Australia's National Science Agency

**GISERA** | Gas Industry Social and Environmental Research Alliance

# Project Order

## Short Project Title

| |
|---|
| Groundwater modelling and predictive analysis to inform CSG impact assessment, monitoring and management |

| | |
|---|---|
| Long Project Title | Groundwater modelling and predictive analyses to inform the baseline and assessment, monitoring and management of CSG impacts to GAB and alluvial aquifers in the Namoi subregion |
| GISERA Project Number | W29 |
| Start Date | 15/09/2022 |
| End Date | 30/10/2025 |
| Project Leader | Sreekanth Janardhanan |

## GISERA State/Territory

- ☐ Queensland
- ☒ New South Wales
- ☐ Northern Territory
- ☐ South Australia
- ☐ Western Australia
- ☐ Victoria
- ☐ National scale project

## Basin(s)

- ☐ Adavale
- ☐ Amadeus
- ☐ Beetaloo
- ☐ Canning
- ☐ Western Australia
- ☐ Carnarvon
- ☐ Clarence-Morton
- ☐ Cooper
- ☐ Eromanga
- ☐ Galilee
- ☐ Gippsland
- ☐ Gloucester
- ☒ Gunnedah
- ☐ Maryborough
- ☐ McArthur
- ☐ North Bowen
- ☐ Otway
- ☐ Perth
- ☐ South Nicholson
- ☒ Surat
- ☐ Other (please specify)

## GISERA Research Program

- ☒ Water Research
- ☐ Health Research
- ☐ Biodiversity Research
- ☐ Social & Economic Research
- ☐ Greenhouse Gas Research
- ☐ Agricultural Land Management Research
- ☐ Other (please specify)

# 1. Project Summary

This project will undertake independent groundwater modelling and predictive analyses to inform coal seam gas (CSG) groundwater impact assessment and regulatory monitoring and management in the Narrabri Gas Project (NGP) area. The study will address community concerns about groundwater impacts to the Great Artesian Basin (GAB) aquifer – the Pilliga Sandstone and Namoi alluvial aquifers including groundwater losses induced by depressurization of coal seams in the underlying Gunnedah Basin. Better understanding of ground flow systems and water balance of the alluvial and the GAB aquifers and their connectivity are crucial for assessing and managing impacts from coal seam gas depressurization in the Gunnedah Basin formations. This will be achieved by iteratively improving the modelling framework based on the previous GISERA study (Sreekanth et al, 2018) by incorporating data from approved CSG production rates, improved understanding of the conceptual model, geology and geologic structures (Matthias et al, 2022), and assimilating field and other data pertaining to groundwater recharge and discharge.

The improved modelling framework will help to estimate aquifer water balance under baseline development and future conditions considering cumulative impacts including the effects of climate change. Combined simulation of the impact assessment model together with simulation of the GAB and alluvial aquifers will be undertaken to quantify the impact of depressurization on fluxes between the GAB aquifer and Lower Namoi Alluvium for the operational scale CSG development. State-of-the-art modelling approaches using MODFLOW USG/MODFLOW 6 and uncertainty quantification techniques will be used for this purpose. Numerical models will be progressively developed and refined by incorporating new and improved hydrological, hydrogeological and CSG production data and conceptual understanding of the system.

Predictive uncertainty in determination of impacts that are relevant to informing community concerns about groundwater resources will be explored and quantified by considering both uncertainty in conceptual models as well as uncertain model parameters and hydrological forcing data. The project will also focus on improving the baseline and future water balance of the aquifers by assimilating recharge and discharge data from field and remote sensing observations (Alzraiee et al, 2022; Tangdamrongsub et al, 2018; Khaki et al, 2020). A methodology will be developed to explore uncertainty in differentiating CSG impacts from cumulative groundwater impacts to economically and environmentally important aquifers of the GAB and Namoi alluvium. Model scenario simulation together with data analytics including Machine Learning will be used for these purposes. Monitoring strategies required for better monitoring and delineating the CSG impacts will also be developed.

# 2. Project description

## Introduction

The Narrabri Gas Project (NGP) was approved by the NSW Government in 2020 (DPIE, 2020). The Water Expert Panel (WEP) and the Department of Planning, Industry and Environment (DPIE) comprehensively reviewed the groundwater impact assessment from Santos's Environmental Impact Statement (EIS) as well as other studies including CSIRO's GISERA research to inform their decision. The phased approval given to the project and its consent conditions warrants improved understanding of the groundwater resources in the region to better quantify potential impacts and devise management strategies to address remaining concerns of the community. Negligible change in groundwater levels in the Namoi alluvial and GAB aquifers are to be ensured to avoid potential impacts to other groundwater users. Given the dynamic nature of groundwater levels in these aquifers, reliable groundwater modelling is required to assess the likelihood of such impacts.

Developing an improved understanding of the baseline groundwater flow and water balance in the alluvial and GAB aquifers and their interactions is critical for assessing impacts caused by depressurization. There are significant knowledge gaps in the current understanding and modelling of these aquifer systems as identified in the following 'Prior Research' section. Updating the groundwater modelling by addressing these knowledge gaps will help quantify and reduce uncertainty in the baseline groundwater balance and simulation of drawdown propagation to overlying aquifers. More importantly this helps in the quantification of impacts to other water users in the context of the baseline state of development of these aquifers. Such an assessment warrants accurate simulation of the baseline considering groundwater dynamics corresponding to historical periods of overexploitation and subsequent stabilisation due to water sharing plans (alluvial aquifer) and GABSI initiative. CSIRO's GISERA have developed a significant knowledge base from previous projects and will increase this knowledge base to further reduce prediction uncertainties by developing model simulation capability that incorporates recently obtained data and knowledge into new model development.

As the NGP proceeds, this knowledge platform will provide an independent assessment of potential impacts against which government and industry monitoring can be compared. This addresses the need for developing improved understanding of the dynamic baseline groundwater balance; refining predictions with improved conceptual understanding of the geology and geological structures; understanding cumulative impacts and differentiating groundwater trends and effects of different stressors in the region including coal seam gas, irrigation water use and climate change effects; and quantifying prediction uncertainty caused by different conceptual models underpinning the groundwater model.

## Prior Research

Between 2016 and 2022 GISERA undertook water research projects to improve conceptual understanding and assess groundwater impacts of onshore gas development in the Narrabri region of NSW (Janardhanan et al, 2018; Holland et al, 2018; Lupton et al, 2019; Raiber et al, 2022). The GISERA modelling study by Janardhanan et al (2018) adopted a generic approach considering a broad range of CSG water production rates to predict the likely range of impacts on groundwater pressures and fluxes in the GAB aquifer in the region. The objective of this past modelling study was to bracket the worst-case impacts for plausible ranges of gas and water production in the region. Given the approval of the project with a specified maximum water take of 37.5 GL over the 25-year period, predictions of impacts need to be updated for the expected water production rates corresponding to this. It is also required to improve groundwater balance estimation of the concerned aquifers (Pilliga Sandstone and Lower Namoi Alluvium) based on improved understanding of the recharge and discharge processes which in turn would help refine CSG impacts assessment and management.

