Australia Pacific LNG Project

Volume 5: Attachments

Attachment 21: Ground Water Technical Report – Gas Fields

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Executive summary

Australia Pacific LNG will be extracting coal seam gas (CSG) from the Jurassic-aged coal measures beneath the eastern part of the Surat Basin in Queensland. The Surat Basin is part of the much larger Great Artesian Basin and is comprised of a composite thickness of continental fluvial and marine sediments extending to depths of 2500 metres or more in some places. The sediments themselves comprise alternating intervals of sandstone aquifers confined from above and below by mudstone, siltstone and shale aquitards.

The target formation for CSG extraction is the Walloon Coal Measures. This interval is encountered as shallow as 250 metres below ground surface and extends to depths of 1600 metres or more below ground surface. The lithology comprises relatively thin coal seams (up to metres) contained within a thick sequence (up to 500 m) of predominantly mudstone and siltstone layers

Recovery of CSG will be accomplished by lowering the hydraulic head in the coal seams to within 35 m of the uppermost coal seams by pumping associated water through dedicated production wells. A total of approximately 10000 wells are proposed; however, on average no more than 5000 wells will be operational during any given year. Potential hydrogeological implications of the CSG and associated water production activities include:

- Drawdown effects to local and regional aquifers
- Drawdown effects to groundwater dependent ecosystems (GDEs) and surface water features
- Secondary effects from CSG well operations (for example, gas liberation and migration)
- Leakage along annular pathways of poorly-constructed CSG wells or older pre-existing water bores
- Aquifer compression and subsidence of the land surface
- Effects to groundwater quality from surface activities including associated water treatment, storage and discharge.

To gain perspective on the basin environment and associated water resources, and assess the effects from CSG development, a robust conceptual model of the geological and hydrogeological conditions was developed. This conceptual model was predicated on a number of relevant reports and documents relating to the geology and hydrogeology of the Surat Basin. This was enhanced through the development of an integrated database consisting of:

- 4933 water levels
- 11232 chemistry records, and
- Over 12000 data points for geological control (obtained from public data sources and directly from Australia Pacific LNG).

Subsequently, a numerical groundwater flow model was developed, using the finite element code FEFLOW, to project effects of CSG development on regional groundwater levels, groundwater users and environmental receptors (i.e. streamflow, springs and groundwater dependent ecosystems). This model represents the first-of-its-kind cumulative effects simulator in the Queensland CSG sector, and an evolution in effects assessment for groundwater resources in the Surat Basin. In particular, it honours the hydrogeological complexity of the system as it:

- Is based on actual bore data

- Is of regional extent, and will therefore not be unduly affected by boundary conditions imposed upon it
- Honours lateral and vertical variation of hydraulic conductivities of the coal seams based on drill stem testing conducted by the CSG industry
- Honours vertical variation of thickness and hydraulic conductivities of other confining and aquifers intervals above and below the Walloon Coal Measures
- Has undergone steady state calibration to measured static water levels, and limited transient calibration to historical CSG water production rates
- Accommodates the combined effects of the Australia Pacific LNG Project as well as other CSG operators in the Surat Basin, including sequencing of the gas field development based on proposed and published development sequences.

Initial simulations were conducted for a 'project case' (Australia Pacific LNG only) and 'cumulative case' (Australia Pacific LNG, all other known and potential CSG developments and other large water entitlements accessing Great Artesian Basin aquifers). Initial results from the groundwater model indicate that drawdown is projected to occur within some aquifers. Given the configuration of these layers and their proximity to the Walloon Coal Measures, the drawdown effect is projected to be highest in the Springbok Sandstone, which is situated closest to the CSG interval. The Hutton Sandstone, which is situated beneath the Walloon Coal Measures, and separated from it by a lower permeability unit, is expected to experience comparatively less drawdown. Small amounts of drawdown are expected to occur in the shallower Gubberamunda Sandstone / BMO Grouping and near-surface Cainozoic Units. Upon completion of CSG development, water levels in the various aquifer intervals will recover towards pre-development conditions.

Following the implementation of proposed control measures, loss or reduction of groundwater supply to local landowner bores is considered to be a medium risk; however, compliance with the *Petroleum and Gas (Production and Safety) Act (2004)*, specifically the 'make good' requirements, may reduce the residual risk to low. The residual risks of other potential impacts are considered low.

It is realised that model projections alone are not enough to accurately assess possible effects from CSG development. Therefore Australia Pacific LNG has implemented, and will be enhancing over time, a comprehensive monitoring program using a network of monitoring wells at strategic locations across the region to assess for changes to water levels and quality conditions in key aquifer intervals. Indicative monitoring locations have been identified using a combination of groundwater model results and other criteria.

Construction of monitoring bores will be phased in concurrently with CSG development. Exact locations and density of the bore network will be adaptive based on changes in the risk profile from assessment of monitoring results, modelling and access issues such as landholder approvals and physical constraints.

In addition to monitoring, Australia Pacific LNG is committed to assessing and managing effects from their CSG development through an adaptive management process. Any associated effects to basin water resources that fall outside of established baseline conditions will be investigated, and if established triggers are exceeded the effects will be mitigated. This may include the option to fulfil the 'make good' requirement of the Petroleum and Gas (Production and Safety) Act (2004).

The modelling-monitoring-management approach being applied to the Australia Pacific LNG project, and surrounding areas, is considered an effective and practical means of identifying and responding to water-related challenges that may arise during CSG development activities in the Surat Basin.

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1. Introduction

1.1 Project background

Australia Pacific LNG Pty Limited (Australia Pacific LNG) proposes to develop a world-scale project sustaining a long-term industry that utilises Australia Pacific LNG's substantial coal seam gas resources in Queensland. The coal seam gas reserves occur in the Surat and Bowen Basins with the main development planned for the Walloons gas fields area.

The Walloons coal seam gas fields cover an area of 570000ha in the Queensland Western Downs region. Australia Pacific LNG's development plan will include up to 10000 wells over a 30 year project lifespan, with an average of no more than 5000 operating within any given year. Gas and water gathering systems will be developed for delivery to gas plant facilities and water treatment facilities, respectively. Associated infrastructure will include roads and access tracks, storage ponds, camps, communication infrastructure and other logistics support areas.

With respect to groundwater resources, a number of potential impacts have been identified that warrant assessment. Of particular interest are potential impacts associated with dewatering the coal measures (to promote gas production) on nearby receptors such as local landowner bores and groundwater dependant ecosystems (for example, local streams, rivers and discharge springs).

The assessment of these potential impacts has been achieved by conducting initial numerical groundwater modelling. It is noted that the groundwater flow model will continue to undergo refinement and re-calibration to constrain a number of sensitive inputs (e.g. recharge volumes) as ongoing data becomes available. This is in accordance with Australia Pacific LNG's adaptive management and continuous improvement process with the goal of achieving a higher level of confidence in future drawdown projections associated with CSG production. Therefore, the model projections discussed in the current document are semi-quantitative only.

1.2 Section layout

This technical report is an attachment to the Australia Pacific LNG Environmental Impact Statement (EIS), providing a groundwater assessment for the proposed gas fields component of the Project. It focuses on the Walloons gas fields and the associated groundwater systems, hereafter referred to as the study area for this report (see Section 5 for a detailed description of the study area).

This report has been designed to provide an understanding of the local and regional groundwater setting, and provide an overview of the baseline hydrogeological conditions. Additionally, a review of potential impacts related to this, and other, CSG developments in the area is provided. This review of site conditions and potential impacts is predicated on the Terms of Reference relating to the proposed project (Section 1.3).

The following layout for this technical report is therefore provided:

Section 1: Introduction

Section 2: Legislative and policy framework

Section 3: Project context

Section 4: Assessment methodology

Section 5: The study area: regional setting

Section 6: Environmental impact assessment

Section 7: Monitoring and assessment

Section 8: Mitigation and management

Section 9: Future activities

Section 10: Conclusions

The intent of the above-noted sections is to provide a comprehensive understanding of the challenges relating to CSG development, as they apply to groundwater resources, and place the Australia Pacific LNG Project into context with other existing or proposed CSG development activities (by BG/QCG, Santos/Petronas and Arrow/Shell) and large water takings occurring in the Surat Basin.

