeholders.

15. Intellectual Property and Confidentiality

<table>
<tr><td rowspan="3">Background IP (clause 11.1, 11.2)</td><td>Party</td><td>Description of Background IP</td><td>Restrictions on use (if any)</td><td>Value</td></tr>
<tr><td>CSIRO</td><td>Bioregional Assessment groundwater model for Namoi Region</td><td></td><td>Unknown</td></tr>
<tr><td>Santos</td><td>3D geological model (leapfrog)</td><td></td><td>unknown</td></tr>
<tr><td></td><td>CSIRO</td><td>Models/data from faults and ongoing aquitard project (OWS)</td><td></td><td>Unknown</td></tr>
<tr><td>Ownership of Non-Derivative IP (clause 12.3)</td><td colspan="4">CSIRO</td></tr>
<tr><td>Confidentiality of Project Results (clause 15.6)</td><td colspan="4">Project results are not confidential</td></tr>
<tr><td>Additional Commercialisation requirements (clause 13.1)</td><td colspan="4">Not Applicable</td></tr>
<tr><td>Distribution of Commercialisation Income (clause 13.4)</td><td colspan="4">Not Applicable</td></tr>
<tr><td rowspan="4">Commercialisation Interest (clause 1.1)</td><td colspan="2">Party</td><td colspan="2">Commercialisation Interest</td></tr>
<tr><td colspan="2">Santos</td><td colspan="2">N/A</td></tr>
<tr><td colspan="2">AGL</td><td colspan="2">N/A</td></tr>
<tr><td colspan="2">CSIRO</td><td colspan="2">N/A</td></tr>
</table>

APPENDIX

Hydrochemical and isotopic assessment by Creswell (2014): this study evaluated new measurements from a sampling campaign in 2014 in the proposed project area. It interpreted these data in the context of earlier work from GABWRA (2012) and other studies, and provides an excellent summary of the existing conceptual understanding. The following knowledge gaps and limitations can be concluded from this study: The initial ^{14}C concentration is unknown and needs to be independently verified with tritium and possibly ^{39}Ar measurements on newly collected samples within the recharge areas. Existing tritium measurements appear to have detection limits of 0.2-0.5 TU and can therefore indicate only admixtures of larger than 10% recent rain. Today's State-of-the-art detection limits are a factor of 10-100 better, which allows for the detection of 1% of young water or less. Radiocarbon values were assessed without knowing the initial ^{14}C in the recharge area or assessed using the model of Fontes & Garnier (1979). Both these assessments are the only possible with the available data, but they both have significant limitations. The geochemical alteration was only partly taken into account: samples with much higher DIC than observed in the CSG beds (Black Jack and Maules Creek) should not be interpreted with the same age model as those in the Pilliga Sandstone.

Similar to ^{14}C, regional ^{36}Cl values have all been interpreted with the same initial $^{36}Cl/Cl$. The interpretation by Creswell (2014) needs a "substantial source of very old chloride" to explain the difference of $^{36}Cl/Cl$ in the same aquifer (Pilliga Sandstone) at different locations. For example, high values were observed southeast of the project area and lower values in the northwest; however, this could simply be an indicator of different recharge areas with different initial $^{36}Cl/Cl$. However, waters with a $^{36}Cl/Cl$ ratio of less than 50 10^{-15} have ^{14}C ages of only 20-30ky (in the range of 5-10pMC) and therefore are not "old" in the sense of ^{36}Cl. Recharge $^{36}Cl/Cl$ therefore needs to be verified with combined ^{14}C and ^{36}Cl measurements on the same samples. No ^{36}Cl measurements exist in the project area, although this seems to be the recharge area. Verification of the ^{36}Cl results with ^{81}Kr is very desirable, because the latter is not influenced by geochemical processes and will not be impacted by the mentioned "substantial source of very old chloride".

Of special interest for the interpretation would be the sampling of multi-level well completions that allow determination of a depth profile of environmental tracers at one location. This way lateral alterations can be excluded and the development of tracer concentration with depth can be directly compared to conceptual models. The new multilevel installations from the NSW drilling initiative allow this assessment.

Conclusions in Creswell (2014) indicate that there is no evidence for upward cross-formational GW movement based on an assessment of hydrochemistry. However, the detection limit of hydrochemical indicators towards influx of groundwater from deeper formations via fractures and faults or aquitard leakage is in the range of 5-10% admixture of deep water (e.g. fluoride concentration in the Maules Creek Formation is 6-12mg/L and 0-1.5mg/L in the Pilliga Sandstone). In contrast, helium can indicate admixtures in the per mil range because deeper aquifers (e.g. Black Jack Group or Maules Creek Group) – if indeed containing much older groundwater – contain up to a factor of 1000 higher helium concentrations than the shallower aquifers (e.g. Pilliga Sandstone). Helium therefore is a much more sensitive parameter for upward flowing groundwater and will provide more robust indications of cross formational flow.