There is improved understanding of hydrological and hydrogeological processes (Kelly et al, 2018; Crosbie et al, 2018; Suckow et al, 2019, 2020; Guerschman et al, 2022) influencing groundwater recharge and discharge of important alluvial and GAB aquifers in the region. The groundwater recharge mechanism for the alluvial aquifers is complex in the Narrabri region. Leakage from the Namoi River contributes a significant component of recharge with lesser amounts contributed by rainfall, irrigation excess and lateral flow between aquifers (Crosbie, 2018).  A combination of these recharge mechanisms is represented in the Namoi subregional model. Based on recent hydrochemical and isotopic studies (Kelly et al, 2018) groundwater in the Lower Namoi Alluvium have a mix of young (<70 years residence time) water associated with periodic flooding and old water mostly outflowing from GAB units underneath. Iverach et al (2017) conducted hydrochemical analysis and concluded that there is up to 70% of artesian contribution (from GAB units) to alluvial aquifer inflow as opposed to 22% accounted for in regional water balance. These estimates based on hydrochemical analyses have not yet been incorporated into regional groundwater models used for water impacts assessment and groundwater management.

Similarly, another recent environmental tracer study (Suckow et al, 2019) indicated that there are two distinct groundwater flow paths for the Pilliga Sandstone GAB aquifer in the Narrabri region with the northern path having much lesser flow velocity compared to the southern path. Another recent study (Clark, 2022) applied deep machine learning-based Neural Networks to abstract prevalent patterns in the groundwater monitoring time series in the Namoi alluvial aquifers, enabling prediction of water levels based on climatic and anthropogenic conditions. This study (Clark, 2022) illustrated that temporal patterns in groundwater levels and drawdown trends are similar among some wells and characteristically distinct in others in the Lower Namoi alluvium.  The results also indicate variations in groundwater level trends over the last 40-year period with a significantly declining period between 1985 and 2009 and a stabilising trend post-2010. These trends could have been influenced by historical over-exploitation, millennium drought and rolling out of the Water Sharing Plan. Such machine learning-based analyses can provide insights about spatial and temporal patterns in groundwater levels and recharge mechanisms in regions like the Namoi where hydrogeology is very complex, and these methods can be explored further to develop conceptual understanding of recharge and discharge mechanisms. More recent GISERA research (Raiber et al, 2022) has developed improved understanding of the subsurface geology of the region including faults and other geological structures. The study, which conducted aquifer assessment by the combined use of geology, geophysics and hydrogeology, identified distinct spatial zonation with some structures in the immediate vicinity of the NGP.

Groundwater modelling undertaken with the objective of quantifying and constraining inter-aquifer fluxes and changes to that resulting from CSG development, needs to incorporate improved hydrogeological conceptual knowledge and data pertaining to these processes to estimate groundwater balance for the Namoi alluvium and Pilliga Sandstone aquifers and refine predictions of impacts. Improved representation of these processes in the numerical model accompanied by predictive uncertainty analysis can better inform quantification of impacts, its monitoring and management.

## Relevant State/Territory Government independent reviews

The most recent review for this project is the Independent Planning Commission's Development Consent (IPC, 2020) for the NGP. Several consent conditions related to groundwater modelling and water impact assessments have been identified in this document. Several of these consent conditions pertain to concerns raised by the community about potential impacts to groundwater resources in the gas development area where economically important aquifers are used for irrigation, stock and domestic uses. IPC consent conditions were further informed by the Water Expert Panel's review of Santos' NGP (WEP, 2020). The Water Expert Panel identified specific improvements required in the modeling, for example, the need for transient modelling, the importance of including GABSI savings in the modelling of GAB aquifer and the sensitivity of flow between GAB and Lower Namoi Alluvium to head difference between the aquifers. The panel identified the need to provide improved estimates of impact on leakage from the GAB to the Lower Namoi Groundwater Source. The Water Expert Panel review and recommendations indicate the need for improved simulation of baseline and future groundwater balance in the important aquifers to aid better prediction and management of CSG impacts.

## Need & Scope

This GISERA project is scoped to address the need for developing improved understanding of groundwater balances in economically important aquifers in the Namoi region that may potentially be impacted by CSG development within the Gunnedah Basin; to undertake predictive analysis of CSG impacts and quantify uncertainties and data-worth to address community concerns about water impacts. Specifically, the project will undertake research that can independently address the following needs:

1. Developing improved understanding of the groundwater balance in economically important aquifers of Namoi alluvium and GAB underpinned by improved conceptual models, hydrological and hydrogeological data accounting for historical changes in groundwater dynamics and storage including the effect of initiatives like the GABSI.
2. Improved representation of connectivity between aquifers in numerical models and matching the spatial and temporal trends in baseline groundwater levels and groundwater flow patterns in the region to improve simulation of water balance and potential changes caused by CSG impacts.
3. Prediction and uncertainty quantification of groundwater drawdown in aquifers and CSG water take from aquifers used by other users for the approved level of CSG water production from the Gunnedah Basin
4. Improved monitoring and management of groundwater in the alluvial and GAB aquifers accounting for any potential impacts from CSG

Addressing these needs will require improved modelling and simulation analyses to understand the baseline and future water balance of the Namoi alluvial and Pilliga Sandstone aquifers. Especially, model simulations should incorporate the effects of the Great Artesian Basin Sustainability Initiative (GABSI), historical overexploitation of the alluvial aquifer and leakage from the GAB to the Lower Namoi Groundwater Source using model predicted heads in these aquifers. This would require detailed characterization and water balance assessments of these aquifers to reliably estimate inter-aquifer leakages and changes to that due to over extractions, millennium drought, GABSI and rolling out of Water Sharing Plans. Predictive analysis of groundwater losses from these aquifers during and post CSG periods would require accurate representation of current and future water uses and changes in recharge and discharge including that caused by climate change. Quantification of volumes lost and associated uncertainties are needed to inform water management decisions including accounting in the water allocation plans for the relevant management areas.

## Objective

The project will develop and apply a subregional groundwater modelling framework to simulate current and future groundwater balance in important aquifers in the GAB and Namoi alluvium in the Narrabri region. This will correspond to an improved conceptual understanding of the system and predictive analyses will be undertaken to quantify groundwater impacts of CSG development with the approved water production rate from the Gunnedah Basin underlying the GAB in this region. Predictive analyses will investigate individual and cumulative impacts and develop methods to differentiate observed and simulated trends in groundwater levels and drawdown.

Specifically, the new project will address the objectives of:

1. **Estimate baseline and future groundwater balance** by assimilating new and improved hydrological and hydrogeological data for the Namoi alluvium and the Pilliga Sandstone aquifer.

This study will use improved hydrological and hydrogeological data to constrain current and future groundwater balance by using fine scale (30 m) remote sensing data for evapotranspiration and improved recharge estimates for the Namoi alluvium and Pilliga Sandstone. Water balance assessments will be undertaken for a 100-year period.