1.3 EIS Terms of Reference

The final Terms of Reference for the Australia Pacific LNG Project were provided by the Coordinator-General in December 2009. Listed within these Terms of Reference are items relating to the assessment of underground waters (groundwater) within the potentially affected area. To fulfil these requirements, the following key areas have been assessed:

- Groundwater quality, quantity and significance of artesian and non-artesian groundwater resources within the study area
- Values identified in the Environmental Protection (Water) Policy, Queensland 2009
- Methods to prevent seepage and contamination of groundwater from waste stockpiles
- Details of any potential disruption to groundwater flow, groundwater and surface water interaction, and potential for contamination or loss of pressure during construction, and any aquifer dewatering works required
- Discussion of potential impacts on the Narran Lakes Nature Reserve from possible reduction of water flow due to depressurising aquifers and/or contamination of groundwater through CSG extraction activities further upstream
- Assessment of the Walloon Coal Measures for inter-connectivity as a regional aquifer, and for inter-connectivity with the Great Artesian Basin
- Assessment of project sustainability, including both quality and quantity
- Review of the physical integrity, fluvial processes and morphology of groundwater resources including:
  - Nature of the aquifer(s), including:
    - Geology/stratigraphy, such as alluvium, volcanic, metamorphic
    - Aquifer type - such as confined or unconfined
    - Depth to and thickness of the aquifers
  - Hydrology of the aquifer(s), including:
    - Depth to water level and seasonal changes in levels
    - Groundwater flow directions (defined from water level contours)
    - Interaction with surface water

- Interaction with sea/salt water
- Possible sources of recharge
- Vulnerability to pollution.

- Review of groundwater dependent ecosystems in the study area, including an assessment of:
  - Environmental outcomes, objectives and assets identified under the Water Resource (Great Artesian Basin) Plan and the Great Artesian Basin Resource Operations Plan
  - Identification of all types of groundwater dependant ecosystems occurring in the study area or potentially impacted by project activities
  - Potential impacts on groundwater dependant ecosystems, with options to avoid or mitigate these impacts, and details of proposed monitoring for each identified groundwater dependant ecosystem
- Completion of a groundwater survey, including an assessment of:
  - Major ionic species present in the groundwater, pH, electrical conductivity and total dissolved solids
  - A survey of existing groundwater supply facilities (bores, wells, or excavations)
  - Location and type of facilities
  - Location, type and status of existing water entitlements
  - Pumping parameters
  - Drawdown and recharge at normal pumping rates
  - Seasonal variations (if records exist) of groundwater levels
- Development of a network of observation points which would satisfactorily monitor groundwater resources both before and after commencement of operations (with consideration given to the Queensland Government's policy proposal for groundwater monitoring, Blueprint for Queensland's LNG Industry)
- Assessment of the potential environmental impact caused by the Project (and its associated project components) to local groundwater resources, including the potential for groundwater induced salinity
- Definition of the extent of area within which groundwater resources are likely to be affected by the proposed operations and the significance of the Project to groundwater depletion or recharge, and proposed management options available to monitor and mitigate these effects
- Description of the response of the groundwater resource to the progression and final cessation of the Project
- Assessment of the potential to contaminate groundwater resources and measures to prevent, mitigate and remediate such contamination.

If groundwater injection is selected as a preferred discharge option for associated water, the potential impacts associated with this option should also be assessed with regard to the issues identified in the Environmental Protection Agency (EPA) Operational Policy, Management of water produced in association with petroleum activity (associated water) 2007, and the Department of Infrastructure and Planning (DIP) Policy, Queensland Coal Seam Gas Water Management Policy (2008).

2. Legislative and policy framework

The relevant legislative framework concerning the management of groundwater production, its storage and disposal in association with the Australia Pacific LNG project is provided in the following State legislation, policy and water resource plan documents:

- Environmental Protection Act, Queensland 1994
- Petroleum and Gas (Production and Safety) Act 2004
- Water Act, Queensland 2000
- Water Supply (Safety and Reliability) Act 2008
- Environmental Protection (Water) Policy, Queensland 2009
- Queensland Government's Department of Infrastructure and Planning 2009 Discussion Paper, Management of Water Produced from Coal Seam Gas Production
- Blueprint for Queensland's LNG Industry (Queensland Government 2009)
- Water Resource (Fitzroy Basin) Plan 1999
- Water Resource (Great Artesian Basin) Plan 2006
- Great Artesian Basin Resource Operations Plan 2007
- Water Resource (Condamine and Balonne) Plan 2004, and Condamine and Balonne Resource Operations Plan 2008
- Moratorium Notice Condamine Catchment Underground Water Area 2008.

Relevant elements of these documents, as they relate to groundwater production management on the Australia Pacific LNG Project, are presented in Table 2.1.

A key document with reference to groundwater production and management on the Australia Pacific LNG Project is the *Petroleum and Gas (Production and Safety) Act 2004* (PAG Act). According to the PAG Act, the petroleum tenure holder may take or interfere with groundwater (with no volumetric limit) taken during the course of an activity authorised under the petroleum tenure such as drilling petroleum wells. Importantly, the 'make good obligation' stipulated in the PAG Act (Part 9 Sections 244 to 280) indicates that if the petroleum activity unduly affects an existing water bore, the tenure holder must implement measures to restore a supply of water to the owner of the bore, or compensate the owner for being unduly affected. The PAG Act further requires the tenure holder to provide a water impact report should groundwater level fluctuations exceed a 'trigger threshold', addressing the extent to which project activities may have contributed to the impact and proposed make good measures.

Other key outcomes of the legislative framework review are as follows:

- Water licences are not required for groundwater extracted in association with CSG production (associated water) in Queensland on the condition the water is being utilised in a manner authorised by the PAG Act. The Fitzroy Basin water resource plan regulates overland flow of water only and is silent on groundwater in the Surat Basin. Groundwater resources in the area are managed in accordance with the Great Artesian Basin water resource plan. Section 10 of the plan excludes water licences for associated water under the PAG Act, from the operation of the water resource plan. The Condamine and Balonne water resources plan regulates the

taking of water from all surface bodies and may pertain to associated water in instances where it is stored in dams or other reservoirs in the plan area.

- Water licences are not required for groundwater extracted in association with CSG production in Queensland. The Great Artesian Basin, Condamine and Balonne and Fitzroy Basin water resource plans therefore do not apply to groundwater extraction proposed as part of the Australia Pacific LNG Project.
- In accordance with the DIP 2009 Discussion Paper, Australia Pacific LNG is responsible for the treatment and disposal of the CSG production water (or associated water). Notably, evaporation ponds are to be discontinued as a primary means for disposing of associated water. Furthermore, unless producers use direct injection of associated water or have arrangements for an environmentally-acceptable beneficial use, the untreated associated water must be treated to a standard defined by DERM before disposal or supply to other users.
- In the event that the associated water is utilised for purposes other than domestic and stock watering, or activities authorised by the petroleum tenure, the operator must acquire a water licence in accordance with the *Water Act 2000*.