2. **Predict groundwater impacts for the approved CSG water production rate** of 37.5 GL over 25 years by the NGP by calibrating the model to estimated water production rates. Cumulative impacts to these aquifers will be quantified considering existing groundwater uses and climate impacts. Groundwater head and flow impacts on the GAB and Namoi alluvial aquifers will be investigated for selected scenarios of groundwater use, CSG development, climate change and other stresses. The scenarios will also consider water uses corresponding to the current water allocation plan. Data-worth analysis will be undertaken to inform the groundwater monitoring network.
3. Develop a methodology to **quantify uncertainties in groundwater level trends and distinguishing impacts among different stressors** due to the transient nature of storage in these aquifers. For example, can we reliably quantify and attribute flow reduction to the alluvial aquifer or drawdown observed in a set of bores to the impacts of CSG production, existing groundwater use, historical and future climate changes, or potentially all stressors to inform management or make good arrangements?
4. Investigate the **effect of conceptual model uncertainty in predicting groundwater impacts** using paired and alternative simple and complex model analysis. A new numerical groundwater model with layers conforming to important geological formations will be developed for this. An improved conceptual model developed in a parallel, companion GISERA project will be used for underpinning the numerical model. The numerical model will be used in conjunction with the Namoi subregional model to explore model structural uncertainty and its effects on CSG impact prediction.
5. **Develop an interactive dashboard** for the community and other stakeholders to visualise the impacts and monitoring and management scenarios. This tool can be used for communicating with community and other stakeholders.

## Methodology

The methodology will make use of state-of-the-art numerical modelling, uncertainty analysis and data analytics including machine learning. The numerical groundwater model developed in the previous GISERA and Bioregional Assessments projects (Sreekanth et al, 2018) will be used as the initial basis for the analyses. This model is referred to as the Namoi subregional model in the remainder of this project proposal. A new model will be built by incorporating improved knowledge about the hydrological and hydrogeological conceptual model. This includes incorporating improved understanding of the hydrological forcing data (recharge, ET, pumping) and subsurface geological conceptual model including geological structures (e.g faults). The new model will be underpinned by a new geological model available from a companion GISERA project (Raiber et al, 2022) and will be used as a simulation platform for refining prediction of CSG and cumulative impacts. The parallel timelines of these two projects enable iteratively refining the geological and numerical models. New model development will make use of MODFLOW USG/ MODFLOW 6 software suite. Given the complexity of the underpinning geology and hydrostratigraphy, paired simulation of models may be required to undertake probabilistic simulation of the shallow unconfined aquifer flow without numerical convergence issues. MODFLOW 6 will be used for this purpose. The methodology used for this will enable coupled application of this model with NSW government models for the alluvial aquifers, to incorporate CSG-induced impacts into groundwater management models, if warranted.

Baseline and future groundwater balance analysis for the Namoi alluvial and the GAB Pilliga Sandstone aquifers will be undertaken after constraining the model using available conceptual models and observations using data assimilation (DA) and uncertainty analysis techniques. Model calibration, DA and uncertainty analysis methods using the PEST++ suite (White et al, 2020, Alzraiee et al, 2022) of software including the Iterative Ensemble Smoother approach will be used for updating and constraining the model using observed groundwater data from the field and estimates of CSG water production rates, in addition to assimilating observations from remote sensing data about the evapotranspiration and regional scale storage changes. The field observations comprise observed groundwater level measurements from the HYDMEAS database of the NSW Office of Water (Dataset 1 NSW Office of Water, 2014) and other data sets pertaining to aquifer hydraulic characteristics in the Namoi region (Aryal et al, 2018). This approach enables quantifying prediction uncertainties using Monte Carlo and analytical approaches and allows evaluation of thousands to millions of parameters. It is the best available approach for quantifying predictive uncertainty and informing decision support for groundwater management. Predictive analysis of CSG groundwater impacts will be undertaken in a probabilistic manner supported by this approach. This component of the methodology corresponds to objectives 1 and 2 with corresponding tasks 2, 3 and 4.

Groundwater recharge and discharge components for the alluvial and GAB aquifers will be investigated using different techniques based on the current conceptual understanding of the hydrogeology. This will utilize water table fluctuation and chloride mass balance data as well as remote sensing estimates of evapotranspiration and regional storage changes. High (30 m) or medium (500 m) resolution estimates of Actual Evapotranspiration (ETA) will be obtained using remote sensing data sets of MODIS, LANDSAT and Sentinel-2 satellites. ETA estimates will be assimilated into the groundwater model using advanced DA techniques to constrain groundwater contribution to evapotranspiration. The field and remote sensing observations will be integrated into groundwater modelling using the DA approach (Alzraiee et al 2022). The method explicitly recognizes that both models and field/remote sensing observations are inherently uncertain. Data-worth analysis (Dausman et al, 2010; Sreekanth et al, 2019) will be used to quantify the relative worth of different types of data (observed groundwater levels, remote sensing estimates of ET) in informing water balance and also to inform future monitoring.

CSIRO climate modelling studies (Crosbie et al, 2021) will be used for incorporating the effects of climate change on recharge processes. Cumulative impacts corresponding to approved CSG water production rates will be initially undertaken using probabilistic numerical modelling using the Namoi subregional model and subsequently refined using a new model. This corresponds to objective 2 and tasks 2,3 and 4.

Given the dynamic nature of storage in the Namoi alluvium and Pilliga Sandstone it will be difficult to monitor and attribute small drawdown caused individually by CSG or other stresses. Machine Learning techniques have proven to be useful in emulating and differentiating hydrological signals. Simulation modelling will be used together with Deep Neural Network Machine Learning algorithms to develop a method for differentiating groundwater drawdown signals corresponding to different sources. This method will be further used to inform sentinel monitoring networks that regulators/Government can potentially use for attributing impacts and mandating make good arrangements if warranted. This component of methodology corresponds to objective 3 and task 5.

Improvements in conceptual models and the accompanying geological model developed in a companion GISERA project (Raiber et al, 2022) will be used to develop a more complex numerical model which will be used in a paired simple and complex model framework to explore the effect of conceptual model uncertainty and bias in groundwater impact predictions. This corresponds to objective 4 and tasks 6 and 7.

An interactive dashboard/app will be developed using the Python Streamlit utilities to communicate the findings to the community and broader stakeholders to address the objective 5 and task 8. The interactive dashboard will be hosted through the web hosting services provided by CSIRO’s IM&T team and linking to the GISERA website. The dashboard will be active for a minimum period of 1 year beyond the completion of the project to ensure its availability for external stakeholders to communicate the findings.

# 3. Project Inputs

## Resources and collaborations

| Researcher | Time Commitment (project as a whole) | Principle area of expertise | Years of experience | Organisation |
|---|---|---|---|---|
| Sreekanth Janardhanan | 250 days | Groundwater modelling, uncertainty, project management | 12+ | CSIRO L&W |
| Russell Crosbie | 85 days | Climate change, recharge | 15+ | CSIRO L&W |
| Trevor Picket | 120 days | Software engineering | 15+ | CSIRO L&W |
| Dan Pagendam | 40 days | Machine Learning, Statistics | 15+ | CSIRO Data61 |
| Dan MacKinlay | 20 days | Machine Learning, data science | 5+ | AIML FSP |
| Jorge Pena-Arancibia | 61 days | Remote sensing, hydrology, modelling | 15+ | CSIRO L&W |
| Yingying Yu | 100 days | Surface water, spatial analysis | 5+ | CSIRO L&W |
| Justin Wu | 80 days | Geological modelling | 3+ | CSIRO L&W |

| Subcontractors (clause 9.5(a)(i)) | Time Commitment (project as a whole) | Principle area of expertise | Years of experience | Organisation |
|---|---|---|---|---|
| Visiting students (2) | 1 FTE | Modelling, Machine Learning | Advanced PhD student | Yet to finalize |

## Technical Reference Group

The project will establish a Technical Reference Group (TRG) aimed at seeking peer-to-peer technical advice on contextual matters and to discuss research needs as well as outputs as the project progresses. The TRG will include the project leader and a group of different stakeholders as appropriate which may include:

- Santos representative
- Water Technical Group representative
- NSW Department of Planning, Industry and Environment (DPIE) representative

## Budget Summary

| Source of Cash Contributions | 2021/22 | 2022/23 | 2023/24 | 2024/25 | 2025/26 | % of Contribution | Total |
|---|---|---|---|---|---|---|---|
| GISERA | $0 | $278,127 | $464,517 | $195,709 | $17,155 | 80% | $955,508 |
| - Federal Government | $0 | $198,166 | $330,968 | $139,443 | $12,223 | 57% | $680,799 |
| - NSW Government | $0 | $79,962 | $133,549 | $56,266 | $4,932 | 23% | $274,709 |
| **Total Cash Contributions** | **$0** | **$278,127** | **$464,517** | **$195,709** | **$17,155** | **80%** | **$955,508** |

| Source of In-Kind Contribution | 2021/22 | 2022/23 | 2023/24 | 2024/25 | 2025/26 | % of Contribution | Total |
|---|---|---|---|---|---|---|---|
| CSIRO | $0 | $69,532 | $116,129 | $48,927 | $4,289 | 20% | $238,877 |
| **Total In-Kind Contribution** | **$0** | **$69,532** | **$116,129** | **$48,927** | **$4,289** | **20%** | **$238,877** |

| TOTAL PROJECT BUDGET | 2021/22 | 2022/23 | 2023/24 | 2024/25 | 2025/26 | - | TOTAL |
|---|---|---|---|---|---|---|---|
| All contributions | $0 | $347,659 | $580,647 | $244,635 | $21,444 | - | $1,194,385 |
| **TOTAL PROJECT BUDGET** | **$0** | **$347,659** | **$580,647** | **$244,635** | **$21,444** | **-** | **$1,194,385** |

# 4. Communications Plan

This communication plan envisages the project team's engagement with relevant stakeholders from the Gas Industry, Government and community during various stages of the project. The purpose of engagement with the industry stakeholder, hydrogeology team in NSW Office of Water and the scientific community representatives of the NGP Water Technical Advisory Group is to communicate the scientific objectives and progress of the project and avail relevant hydrogeological and other information and data sets from past or ongoing initiatives that could be useful for the project. Communication plan will adopt diverse modes to communicate research findings towards the end of the project. These include the following:

- Fact sheets and other media outputs will be produced as the project progresses to communicate with the wider stakeholders including regional community and wider public.
- Presentations tailored to the technical audience will be delivered at a Knowledge Transfer Session to audience comprising Government and Gas Industry stakeholders focussing on the scientific outputs and key findings.
- Another presentation will be delivered to broader stakeholders from the regional community to communicate the key findings.
- Factsheets and project final reports will be made available on GISERA website for broader dissemination.

| Stakeholder | Objective | Channel<br>(e.g. meetings/media/factsheets) | Timeframe<br>(Before, during at completion) |
|---|---|---|---|
| NGP Water Technical Advisory Group | To communicate the science objectives and methodology of the project. | Meeting with the NGP Water Technical Advisory Group within 6 months of the commencement of the project to discuss the project methodology. | First meeting within 6 months of commencement of the project. |
| NSW Office of Water | Present the research objectives and identify relevant data sets and/or ongoing complementary initiatives by the NSW Government to maximise the benefits of the outputs that the project will deliver | Meeting with NSW Office of Water hydrogeology team | During the project with one meeting within 6 months of the start of the project. Further meetings will be sought as deemed necessary based on the timelines of aligning activities of NSW Office of Water |

| Stakeholder | Objective | Channel<br>(e.g. meetings/media/factsheets) | Timeframe<br>(Before, during at completion) |
|---|---|---|---|
| Regional community / wider public | To communicate project objectives and key messages from the research | Briefing with Shire Councils, Chambers of Commerce and other stakeholders to communicate the objectives and context within 6 months of the project<br><br>Fact sheets (including development of one at commencement of project which will explain in plain English the objective of the project and one at the end of the project – these may be updated periodically as project progresses).<br><br>Project progress reported on GISERA website to ensure transparency for all stakeholders including regional communities.<br><br>Media release (optional) | Within 6 months of commencement<br>From commencement of project and with updates as they come to hand.<br><br>As required at the end of each milestone<br><br>At completion |
| Gas Industry | Presenting the objectives of the project and securing relevant data from the proponent;<br>Industry adopts methods for better monitoring and management of water impacts | Presentation of findings at joint Gas Industry/Government Knowledge Transfer Session | In the beginning and<br>At Completion |
| Government (DPIE) | Advice provided to senior bureaucrats / ministers /<br>policy makers | Presentation of findings at joint Gas Industry/Government Knowledge Transfer Session | At Completion |
| Community stakeholders | Presentation of research findings, interactive dashboard demonstrations | Presentation of findings through community forum or briefing | At Completion |
| Regional community/wider public, government, scientific community and industry | To report on key findings | Public release of final report | At project completion |
| Traditional Owner communities | To explore collaboration opportunities for information exchange. | Engagement with representatives of relevant land councils where appropriate to determine interest/availability in making information available to communities | Ongoing |

# 5. Project Impact Pathway

| Activities | Outputs | Short term Outcomes | Long term outcomes | Impact |
|---|---|---|---|---|
| Tasks 1 to 4 | Baseline and future water balances, CSG impact predictions for the alluvial and Pilliga Sandstone aquifer in the Namoi region<br><br>Relative data-worth of different data types in informing water balance<br><br>Factsheet based on these findings<br><br>Draft journal paper manuscript describing the methodology | Improved understanding of groundwater balance in economically important alluvial and GAB aquifers<br><br>Improved knowledge base to inform assessment and management of groundwater accounting for industry water use:<br><br>Regulatory agency uses information on CSG water impacts in the GAB and alluvial aquifers to inform management plans<br><br>Independent assessment of impacts against which industry/regulatory modelling could be compared and reviewed<br><br>Improved modelling, DA and uncertainty analysis methodology based on the real-world case study made available for the broader scientific community through the journal paper | Improved regulatory framework allocation rules for groundwater management | Better management of groundwater use by CSG and extractive industries by informed regulatory decision-making accounting for future water demand and availability considering climate change |
| Tasks 5 | Methodology applied to differentiate groundwater level trends in the broader region due to CSG impacts from other natural and anthropogenic changes in the region: | Improved understanding of groundwater level trends in the aquifers<br><br>Scientific know how and methods to inform accountability and responsibility for managing impacts For eg:<br>Attribution of potential drawdown in a set of bores to CSG impacts with increased certainty | | |
| Tasks 6 and 7 | Refining predictive assessments considering improved knowledge of geology and geological structures of the Surat and Gunnedah Basins | Inform stakeholders about potential impacts of faults and structures, and water management implications | Improved risk assessments and management plans to protect risk receptors near areas of concern<br><br>Informed decision making by stakeholders | |
| Task 8 | Interactive web-based dashboard/app | Stakeholders able to explore potential spatial and temporal impacts of CSG with the help of interactive dashboard<br><br>Better communication of potential impacts and monitoring and management plans to stakeholders | | |