Table 2.1 Relevant legislation, policies and plans

Reference	Key elements
Environmental Protection Act, Queensland 1994	Relevant legislation associated with the Environment Protection Act 1994 includes the Environmental Protection Regulation 2008, the Environmental Protection (Waste Management) Policy 2000 and the Environmental Protection (Waste Management) Regulation 2000. This legislation is also supported by the former Environmental Protection Agency's (EPA) 2007 Operational Policy titled, Management of water produced in association with petroleum activities (associated water). Key objectives of the EPA 2007 Operational Policy are to: (1) to provide consistency, certainty and transparency in decision-making about appropriate management strategies for associated water during the pre-design phase of applications for non-code compliant environmental authorities (petroleum activities), (2) to promote where feasible, beneficial use or injection in preference to any disposal options for the management of associated water, and (3) to achieve the best net environmental, social and economic outcomes for the management of associated water whilst providing flexibility in how the outcome is achieved. The Operational Policy stipulates a waste management hierarchy with two categories to provide guidance on the preferred methods for managing associated water: the preferred management options (Category 1) and non-preferred management options (Category 2). The applicant must determine their method of managing associated water in accordance with this hierarchy. For clarification, the management options in Category 1 can be adopted in any order. If management options in Category 2 are proposed to be applied, "the application must include a statement providing information sufficient to demonstrate that Category 1 management options are not feasible because of, for example, environmental, technological, economic, legislative or social considerations". Whilst the proportion of total associated water subject to Category 1 should be maximised to the greatest possible extent, the policy document does acknowledge that "preferred management options will at times necessarily involve the construction of water storages to aggregate water from multiple wells prior to on-supply or as reservoirs to contain water if discharge criteria are not met". Furthermore, "scope exists to stage water management strategies, whereby Category 2 options may be employed initially pending the outcome of trials or pilot studies for beneficial use projects or other Category 1 management options". Notably, if Category 2 options are applied, a re-evaluation of the opportunities and feasibility of Category 1 options to be established and commenced must be made available to the administering authority for review annually.
Petroleum and Gas (Production and Safety) Act 2004	With reference to groundwater management, the relevant sections of the *Petroleum and Gas (Production and Safety) Act 2004* are largely contained in Part 4: Water Rights for Petroleum Tenures, and Part 5: Water Monitoring Authorities and Part 9 Existing Water Act Bores. Associated water use According to Part 4 (Sections 185 to 189), a petroleum tenure holder may take or interfere with groundwater whilst carrying out an authorised petroleum activity. Otherwise the petroleum tenure holder cannot take or interfere with or use water, without a water licence, as defined under the

Reference	Key elements
	Water Act. If extracted for an authorised petroleum activity, there is no limit to the volume of groundwater that may be taken, provided that the take is 'necessary or unavoidable'. The associated water can be used for the authorised petroleum activity or for domestic and stock purposes on the land covered by the tenure and adjoining land or by any land owned by the land owner. If the tenure holder plans to use the associated water for another purpose, the holder must obtain a water licence in accordance with the *Water Act 2000*. Furthermore, a petroleum tenure holder may carry out a range of monitoring activities in the area of the tenure to comply with, or assess the need to comply with, the 'make good' obligation for the tenure. With reference to Part 5 (Sections 190 to 203), a petroleum tenure holder may apply for a water monitoring authority for stated land outside the area of the tenure to allow the holder to comply with, or assess the need to comply with, the make good obligation for the tenure. Water impacts and impact reporting Part 9 (Sections 244 to 280) imposes obligations on each petroleum tenure holder to take restorative measures in relation to particular water bores or compensate the owners of particular water bores. The make good obligation stipulated in Section 250 indicates that if the exercise of a petroleum tenure holder's underground water rights unduly affects an existing Water Act bore, the holder must: (a) within a reasonable period, take measures to restore the supply of water to the owner of the bore; or (b) compensate the owner for the bore being unduly affected. A bore is regarded as being 'unduly affected' when either: the water level in the bore drops below a trigger threshold for the relevant aquifer; or the bore is recognised as having 'impaired capacity'. Section 247 notes that a bore is generally recognised as having impaired capacity in the following circumstances: (i) in the case of a bore for domestic purposes: where the bore is no longer able to provide a reasonable supply of water for the domestic purpose required at the location; (ii) in the case of a bore for stock purposes: where there is a material reduction in the number of stock able to be watered from the bore (having regard to the stock carrying capacity of the land serviced by the bore); or (iii) under a water licence: where there is a material reduction in the pumping supply required to service the relevant enterprise or town water supply. Furthermore, if an existing Water Act bore is likely, after the petroleum tenure ends, to become unduly affected by the exercise of the rights, the holder must, before the tenure ends, comply with the before mentioned obligations. Trigger values The holder of the tenure must provide a water impact report of its activities (Section 252 to 257). The Act requires the fixing of a 'trigger threshold' for aquifers in the area affected by the exercise of underground water rights for a petroleum tenure in order to prepare an underground impact report for the tenure. However, Section 253 states that "the petroleum tenure holder may ask the chief executive what the trigger threshold is for the aquifers". The trigger value is defined as "the water level drop in the aquifers that the chief executive considers would be a level that causes a significant

Reference	Key elements
	reduction in the maximum pumping rate or flow rate of the existing Water Act bores in the area affected by the exercise of the underground water rights". In defining the trigger threshold, consideration must be afforded to permeability, geometry and water levels of the aquifers. The time period over which the pumping is conducted is not stipulated in the Act.
Water Act 2000	The *Water Act 2000* vests the use and control of all water in the state of Queensland. The Act was developed to provide for the sustainable management of water and other resources and the establishment and operation of water authorities. According to Section 206(4), a petroleum tenure holder may apply for a water licence for taking water or interfering with the flow of water if such water is produced as a result of testing or commercial production activities for which a right is not conferred under the PAG Act. The requirements for a water licence application by a petroleum tenure holder are outlined in Section 206 and 206A. If a water licence is granted to a petroleum tenure holder, there may be a requirement under Section 214 (2)(e) "to carry out and report on a stated monitoring program".
Water Supply (Safety and Reliability) Act 2008	The purpose of the Act is to provide for the safety and reliability of water supply. These objectives are achieved in the Act by providing: (i) a regulatory framework for the provision of water and sewerage services in the State, (ii) a regulatory framework for providing recycled water and drinking water quality, primarily for protecting public health; (iii) the regulation of referable dams; (iv) flood mitigation responsibilities; and by protecting the interests of customers of service providers. The Act refers to manufactured water which is defined as water, including desalinated or recycled water or any substance resulting from the production of desalinated or recycled water, from any source. The Act stipulates that the owner of one or more elements of infrastructure for supplying water or sewerage services for which a charge is intended to be made must apply for registration as a water service provider. This Act will be relevant in the event that raw or treated associated CSG production water is to be reused for a beneficial use.
Department of Infrastructure and Planning 2009 Discussion Paper 'Management of Water Produced from Coal Seam Gas Production'	In May 2009, the Queensland Government (Department of Infrastructure and Planning) issued a Discussion Paper, Management of Water Produced from Coal Seam Gas Production. The intent of the Paper is to inform stakeholders of various government criteria concerning the management of CSG and secondly, to seek stakeholder views on a number of specific issues related to these decisions prior to finalising the policy positions. A key policy decision stated in the Discussion Paper is that "evaporation ponds are to be discontinued as a primary means for disposing of CSG water" with "remediation of existing evaporation ponds to occur within the next three years". Furthermore, the policy stipulates that "unless the producers use direct injection of CSG water or have arrangements for environmentally-acceptable direct use of untreated CSG water, the producers must treat CSG water to a standard defined by the Environmental Protection Agency (EPA) before disposal or supply to other users". With reference to the injection of CSG production water, clarification sought from the Queensland Government's Department of Environment and