# 6. Project Plan

## Project Schedule

| ID | Activities / Task Title | Task Leader | Scheduled Start | Scheduled Finish | Predecessor |
|---|---|---|---|---|---|
| **Task 1** | Project inception meeting | Sreekanth Janardhanan | Sep-22 | Mar-23 | None |
| **Task 2** | Updating, calibrating and prediction analysis including data-worth using Namoi subregional model | Sreekanth Janardhanan, Russell Crosbie | Oct-22 | Oct-23 | None |
| **Task 3** | Groundwater recharge and discharge | Russell Crosbie | Oct-22 | Oct-23 | None |
| **Task 4** | Data assimilation and water balance | Russell Crosbie, Sreekanth Janardhanan | Jul-23 | Jun-24 | 2, 3 |
| **Task 5** | Machine Learning methods and application | Dan Pagendam | Sep-23 | Jun-24 | 2, 3 |
| **Task 6** | New groundwater model development | Sreekanth Janardhanan | Mar-24 | Dec-24 | 2,3,4,5, Corresponding task in companion project (Raiber et al, 2022) |
| **Task 7** | Paired simple and complex model analysis | Sreekanth Janardhanan | Jul-24 | Jul-25 | 6 |
| **Task 8** | Interactive dashboard | Trevor Pickett | Jan-23 | Mar-25 | None |
| **Task 9** | Student engagement | Sreekanth Janardhanan | Sep-22 | Jul-25 | 1 |
| **Task 10** | Project reporting | Sreekanth Janardhanan | Sep-22 | Jul-25 | 1 to 8 |
| **Task 11** | Communication findings to stakeholders | Sreekanth Janardhanan | Full duration of project | | |

## Task description

**Task 1: Project inception and stakeholder meeting**

OVERALL TIMEFRAME: 7 months (Sep 2022 – Mar 2023)

BACKGROUND**:** Santos Limited, NSW DPIE and the Office of Water are key stakeholders of the project. These stakeholders would be able to provide information about CSG water production rates and times and other valuable data and knowledge regarding the hydrogeological context.

TASK OBJECTIVES**:** Set the scene for the project, establish contact points with stakeholders, establish the technical reference group and facilitate data provisions.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Stakeholder meeting completed.

**Task 2: Updating and calibrating the Namoi subregional model and predictive analysis including data-worth analysis**

OVERALL TIMEFRAME: 13 months (Oct 2022 to Oct 2023)

BACKGROUND: Previous GISERA/BA modelling considered a wide range of CSG water production rates to quantify and bracket potential maximum impacts to groundwater heads and fluxes. Those studies used a rejection sampling approach to constrain predictions and were not calibrated to observed groundwater heads and fluxes and estimated CSG and mine water production rates through history matching. This task will refine those predictions by calibrating the model to the maximum water production rate of 37.5 GL over a 25-year period. A PEST++ -based approach will be used for history matching to observed groundwater levels and fluxes as well as time series of estimated CSG water production rates.

TASK OBJECTIVES: The model set up will be updated and calibrated to observed groundwater heads and estimated CSG production rates; predictive analysis of CSG impacts conducted using updated and calibrated model.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Updated and calibrated model, predictive analysis including relative data-worth for monitoring decisions. Report the findings in a peer-reviewed journal paper.

**Task 3: Groundwater recharge and discharge (including evapotranspiration)**

OVERALL TIMEFRAME: 13 months (Oct 2022 to Oct 2023)

BACKGROUND: Conceptual understanding and data pertaining to groundwater recharge and discharge processes are important to quantify the dynamic water balance of aquifers. This is in turn important to assess the impacts caused by CSG development and other cumulative stresses. Climate change impacts will have a considerable impact on the groundwater balance of the GAB and alluvial aquifers of the

Namoi region in the coming decades. Assessment of impacts from resource development should account for the cumulative impacts including that of climate change to devise management strategies.

**TASK OBJECTIVES:** Investigating recharge and discharge processes including groundwater contribution to evapotranspiration based on current and improved understanding of conceptual models for the Namoi Alluvium and Pilliga Sandstone aquifers using appropriate methods including Water Table Fluctuation, chloride mass balance and/or modelling. Key changes to these processes due to climate change for major aquifers will also be investigated to include in the simulation of long-term groundwater balance.

**TASK OUTPUTS AND SPECIFIC DELIVERABLES:** Estimate of recharge and discharge including groundwater contribution to evapotranspiration and its representation in the numerical groundwater model.

### Task 4: Data assimilation from field and remote sensing data and water balance and data-worth analysis

**OVERALL TIMEFRAME:** 12 months (Jul 2023 to Jun 2024)

**BACKGROUND:** In addition to observed water levels in the alluvial and GAB aquifers there is a large amount of remote sensing data and other information available to constrain water balance. This includes fine scale (30) estimates of evapotranspiration, estimates of recharge, estimates of groundwater pumping and observed inter-aquifer head gradients. Estimation of pre-development water balance is important to set the baseline trends in groundwater balance and storage trends. Similarly, future water balance corresponding to a combination of scenarios including gas development and climate change are required to inform individual and cumulative impacts of CSG with other stresses including groundwater use and climate change.

**TASK OBJECTIVES:** Use field and remote sensing data sets to constrain modelled water balance for the Namoi alluvial aquifers and the Pilliga Sandstone aquifer (GAB) and quantify the relative data-worth of multiple data types and data sets in informing aquifer water balance.

**TASK OUTPUTS AND SPECIFIC DELIVERABLES:**

- Improved baseline and future water balance for the GAB and alluvial aquifers in the simulation model for CSG impacts assessment.
- Relative data-worth of different data types in informing the groundwater level and water balance simulation quantified
- Findings summarised in a factsheet and methodology written up as a journal paper manuscript

**Task 5: Machine Learning method for differentiating groundwater trends and impact predictions**

OVERALL TIMEFRAME: 10 months (Sep 2023 to Jun 2024)

BACKGROUND: The Namoi subregion has very complex hydrogeology and spatiotemporal patterns in groundwater levels and aquifer connectivity varies significantly across the region. Recharge processes are also complex. In such regions, it is difficult to differentiate, and attribute observed trends in data, e.g., groundwater levels to specific recharge processes. Nor is it easy to attribute an observed drawdown to any specific stressor, e.g., irrigation water use or CSG water production. Current and future observations of groundwater drawdown in the GAB or alluvial aquifers could potentially be caused by gas development, mining, over allocation for irrigation or climate change impacts. However, spatiotemporal patterns invisible to the human eye could be assessed using advanced Machine Learning techniques. Such analyses may help develop improved conceptual understanding of processes and better constrain models.

TASK OBJECTIVES: Develop and test a methodology based on simulations and Machine Learning to differentiate trends in observed and simulated groundwater patterns.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Novel methodology for differentiating trends in observed and simulated spatiotemporal patterns in groundwater variables and application to the Namoi subregion.