Reference	Key elements
	Resource Management indicates that the water management options stipulated in the EPA 2007 Operational Policy remain applicable. That is, the preferred options include injection into natural underground reservoirs or aquifers of equal or lesser water quality, direct use or treated use. Importantly, with reference to aquifer disposal, the condition regarding water quality concerns all the chemical constituents in the water (that is, not only the salinity compatibility of the receiving and injecting waters).
Queensland Government's "Blueprint for Queensland's LNG Industry"	The Blueprint for Queensland's LNG Industry presents the Government's approach to facilitating and managing development of the LNG industry in Queensland. A number of the stipulations concerning water management and disposal, as documented in the Queensland Government's 2009 Discussion Paper, Management of Water Produced from Coal Seam Gas Production, are re-iterated in this document. Of relevance to groundwater management in the LNG industry, the Blueprint indicates the Government will commit to the following: (i) implementation of groundwater monitoring, assessment and reporting in accordance with the requirements of the *Petroleum and Gas (Production and Safety) Act 2004*, (ii) simplification of the process for defining trigger thresholds for obligations to 'make good' impacts on water bores, (iii) expansion of the application of 'make good' requirements to include impacts on bores built after the LNG proponents have received their environmental authority, and impacts on springs, (iv) expansion of the application of 'make good' requirements to include cumulative impacts, and (v) development of a regional groundwater monitoring regime, to be funded via an industry levy on CSG producers with oversight by an independent monitoring body.
Environmental Protection (Water) Policy 2009	The Environmental Protection (Water) Policy 2009 aims to support the *Environmental Protection Act 1994* with a range of water management guidelines. Section 6 of this policy describes the environmental values of waters to be enhanced or protected under the policy and Section 7 outlines the indicators and water quality guidelines for environmental values. The direct release of waste water to waters is regulated according to Section 13 of the Policy; a four step hierarchy of preferred procedures. The last (fourth) step stipulates that if waste water treatment and recycling does not, or is not likely to, eliminate the release of waste water or contaminants to waters, the following options must be evaluated (in order of priority): (i) appropriate treatment and release to waste facility or sewer (ii) appropriate treatment and release to land (iii) appropriate treatment and release to surface waters or groundwater.
Water Resource (Fitzroy Basin) Plan 1999	The Water Resources (Fitzroy Basin) Plan 1999 provides a framework for sustainably managing water and the taking of water, and provides a framework for establishing water allocations and regulates the taking of overland flow water. Groundwater in the Surat Basin is not managed under the Plan. Groundwater resources in the area are managed in accordance with the Water Resource (Great Artesian Basin) Plan 2006.

Reference	Key elements
Water Resource (Great Artesian Basin) Plan 2006	The Water Resources (Great Artesian Basin) Plan 2006 is the primary legislation for groundwater management of the Great Artesian Basin in Queensland. The purpose of the plan is (a) to define the availability of water in the plan area; (b) to provide a framework for sustainably managing water and the taking of water; and (c) to identify priorities and mechanisms for dealing with future water requirements. Notably, water licences for associated water under the *Petroleum and Gas (Production and Safety) Act 2004* are excluded from the allocation and management of water in the plan area. The management areas for the plan area are presented in Schedule 2. The Australia Pacific LNG Project is within the Eastern Downs, Surat East, Surat and Surat North management areas.
Great Artesian Basin Resource Operations Plan 2007	The Great Artesian Basin Resource Operations Plan 2007 implements the Water Resource (Great Artesian Basin) Plan 2006. Twenty-five groundwater management areas (GMAs) and associated groundwater management units (GMUs) are identified in the plan. A groundwater management unit corresponds to a formation or to a group of formations. For each unit a specified upper annual allocation of water is identified. Specifically, the Surat Basin is divided into seven GMAs and 26 GMUs. The plan specifies a process for making up to 23,000ML per annum of unallocated water available across the Basin from the general reserve. Furthermore, the plan indicates that 10,000ML of unallocated water for projects of state or regional significance, or for future town water supply, has been reserved to provide for further economic opportunity in the Basin.
Water Resource (Condamine and Balonne) Plan 2004 and Condamine and Balonne Resource Operations Plan 2008	The Water Resources (Condamine and Balonne) Plan 2004 defines the availability of surface water in the plan area and regulates the taking of water from all surface water bodies. The Plan may pertain to associated CSG production water in instances where it is stored in dams or other reservoirs in the plan area. Groundwater is not yet included in the Plan. The Condamine and Balonne Resource Operations Plan 2008 provides the strategy to implement the management requirements contained in the Water Resource (Condamine and Balonne) Plan 2004. The plan applies to surface watercourses, lakes, springs connected to artesian water or sub-artesian water which is connected to artesian water and overland flow.
Moratorium Notice Condamine Catchment Underground Water Area 2008	A moratorium on new extraction of groundwater in the Condamine Catchment Underground Water Area was issued on 10 July 2008. The moratorium affects groundwater contained in the Main Range Volcanics (Basalt) Aquifer System, excluding water in this aquifer system that is captured by the Toowoomba Moratorium Notice; the Condamine River and Tributaries Alluvium Aquifer System and the Tertiary Chinchilla Sands Aquifer System. The moratorium notice does not apply to the taking of water for a project of State significance or Regional significance pursuant to the State Development and Public Works Organisation Act 1971.

3. Project context

3.1 Current and future CSG development

3.1.1 Australia Pacific LNG operation

Origin Energy (a 50% partner with ConocoPhillips in the Australia Pacific LNG Project) currently has CSG operations underway in the study area. These operations consist of a limited number of approved CSG wells (currently 15 with up to 100 planned) and related production facilities located in the southern part of the Talinga development area. This field is approximately 25km south-west of the town of Chinchilla and has been in operation since 2005.

3.1.2 Other existing and potential developments

The Australia Pacific LNG Project represents only one of many other proposed CSG projects in the region accessing natural gas reserves in the Jurassic Coal Measures. Other CSG operations in the region that have been operational since mid-2005 include:

- Arrow Energy, operating the Daandine (late-2005), Kogan North (mid-2005) and Tipton West (mid-2005) fields
- Queensland Gas Company, operating the Argyle (late-2007), Argyle East (late-2008), Berwyndale South (mid-2005) and Kenya fields (mid-2007)
- Santos Limited, operating Coxon Creek (mid-2007).

Other CSG projects currently before the Government of Queensland for consideration include:

- Queensland Gas Company Queensland Curtis LNG project, located near the Chinchilla area
- Santos Limited Gladstone LNG project, located near the Roma area.

The disposition of CSG tenements across the region, and the related owner, is shown in Appendix A, Map 1.

Additional CSG tenements exist that are likely to be developed at some point in the future. These tenements are currently owned by the following companies:

- Arrow Energy
- Blue Energy
- Bow Energy
- Origin Energy
- BG Group (that is, the Queensland Gas Company)
- Santos.

In addition to CSG tenements, underground coal gasification (UCG) tenements also exist within the study area. These include:

- Linc Energy
- Carbon Energy

- MetroCoal.

3.2 Spatial and temporal boundaries

To provide perspective on the Australia Pacific LNG Project, consideration must be given to the spatial and temporal boundaries of the proposed activities. Because CSG development occurs in phases, not all parts of the Project will be operating consistently. The proposed development approach is to phase in various portions of the Project over time. The following sections provide some context to these changing conditions.

3.2.1 Study area extents

The regional study area under assessment comprises approximately 173000km^2 of the Surat Basin. This area represents the domain considered for the cumulative effects numerical groundwater model developed in support of this project (refer to Section 6.2.1). Established towns and municipalities within this study area include:

- Chinchilla
- Dalby
- Diranbandi
- Goondiwindi
- Injune
- Ingelwood
- Jandowee
- Miles
- Millmerran
- Mitchell
- Oakey
- Roma
- St. George
- Surat
- Tara
- Taroom
- Texas
- Wandoan

The closest towns to Australia Pacific LNG's CSG tenements are Dalby, Chinchilla, Miles and Roma.

Predominant land use in the region is agricultural development and the raising of livestock. A significant portion of the water in the region is used to accommodate these sectors of the economy.

The boundaries of the study area have been established either using natural landscape features or constraints based on the numerical groundwater flow model. With respect to natural boundaries, the outcrop margin of the base of the Precipice Sandstone (the bottom of the Jurassic-aged sequence defining the Surat Basin, which is underlain by low permeability geology) is therefore suitable as the model base. The western boundary of the study area conforms to the long-axis of the Nebine Ridge, which separates the sediments of the Surat Basin from the adjacent Eromanga Basin. The eastern boundary corresponds to the basin margin in the vicinity of Toowoomba and is defined by the foothills of the Great Dividing Range. Finally, the southern boundary was selected roughly along the border between Queensland and New South Wales, and at a distance far enough from CSG activity to be un-affected by currently proposed development.

Australia Pacific LNG's existing CSG tenements extend across the north-eastern and central portion of the study area. These tenements (development areas), and their proposed years of commissioning are outlined in Table 3.1.

Table 3.1 Australia Pacific LNG development areas

Field	Proposed year of commissioning
Combabula	2012
Talinga	2013
Condabri South	2013
Pine Hills	2013
Reedy Creek	2013
Orana	2014
Orana North	2014
Condabri Central	2014
Kainama	2015
Ramyard	2015
Dalwogan	2015
Wooleebee	2016
Gilbert Gully	2016
Carinya	2017

Upon approval, each of these proposed CSG fields will be phased in over a period extending between 2012 and 2017. It is assumed that a total of 10000 wells will be developed over the lifetime of the Project; however, on average no more than 5000 wells will be operational during any given year. This is because the gas wells will become depleted over time hence the number of wells drilled will be larger than the number operating in a given year. This should ensure a steady flow of CSG to the LNG facility.

3.3 Potential project effects

There are a number of potential effects associated with CSG development, both from a gas extraction and gas delivery perspective. Potential project effects assessed as part of this application include:

- Drawdown effects to local and regional aquifers
- Drawdown effects to groundwater dependent ecosystems (GDEs) and surface water features
- Secondary effects from CSG well operations (for example, gas liberation and migration)
- Leakage along annular pathways of poorly-constructed CSG wells or older pre-existing water bores
- Aquifer compression and subsidence of the land surface
- Effects to groundwater quality from surface activities including associated water treatment, storage and discharge.

Each of these potential effects has been reviewed from a risk perspective, considering the temporal extent of the Project. For the purpose of this groundwater assessment, a project life extending to 2070 has been used. However, potential effects from dewatering of the coal measures are anticipated to extend further into the future (Section 6.2.1).

3.4 Previous and related studies

A large number of hydrogeological studies have been completed to date with respect to the Great Artesian Basin. Most of these studies have been funded or authored by state or federal government institutions with the objective of characterising the system and identifying tools to enable effective management of water resources within the basin.

Key technical reports that were accessed to provide hydrogeological context to the current study are listed in Table 3.2. In particular, the comprehensive stratigraphy and structural geology of the Surat Basin presented in Exon (1976) provided the foundation for the hydrogeological conceptual model developed to support this EIS (Section 5).

Table 3.2 Key technical reports

Reference	Relevant content
Great Artesian Basin Water Resource Plan, River Baseflow from Aquifers of the GAB (AGE 2005)	Presentation of potential areas of groundwater and surface water interaction in the GAB WRP area, and contains mapping of the river reaches of river systems where there is a potential interaction with groundwater from aquifers of the GAB.
Isotope Hydrology of the Great Artesian Basin, Australia (Airey et al. 1983)	Environmental isotope and hydrochemistry interpretation to confirm recharge areas and regional groundwater flow patterns in the Great Artesian Basin.
Progress Report on the Great Artesian Basin Hydrogeological Study 1972 – 1974 (Audibert 1976)	Findings of a mathematical model simulating groundwater flow in the Great Artesian Basin. Hydraulic parameters are also presented for the confined aquifers and confining beds.
Upper Condamine Groundwater Model Calibration Report (Barnett et al. 2008)	Findings of a numerical groundwater model constructed for the Upper Condamine region to evaluate groundwater level trends impacted by irrigation withdrawals and long-term sustainability of the groundwater resource. A multi-disciplinary assessment quantifying the model and magnitude of recharge to major Great Artesian Basin aquifers in Queensland.
Groundwater Recharge in the Great Artesian Basin Intake Beds, Queensland (Bureau of Rural Sciences and Queensland Department of Natural Resources and Mines 2003)	Quantification of recharge rates to the intake beds of the Great Artesian Basin, for the purposes of providing a sound scientific basis for the development of Groundwater Management Plans and policies to ultimately ensure that groundwater is used within sustainable limits throughout the intake beds and adjacent management zones.

Reference	Relevant content
Bowen and Surat Basins, Clarence-Moreton Basin, Sydney Basin, Gunnedah Basin and other minor onshore basins, Qld, NSW and NT (Cadman and Pain 1998)	Presentation of data concerning identified petroleum resources, in the Bowen and Surat Basins, Clarence-Moreton Basin, Sydney Basin and Gunnedah Basin, and an appraisal of their geological setting, hydrocarbon potential and general character.
Surat and Bowen Basin South-east Queensland (DME 1997)	Comprehensive summary of stratigraphy and the structural, petroleum and economic geology of the Surat Basin updated from Exon (1976)
The Geology of the Surat Basin in Queensland (Exon 1976)	Comprehensive summary of stratigraphy and the structural, petroleum and economic geology of the Surat Basin.
Stratigraphic Drilling in the Surat and Bowen Basins, 1967-1970 (Gray 1972)	Results of stratigraphic drilling in the Surat and Bowen Basins undertaken between 1967 and 1970 by the Department of Mines.
Great Artesian Basin Resource Study (Great Artesian Basin Consultative Council 1998)	A review of groundwater extraction and impacts, existing arrangements for groundwater management and significant issues for groundwater management within the Great Artesian Basin.
Report on the Groundwater Impact Study for the Coal Seam Gas Operations Chinchilla, Surat Basin Queensland (Golder Associates Pty Ltd 2008)	A summary of a simplified conceptual hydrogeological model encompassing the current and proposed CSG development areas owned by the Queensland Gas Company and Origin Energy in the Chinchilla region. Findings of a simplified numerical groundwater model of the region are also presented along with the evaluation of potential groundwater level impacts associated with CSG production.
The Great Artesian Basin, Australia (Habermehl 1980)	A comprehensive discussion on the Great Artesian Basin's climate, surface water systems, vegetation, land use and economy, groundwater exploration and development, stratigraphy, structure, geological and hydrogeological setting, discharge and recharge processes, groundwater flow, hydrochemistry and groundwater management.
Springs in the Great Artesian Basin, Australia – Their Origin and Nature (Habermehl 1982)	A survey of the occurrence of discharge features (springs) associated with the Great Artesian Basin.
Hydrogeology and Environmental Geology of the Great Artesian Basin, Australia (Habermehl 2001)	A summary of the geological and hydrogeological setting of the Great Artesian Basin, including recharge and discharge mechanisms, groundwater extraction, groundwater flow, groundwater level variations, hydrochemistry and groundwater assessment and management requirements.
A Summary of the Hydrogeology of the Southern	A summary of the hydrogeological setting, recharge

Reference	Relevant content
Eromanga and Surat Basins of the Great Artesian Basin (Henning 2005)	and discharge processes and water chemistry properties of the Southern Eromanga and Surat Basins. A discussion of the challenges with the current basin-wide groundwater monitoring program is also provided.
Geochemistry of Groundwaters from the Great Artesian Basin (Herczeg 1991)	A concise summary of the geochemical characteristics of groundwater in the Great Artesian Basin and its chemical evolution along flow paths.
Condamine River Groundwater Investigation (Huxley 1982)	Assessment of the groundwater input and output quantities of the alluvial aquifers and generation of a water balance within the Condamine River catchment.
Progress Report on the Condamine Underground Investigation to December 1978 Volume 1 (Lane 1979)	Report of an investigation conducted to establish the feasibility of enhancing groundwater recharge through the clay soils along the Condamine River and the North Branch and in areas away from the North Branch on either side. As part of the investigation, a series of artificial recharge trials were conducted to facilitate actual measurements of absorption rates and assessment of likely recharge potential.
Coal Seam Gas Water Management Study (Parsons Brinkerhoff 2004)	Findings of a desk-top study to evaluate the potential hydrogeological impacts of CSG production in the Surat Basin and the feasibility of various water disposal options to manage water generated from CSG production.
Hydrochemistry and Implied Hydrodynamics of the Cadna-owie – Hooray Aquifer, Great Artesian Basin, Australia (Radke et al. 2000)	A comprehensive study of a regional interpretation of the hydrochemistry of the Cadna-owie – Hooray Aquifer, outlining regional variations in ion concentrations, evaluation of hydrochemical processes in groundwater evolution, quantification of flow rates and delineation of flow regimes.
Revised Geology and Coal Seam Gas Characteristics of the Walloon Sub-group – Surat Basin, Queensland (Scott 2004)	A comprehensive stratigraphic review and clarification of CSG characteristics of the Walloon sub-group in the Surat Basin.