**Task 6: New model development based on improved conceptual model**

OVERALL TIMEFRAME: 10 months (Mar 2024 to Dec 2024)

BACKGROUND: A relatively simplified 15-layer conceptualization of the subsurface geology was adopted for the Namoi subregional model. The simplified conceptualisation provided a robust model that could be evaluated for a wide range of plausible parameterisations to quantify prediction uncertainties. However, the simplification of the geology can potentially cause bias and uncertainties induced by the model structure in prediction. In this task a numerical model based on an improved conceptual model (that is developed in parallel in the companion GISERA project by Raiber et al. (2022)) will be developed. This will be a 2D or 3D model to suit the purpose of paired simple and complex model evaluation.

TASK OBJECTIVES: Develop a new model based on the improved conceptualisation to refine predictions in the Namoi subregional model with improved representation of geology obtained from Raiber et al. (2022) and data analyses in the previous tasks.

TASK OUTPUTS AND SPECIFIC DELIVERABLES Numerical model based on improved conceptual model.

**Task 7: Paired model analysis and refining prediction around faults**

OVERALL TIMEFRAME: 12 months (Jul 2024 to Jul 2025)

BACKGROUND: A simplified conceptual model was adopted for the Namoi subregional model to enable easy model convergence during probabilistic analysis. The development of a new model with improved representation of geology and data provides an opportunity to refine the regional model predictions of CSG impacts by using a paired simple and complex model analysis to correct any predictive bias.

TASK OBJECTIVES: The Namoi subregional model and the new model will be used in a paired framework to quantify the bias and uncertainty caused using a simple conceptual model for groundwater impact predictions. Refine the prediction of impacts around structural features including faults near the NGP area.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Predictive bias and uncertainty quantified; impact predictions to risk receptors near faults.

**Task 8: Web-based interactive dashboard/app**

OVERALL TIMEFRAME: 27 months (Jan 2023 to Mar 2025)

BACKGROUND: GISERA experience teaches us that communicating groundwater impact predictions and management to stakeholders need intuitive visualisation methods. The interactive dashboard will visualise drawdown impact probability maps and its spatial extents with respect to risk receptors for CSG development and other scenarios.

TASK OBJECTIVES: Develop an interactive web-based dashboard for this purpose. This dashboard will complement GISERA communications initiatives to disseminate scientific knowledge emerging from the study to broader stakeholders.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: The app can potentially be deployed on GISERA/other website with access to relevant stakeholders subject to data/privacy requirements.

**Task 9: Research student collaboration**

OVERALL TIMEFRAME: 2 ¾ years (Sep 2022 to Jul 2025)

BACKGROUND: Significant amount of hydrogeological and modelling knowledge is generated as part of GISERA projects. Engaging research students aligning with these applied research projects have been very successful to test novel ideas as well as provide applied experience to higher degree researchers and enable knowledge transfer to the next generation of modellers.

TASK OBJECTIVES: Engage two higher degree research students to work on novel ideas applying machine learning and simulation techniques to quantify uncertainties in onshore gas impact predictions.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Journal paper based on the student topic.

**Task 10: Project reporting**

OVERALL TIMEFRAME: 2 ¾ years (Sep 2022 to Jul 2025)

BACKGROUND: Report the project findings using appropriate medium for reporting to the clients and stakeholders.

TASK OBJECTIVES: Consolidate the methods in methodology development, conference presentations and relevant findings in the final project report in a form easily understood by the broader stakeholders.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Final project report, conference abstracts and journal papers describing the methodologies and case study.

1) Preparation of a final report outlining the scope, methodology, scenarios, assumptions, findings and any suggestions/options for future research;

2) Following CSIRO ePublish review, the report will be submitted to the GISERA Director for final approval; and

3) Provide 6 monthly progress updates to GISERA office.

**Task 11: Communicate project objectives, progress and findings to stakeholders**

OVERALL TIMEFRAME: Full duration of project

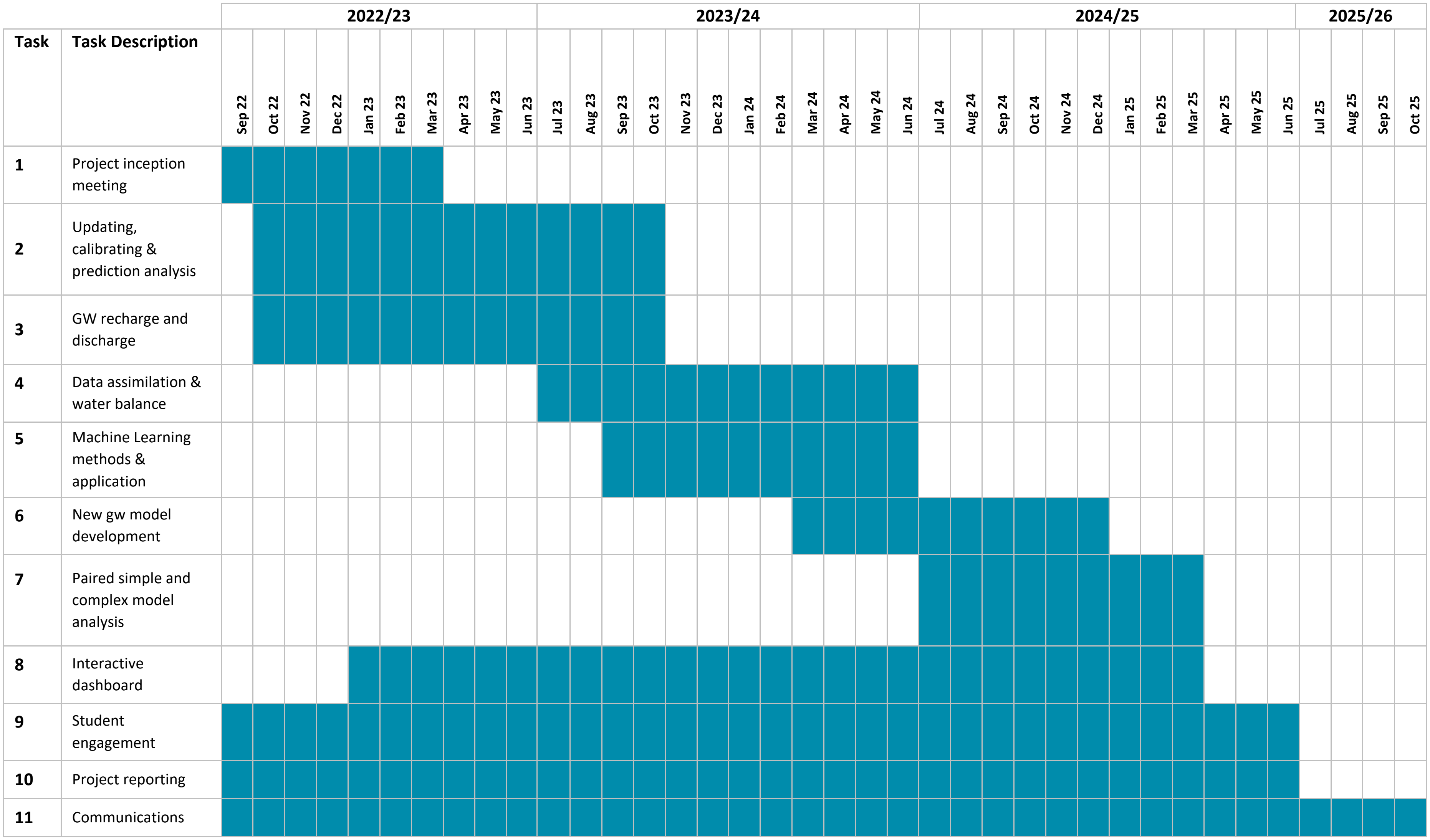
BACKGROUND: Communications of GISERA research are an important component of outreach and dissemination of findings to diverse audiences.