With reference to specific hydrogeological studies conducted in relation to CSG production within the Surat Basin, the Queensland Department of Natural Resources Mines and Energy (NRME) (now the Department of Environment and Resource Management – DERM) funded a desk-top evaluation in 2004 to assess the potential effects arising from such operations. Although a detailed hydrogeological assessment was not undertaken, the study did identify key issues and concerns relating to potential groundwater impacts and water management options from CSG development.

In 2008, the Queensland Gas Company and Origin Energy funded a desk-top hydrogeological study to evaluate the potential groundwater level and quality effects associated with their current and proposed CSG operations in the Chinchilla region. The primary objective of the study was to characterise the

regional groundwater system and identify 'order of magnitude' potential impacts to the groundwater system arising from the imposed drawdown of hydraulic heads in the coal seam aquifers.

A key project concerning sustainable water management in the context of the CSG industry is currently being conducted as part of the Commonwealth-funded Healthy Head Waters project in the Queensland part of the Murray-Darling Basin. The feasibility study (ongoing until 2012) will examine the use of CSG production water to address water sustainability and social adjustment issues, in particular, relieving demand on groundwater for irrigation in heavily-committed aquifer systems near the Condamine River.

4. Assessment methodology

4.1 Information sources

Information used for this groundwater assessment relies heavily on pre-existing data and reports. This information has been supplemented with data collected during a reconnaissance field program, conducted in June 2009. The main sources of data are briefly described below, with specific references provided.

4.1.1 Climate data

Climate data was obtained from Australia's Bureau of Meteorology (BOM). Monthly temperature and evaporation data was obtained from the Bureau's website, whereas daily rainfall data was purchased from the BOM Climate Services Centre.

4.1.2 Regional geology

The geology of the Surat Basin has been extensively studied – see, for example, Geology of the Surat Basin in Queensland (Exon 1976) and The Surat and Bowen Basins South-East Queensland (DME 1997). This work has been used as the basis for understanding and describing the regional geology in this EIS. It has been supplemented with more specific information on individual hydrogeologic units, and more general information pertaining to the Great Artesian Basin. The following main sources of information have been used:

- Habermehl 1980, The Great Artesian Basin, Australia
- Radke et al. 2000, Hydrochemistry and implied hydrodynamics of Cadna-owie – Hooray Aquifer – Great Artesian Basin
- Scott et al. 2004, Revised Geology and Coal Seam Gas Characteristics of the Walloon Sub-group
- Cadman et al. 1998, Bowen and Surat Basins, Clarence-Moreton Basin, Sydney Basin, Gunnedah Basin and other minor onshore basins, Qld, NSW and NT
- Geological maps (1:250,000 scale) for the study area, including the following sheets:
  - Eddystone; (Exon 1967)
  - Goondiwindi (Mond et al. 1972)
  - St. George (Senior and Senior 1971)
  - Dalby (Exon et al. 1972)
  - Chinchilla (Exon et al. 1971)
  - Maryborough (Cranfield 1992)
  - Munduberra (Whitaker et al. 1980)
  - Surat (Thomas and Reiser 1971)
  - Roma (Milligan et al. 1971)
  - Taroom (Forbes et al. 1967).

4.1.3 Regional hydrogeology

The geology and hydrogeology of the Great Artesian Basin has been extensively studied, and a large amount of reference material was accessed for this study to help understand the local and regional context. The main reference sources accessed include:

- Habermehl 1980, The Great Artesian Basin, Australia
- Radke et al. 2000, Hydrochemistry and implied hydrodynamics of Cadna-owie – Hooray Aquifer – Great Artesian Basin
- Great Artesian Basin Consultative Council 1998, Great Artesian Basin Resource Study
- Henning 2000, A Summary of the Hydrogeology of the Southern Eromanga and Surat Basins of the Great Artesian Basin
- BRS & NRM 2003, Groundwater Recharge in the Great Artesian Basin Intake Beds, Queensland
- CSIRO 2008, Upper Condamine Groundwater Model Calibration Report.

4.1.4 Borehole data

Borehole data was acquired to supplement the geology of the regional and local study areas. This information was obtained from four primary sources:

- Queensland DERM groundwater bore database (GWBD), supplied on 7 January 2009
- Borehole logs, drill stem test (DST) results and geophysical logs for petroleum exploration bores and CSG wells, provided by Origin Energy
- The database associated with the acquisition of wire-line logs from selected water bores in the Great Artesian Basin (GABLOG) (Habermehl 2001)
- Groundwater license data from the DERM water entitlements register database (WERD), which included approved licenses as of 18 June 2009 and estimates of stock and domestic groundwater use from DERM (2004).

The type of data acquired from each source is tabulated in Table 4.1.

Table 4.1 Summary of borehole data sources

Data source	Location and elevations	Stratigraphy	Water levels	Chemistry	Hydraulic parameters	Groundwater use
GWBD	●	●	●	●		
Origin Energy	●	●	●		●	
GABLOG	●	●				
WERD	●					●
DERM (2004)						●

The bore data from the various sources was compiled into a database for each aspect of the hydrogeology. In excess of 27000 individual bore records were accessed for use; however, many of these were filtered out due to poor data quality or lack of useful information. During development of

this supporting database, it was recognised that different co-ordinate systems, projections and reference datums were utilised by the various sources, which were often not referenced. Universal Transverse Mercator (UTM) co-ordinates (eastings and northings) in Map Grid Australia (MGA) Zone 55 were used as a universal co-ordinate system for the bore data locations. It is recognised that the study area extends across both MGA zones 55 and 56; however, the numerical groundwater model (FEFLOW – see section 4.4) cannot accommodate multiple zones and cannot utilise latitude and longitude. It was recognised that there may be inaccuracies in the location of some of the spatial data, but given the regional extent of the study area, minor discrepancies due to the differing datums was considered unlikely to impact the modelling process or associated outcomes.

It is similarly true that the various databases accessed contained un-verified and un-validated data records. Where obvious inaccuracies were observed, this data was removed from the final integrated database. This final data set was generally considered suitable for the purposes of this regional-scale assessment.

Much of the bore data was found to be clustered within current and previous petroleum development areas, with large gaps between these areas. While due care has been taken in making assumptions to fill these gaps, particularly in the compilation of geological layers for the numerical model, it is recognised that these assumptions may affect the results of the assessment. The data is, however, considered generally suitable for the purposes of this regional-scale assessment.

4.1.5 Physiography and drainage

The digital elevation model (DEM) used in the hydrogeological assessment was part of a global 30 arc-second elevation data (GTOPO30) obtained from the United States Geological Survey (USGS). The spatial resolution of this information is 1000m by 1000m, with a vertical accuracy (standard deviation) of 30m. A DEM is least accurate in an area of high topographic relief. Thus in a relatively flat regional study area (like the current study area), the accuracy of the GTOPO30 DEM is considered suitable for the purposes for which it was used.