TASK OBJECTIVES: Communicate project objectives, progress and findings to stakeholders through meetings, knowledge transfer sessions, factsheets and journal articles, in collaboration with GISERA Communications officers.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Communicate project objectives, progress and results to GISERA stakeholders according to standard GISERA project procedures which may include, but are not limited to:

1) Knowledge Transfer session with Government/Gas Industry
2) Presentation of findings to Community members/groups
3) Preparation of article for GISERA newsletter and other media outlets e.g. The Conversation
4) Revision of project factsheet to include final results (a factsheet is developed at project commencement and another will be done at completion)
5) Peer reviewed scientific manuscript ready for submission to relevant journal

# Project Gantt Chart



# 7. Budget Summary

| Expenditure | 2021/22 | 2022/23 | 2023/24 | 2024/25 | 2025/26 | Total |
|---|---|---|---|---|---|---|
| Labour | $0 | $320,659 | $553,147 | $230,635 | $17,444 | $1,121,885 |
| Operating | $0 | $17,000 | $17,500 | $4,000 | $4,000 | $42,500 |
| Student | $0 | $10,000 | $10,000 | $10,000 | $0 | $30,000 |
| **Total Expenditure** | **$0** | **$347,659** | **$580,647** | **$244,635** | **$21,444** | **$1,194,385** |

| Expenditure per task | 2021/22 | 2022/23 | 2023/24 | 2024/25 | 2025/26 | Total |
|---|---|---|---|---|---|---|
| Task 1 | $0 | $32,244 | $0 | $0 | $0 | $32,244 |
| Task 2 | $0 | $105,221 | $83,717 | $0 | $0 | $188,938 |
| Task 3 | $0 | $104,871 | $70,416 | $0 | $0 | $175,287 |
| Task 4 | $0 | $0 | $119,909 | $0 | $0 | $119,909 |
| Task 5 | $0 | $0 | $100,022 | $0 | $0 | $100,022 |
| Task 6 | $0 | $0 | $94,935 | $80,652 | $0 | $175,587 |
| Task 7 | $0 | $0 | $0 | $50,894 | $0 | $50,894 |
| Task 8 | $0 | $50,233 | $51,651 | $65,160 | $0 | $167,044 |
| Task 9 | $0 | $23,000 | $27,000 | $14,000 | $0 | $64,000 |
| Task 10 | $0 | $32,090 | $32,996 | $33,930 | $8,722 | $107,738 |
| Task 11 | $0 | $0 | $0 | $0 | $12,722 | $12,722 |
| **Total Expenditure** | **$0** | **$347,659** | **$580,647** | **$244,635** | **$21,444** | **$1,194,385** |

| Source of Cash Contributions | 2021/22 | 2022/23 | 2023/24 | 2024/25 | 2025/26 | Total |
|---|---|---|---|---|---|---|
| Federal Govt (57%) | $0 | $198,166 | $330,968 | $139,443 | $12,223 | $680,799 |
| NSW Govt (23%) | $0 | $79,962 | $133,549 | $56,266 | $4,932 | $274,709 |
| **Total Cash Contributions** | **$0** | **$278,127** | **$464,517** | **$195,709** | **$17,155** | **$955,508** |

| In-Kind Contributions | 2021/22 | 2022/23 | 2023/24 | 2024/25 | 2025/26 | Total |
|---|---|---|---|---|---|---|
| CSIRO (20%) | $0 | $69,532 | $116,129 | $48,927 | $4,289 | $238,877 |
| **Total In-Kind Contributions** | **$0** | **$69,532** | **$116,129** | **$48,927** | **$4,289** | **$238,877** |

| | Total funding over all years | Percentage of Total Budget |
|---|---|---|
| Federal Government investment | $680,799 | 57% |
| State Government investment | $274,709 | 23% |
| CSIRO investment | $238,877 | 20% |
| **Total Expenditure** | **$1,194,385** | **100%** |

| Task | Milestone Number | Milestone Description | Funded by | Start Date (mm-yy) | Delivery Date (mm-yy) | Fiscal Year Completed | Payment $ (excluding CSIRO contribution) |
|---|---|---|---|---|---|---|---|
| **Task 1** | 1.1 | Project inception meeting | GISERA | Sep-22 | Mar-23 | 2022/23 | $25,795 |
| **Task 2** | 2.1 | Updating, calibrating and prediction analysis including data-worth using Namoi subregional model | GISERA | Oct-22 | Oct-23 | 2023/24 | $151,150 |
| **Task 3** | 3.1 | Groundwater recharge and discharge | GISERA | Oct-22 | Oct-23 | 2023/24 | $140,230 |
| **Task 4** | 4.1 | Data assimilation and water balance | GISERA | Jul-23 | Jun-24 | 2023/24 | $95,927 |
| **Task 5** | 5.1 | Machine Learning methods and application | GISERA | Sep-23 | Jun-24 | 2023/24 | $80,018 |
| **Task 6** | 6.1 | New groundwater model development | GISERA | Mar-24 | Dec-24 | 2024/25 | $140,470 |
| **Task 7** | 7.1 | Paired simple and complex model analysis | GISERA | Jul-24 | Mar-25 | 2024/25 | $40,715 |
| **Task 8** | 8.1 | Interactive dashboard | GISERA | Jan-23 | Mar-25 | 2024/25 | $133,635 |
| **Task 9** | 9.1 | Student engagement | GISERA | Sep-22 | Jul-25 | 2025/26 | $51,200 |
| **Task 10** | 10.1 | Project reporting | GISERA | Sep-22 | Jul-25 | 2025/26 | $86,190 |
| **Task 11** | 11.1 | Communication findings to stakeholders | GISERA | Sep-22 | Oct-25 | 2025/26 | $10,178 |

# 8. Intellectual Property and Confidentiality

| | | | | |
|---|---|---|---|---|
| **Background IP (clause 11.1, 11.2)** | **Party** | **Description of Background IP** | **Restrictions on use (if any)** | **Value** |
| | CSIRO | Namoi subregional model and climate data | None | $ |
| | | | | |
| **Ownership of Non-Derivative IP (clause 12.3)** | CSIRO | | | |
| **Confidentiality of Project Results (clause 15.6)** | Project Results are not confidential. | | | |
| **Additional Commercialisation requirements (clause 13.1)** | Not Applicable | | | |
| **Distribution of Commercialisation Income (clause 13.4)** | Not Applicable | | | |
| **Commercialisation Interest (clause 13.1)** | **Party** | **Commercialisation Interest** | | |
| | CSIRO | N/A | | |
| | Santos | N/A | | |
| | Origin Energy | N/A | | |

# 9. References


Aryal SK, Northey J, Slatter E, Ivkovic K, Crosbie R, Janardhanan S, Peña-Arancibia J and Bell J (2018) Observations analysis, statistical analysis and interpolation for the Namoi subregion. Product 2.1-2.2 for the Namoi subregion from the Northern Inland Catchments Bioregional Assessment. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. http://data.bioregionalassessments.gov.au/product/NIC/NAM/2.1-2.2.

Alzraiee, A. H., White, J. T., Knowling, M. J., Hunt, R. J., & Fienen, M. N. (2022). A scalable model-independent iterative data assimilation tool for sequential and batch estimation of high dimensional model parameters and states. *Environmental Modelling & Software*, *150*, 105284.

Clark, S. R. (2022). Unravelling groundwater time series patterns: Visual analytics-aided deep learning in the Namoi region of Australia. *Environmental Modelling & Software*, 105295.

Crosbie, R., Aryal, S. K., Janardhanan, S., & Peña-Arancibia, J. (2018). Water balance assessment for the Namoi subregion. Product 2.5 for the Namoi subregion from the Northern Inland Catchments Bioregional Assessment. Department of the Environment and Energy, Bureau of Meteorology.

Crosbie, Russell; Charles, Steve; Rojas, Rodrigo; Dawes, Warrick; Fu, Guobin; Rassam, David; et al. Impact of climate change on groundwater in NSW Preliminary assessment of the sensitivity of recharge and groundwater resources to a projected drying climate . Australia: CSIRO; 2021.

Dausman, A. M., Doherty, J., Langevin, C. D., & Sukop, M. C. (2010). Quantifying data worth toward reducing predictive uncertainty. *Groundwater*, *48*(5), 729-740.

DPIE (2020) Narrabri Gas Project, State Significant Development, Microsoft Word - Narrabri Gas Project - Assessment Report 11 JUNE 2020 7 pm.docx (nsw.gov.au)
WEP(2020), Report of the Water Expert Panel, Review of the Narrabri Gas Project, Microsoft Word - Narrabri Gas Project - Assessment Report 11 JUNE 2020 7 pm.docx (nsw.gov.au), pp 156.

Guerschman, J. P., McVicar, T. R., Vleeshower, J., Van Niel, T. G., Peña-Arancibia, J. L., & Chen, Y. (2022). Estimating actual evapotranspiration at field-to-continent scales by calibrating the CMRSET algorithm with MODIS, VIIRS, Landsat and Sentinel-2 data. *Journal of Hydrology*, *605*, 127318.

Holland, K., Gonzalez, D., Mitchell, P., O'Grady, A., & Janardhanan, S. (2018). Hydrogeological and Ecohydrological Connections in the CSG Development Areas of the Namoi Region.

Janardhanan, S., Cui, T., Pickett, T., & Barrett, D. (2018). Uncertainty analysis of CSG-induced GAB flux and water balance changes in the Narrabri Gas Project area–Final report.

IPC (2020), Development Consent Department of Planning Industry and Environment, State Significant Development – Narrabri Gas Project, ssd-6456-development-consent.pdf (nsw.gov.au)

IPC media release (2020), IPC's phased approval of $3.6 Billion Narrabri Gas Project comes with strict conditions, [200930narrabri-gas-projectfinal.pdf (nsw.gov.au)]

Iverach, C. P., Cendón, D. I., Meredith, K. T., Wilcken, K. M., Hankin, S. I., Andersen, M. S., and Kelly, B. F. J.: A multi-tracer approach to constraining artesian groundwater discharge into an alluvial aquifer, Hydrol. Earth Syst. Sci., 21, 5953–5969, https://doi.org/10.5194/hess-21-5953-2017, 2017.
Kelly, B. F. J., Cendón, D. I., & Iverach, C. P. (2018). Baselining lower Namoi groundwater and evaluating Pilliga CSG developments.

Khaki, M., Hendricks Franssen, H. J., & Han, S. C. (2020). Multi-mission satellite remote sensing data for improving land hydrological models via data assimilation. *Scientific reports*, *10*(1), 1-23.

Lupton, N., Janardhanan, S., Connell, L. D., & Pickett, T. (2019). Improving groundwater models to better represent coal seam gas extraction impacts in the Namoi region. May 2019.

Dataset 1 NSW Office of Water (2014) Hydstra Groundwater Measurement Update - NSW Office of Water, Nov2013. Bioregional Assessment Source Dataset. Viewed 05 September 2016, http://data.bioregionalassessments.gov.au/dataset/08b34518-c947-4665-82e5- c144b5b24e01.

Raiber Matthias, Martinez Jorge, Suckow Axel, Deslandes Alec, Assessment of the influence of geological structures on aquifer connectivity in the Pilliga Forest area, NSW – an integrated hydrogeological, geophysical, hydro-chemical and environmental tracer approach, A technical report from CSIRO to GISERA, 2022

Sreekanth J, Tao Cui, Trevor Pickett (2017) Uncertainty analysis of CSG induced GAB flux and water balance changes in the Narrabri Gas Project area, [Uncertainty analysis of CSG- induced GAB flux and water balance changes in the Narrabri Gas Project area (csiro.au)]

Sreekanth J, Crosbie R, Pickett T, Cui T, Peeters L, Slatter E, Northey J, Merrin LE, Davies P, Miotlinski K, Schmid W and Herr A (2018) Groundwater numerical modelling for the Namoi subregion. Product 2.6.2 for the Namoi subregion from the Northern Inland Catchments Bioregional Assessment. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. http://data.bioregionalassessments.gov.au/product/NIC/NAM/2.6.2

Sreekanth, J., Gladish, D., Gonzalez, D., Pagendam, D., Pickett, T., & Cui, T. (2019). Optimal design and prediction-independent verification of groundwater monitoring network. *Water*, *12*(1), 123.

Sucknow, A., Deslandes, A., Gerber, C., Taylor, A., Raiber, M., Barrett, D., & Meredith, K. T. (2019). Groundwater recharge at the eastern intake beds of the Great Artesian Basin using multi-isotope studies.

Suckow, A., Deslandes, A., Gerber, C., Lamontagne, S., Mallants, D., Davies, P., ... & Barrett, D. (2020). Multi-isotope studies investigating recharge and inter-aquifer connectivity in coal seam gas areas (Qld, NSW) and shale gas areas (NT). *The APPEA Journal*, *60*(1), 335-347.

Tangdamrongsub, N., Han, S. C., Tian, S., Müller Schmied, H., Sutanudjaja, E. H., Ran, J., & Feng, W. (2018). Evaluation of groundwater storage variations estimated from GRACE data assimilation and state-of-the-art land surface models in Australia and the North China Plain. *Remote Sensing*, *10*(3), 483.

White, J. T., Hunt, R. J., Fienen, M. N., & Doherty, J. E. (2020). *Approaches to highly parameterized inversion: PEST++ Version 5, a software suite for parameter estimation, uncertainty analysis, management optimization and sensitivity analysis* (No. 7-C26). US Geological Survey.