4.2 Data evaluation

4.2.1 Geological surfaces

A review of published geological and hydrogeological information was conducted to gain an understanding of the basin-scale hydrogeology of the study area. Given the current understanding, the various geological units were combined on the basis of similar hydrogeological characteristics to create twelve hydrostratigraphic units (Section 5.4.1). Stratigraphic logs were simplified to represent these hydrostratigraphic units. Stratigraphic data was used (in order of preference) from:

- Origin Energy
- GWBD
- GABLOG

A database was compiled with depths to the top of each unit for each bore location. The number of bore data for each unit is shown in Figure 4.1**Error! Reference source not found.**, which does not include outcrop data or digitised information. Notably, the Kumbarilla Beds, which is the outcrop equivalent in the eastern part of the study area of the Bungil Formation, Mooga Sandstone, Orallo Formation, Gubberamunda Sandstone, Westbourne Formation and Springbok Sandstone, has been included in the Gubberamunda Sandstone hydrostratigraphic unit. Any geological unit pre-dating the

Precipice Sandstone was considered to be below the base of the groundwater model domain. The Cainozoic Unit was not mapped as a distinct layer due to its minimal thickness. Instead, an isopach (thickness) was generated on the basis of CSIRO (2008) for inclusion in the FEFLOW model.

The 1:250000 surface geology data was simplified to be consistent with the defined hydrogeological units. Using a Geographical Information System (GIS) approach, the DEM was used to obtain ground surface elevation where each hydrostratigraphic unit outcropped. This data was then added to the borehole formation top data in the borehole database.

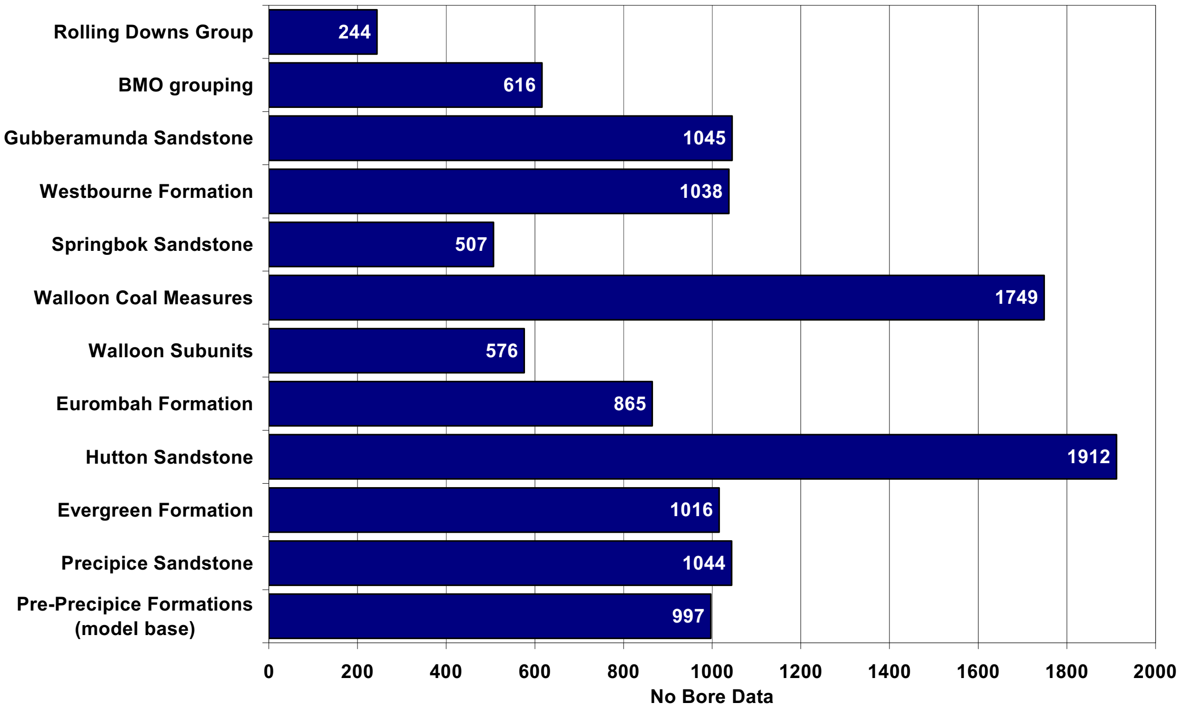


Figure 4.1 Numbers of bore data used in the compilation of the geological surfaces

Locations of the various bore data and outcrops used to constrain geological surfaces for the model have been shown in Figure 4.2 .

From this figure some general trends in the distribution of data can be recognised:

- There is minimal bore data in the west and south-west of the study area for all units
- Bore data is sparse or non-existent through the axis of the Taroom Trough with the exception of the northern part of the study area where the units sub-crop and are shallow, and where there is good GWBD bore data coverage. There is, however, good data coverage on the margins of the Taroom Trough associated with current and historical petroleum exploration/production activity
- Data for the Springbok Sandstone, Walloon Coal Measures sub-units and the Eurombah Formation is generally concentrated in the Australia Pacific LNG development areas, and is sparse elsewhere

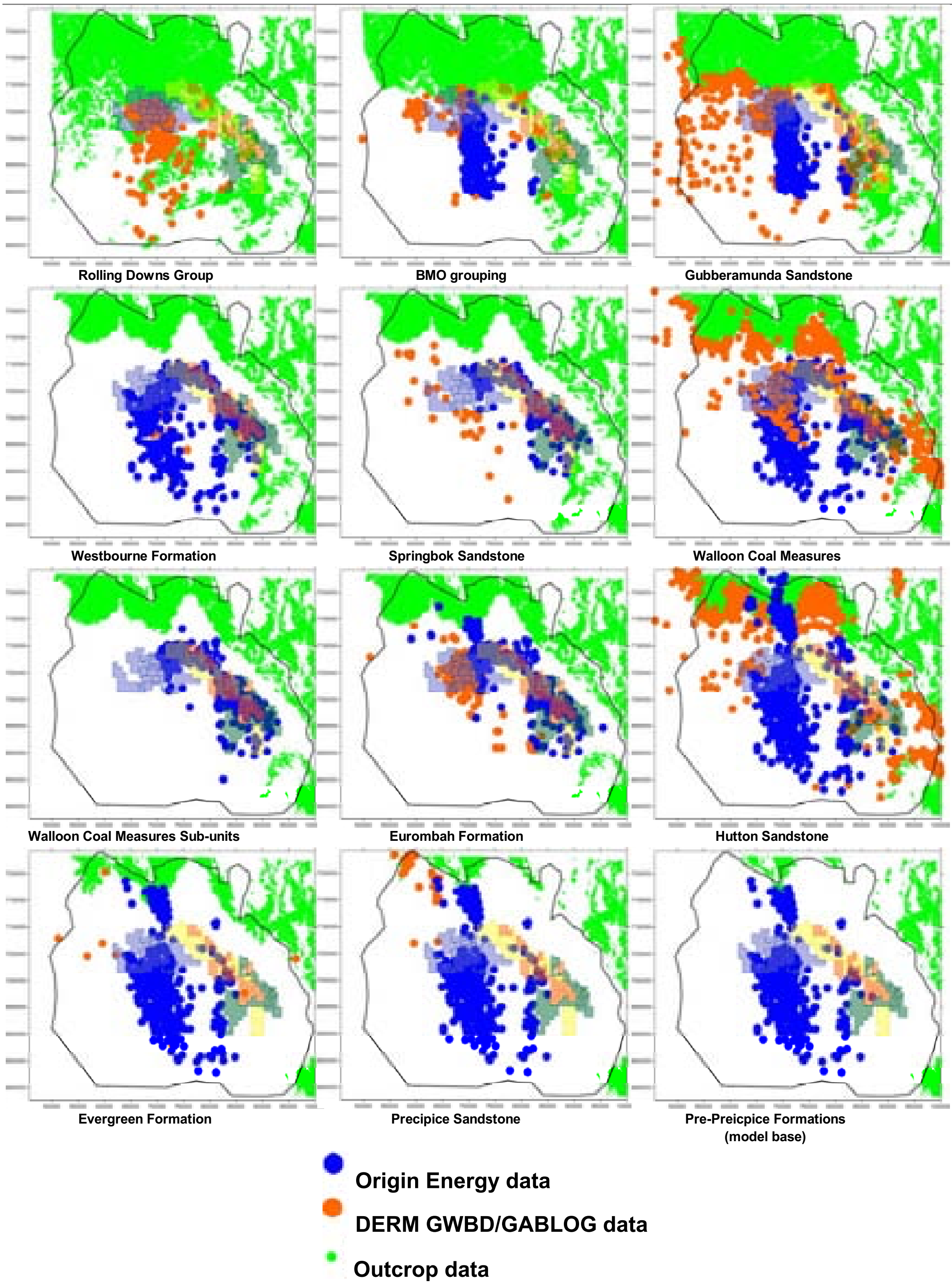


Figure 4.2 Locations of stratigraphic bore data and outcrop data

Structured contour maps provided by Exon (1976) were digitised to augment the borehole data, specifically for the following geological surfaces:

- Walloon Coal Measures
- Evergreen Formation
- Pre-Precipice Formations (model base).

The digitised data was only used to fill gaps, that is, if borehole data was available this approach was used in the first instance. Where neither bore data nor published maps were available data points were added to minimise contouring artefacts. When adding data points, consideration was given to the general underlying structure of the Surat Basin using the published structured contours (Exon, 1976) as a guide and formation isopachs (Exon, 1976 and DME, 1997) and general knowledge of depositional environments consistent with the setting.

Surfer© (Golden Software 2007) was used to contour the data, using the point Kriging algorithm to interpolate between data points. Obvious data discrepancies were removed from each dataset. Isopach (unit thickness) maps were prepared by subtracting the older unit from the immediately younger unit. Mapping depths to the top of a unit was completed by subtracting the particular mapped elevation of the surface from the DEM elevations. Additionally, geological cross-sections were created from the contoured data forming the geological surfaces.

This consistent set of hydrostratigraphic unit surfaces has been used for the following:

- numerical groundwater flow model development (Section 6.2.1)
- development of the water level and water chemistry database.

4.2.2 Hydraulic properties

Measured hydraulic parameter values (including permeability, hydraulic conductivity, transmissivity and storativity) for the various hydrostratigraphic units constituting the conceptual model were collated from exploration activities conducted by Origin Energy and other data sources. Selected geophysical logs were also interrogated to evaluate the variability of formation properties and permeability characteristics across sequences of units at particular locations.

The range in measured and inferred hydraulic parameter properties was adopted in the initial construction of the numerical groundwater model. In turn, the calibration process further constrained values of hydraulic parameters for each geological unit applied in the model.

A summary table of the hydraulic properties used in the model construction is provided as Table 6.1.

4.2.3 Water levels and potentiometry

Water level data obtained from the GWBD was used to generate potentiometric surfaces for various aquifer intervals. Data from this source was only considered useful if it could be assigned to a particular hydrostratigraphic unit. To maximise the dataset, open and perforated intervals, determined from the GWBD construction data, were compared with the surfaces generated for each of the hydrostratigraphic units. Where the top and bottom of an open or perforated interval was clearly positioned within one unit, that unit was assigned to the bore and the water level data was utilised. If the analysis returned multiple units for an individual bore, that bore was removed from the resulting dataset. Bores without construction data were not considered.

A search of the GWBD returned approximately 223400 individual water level readings. This initial dataset was filtered to return only the most recent water level reading for each bore assigned to a particular hydrostratigraphic unit. Reduced water levels (RWL) – that is, water levels measured to a common datum (mAHD) – were obtained by subtracting the measured depth of water below ground level from the ground surface elevation at the bore. If a ground surface elevation was not available, the elevation from the DEM was used.

For the Walloon Coal Measures, reservoir pressures collected during drill stem tests were converted to reduced water levels and included in the dataset.

The dataset was then split into individual units and contoured using Surfer© to produce potentiometric surfaces. Following review of the resulting maps, obvious data anomalies associated with particular intervals were removed and the map was re-contoured.

4.2.4 Hydrochemistry

To facilitate an assessment of the hydrochemistry of the various aquifer intervals, all available groundwater geochemical data within the study area and its surrounds was sourced and collated into an integrated database. Following an evaluation of data integrity (using various screening techniques), each groundwater sample result was classified according to the inferred hydrostratigraphic unit from which the sample was derived.

For each hydrostratigraphic unit, the median and 20th and 80th percentile of the concentrations of salinity and selected analytes were calculated for the purposes of characterising the groundwater quality and its variability, both spatially and across different units. Additionally, groundwater salinities and dominant hydrochemical facies in each hydrostratigraphic unit were regionally mapped. This was accomplished using Piper diagrams to evaluate regional scale salinity and hydrochemical facies trends and potential relationships including:

- Recharge processes
- Groundwater-rock interaction along flow paths
- Mixing of otherwise discrete water types
- Inter-aquifer flow

4.2.5 Groundwater use

Groundwater usage data was obtained from DERM's WERD, which included approved licenses as of 18 June 2009. Each license was specific to a geological formation or management unit under the Water Resource (Condamine and Balonne) Plan 2004 or Water Resource (Great Artesian Basin) Plan 2006, respectively. In utilising the data, the license was allocated to the hydrostratigraphic unit that corresponded to the formation or unit as shown in Table 4.2, unless a specific geological formation was identified, in which case the bore was allocated to the hydrostratigraphic unit corresponding to that geological formation (see Table 5.1). Most of the licenses had more than one associated extraction bore. In such cases, the first bore in the list was used and it was assumed that the entire allocation applied to that bore. Bore location details provided in the WERD dataset were used.

Stock and domestic bore data for the Great Artesian Basin aquifers was obtained from background studies used for the development of the water resource plans (DERM, 2004). The formation which these bores accessed was identified in the dataset, hence the bore was assigned directly to the corresponding hydrostratigraphic unit (Table 5.1). The GWBD was used to identify potential locations of bores and estimate associated groundwater use for stock and domestic purposes from the

Cainozoic Units. A search of the entire model domain was undertaken to identify active and equipped waterbores that access the geological units that comprise the Cainozoic Units. From this list, those bores identified in the WERD search were excluded. Water usage was then estimated based on pump type by assigning a usage of 1ML/a to low volume pumps, such as windmills, and 5ML/a to high volume pumps, such as turbine or helical screw pumps (based on DERM, 2004 methodology). A sensitivity analysis was completed to assess the variation in water use estimates. It was found that by varying the usage assigned to a pump type the range in the total estimate was approximately 8 to 12 ML/a. The usage values were assigned such that the total stock and domestic usage from the Cainozoic Units was approximately 10.7 ML/a.

Table 4.2 Water resource plan operation units and associated hydrostratigraphic units

Management unit	Aquifers	Assigned hydrostratigraphic unit
Condamine River Alluvium		Cainozoic Units
Condamine Tributary Alluvium		
Main Range Volcanics		
Surat 2	Wyandra Sandstone Member	BMO Grouping
	Bungil Formation	
	Minmi Member	
	Nullawart Sandstone Member	
	Kingill Member	
Surat 3	Mooga Sandstone	
Surat East 1	Kumbarilla Beds	Gubberamunda Sandstone
Surat 4	Orallo Formation	
	Gubberamunda Sandstone	
Surat 5	Westbourne Formation	Springbok Sandstone
	Springbok Sandstone	
	Birkhead Formation	
	Walloon Coal Measures	
	Eurombah Formation	
	Injune Creek Group	
Surat East 2	Walloon Coal Measures	Walloon Coal Measures
Eastern Downs 1	Walloon Coal Measures	
Surat 6	Hutton Sandstone	Hutton Sandstone
	Evergreen Formation	
	Boxvale Sandstone Member	

Management unit	Aquifers	Assigned hydrostratigraphic unit
Surat East 3	Hutton Sandstone Evergreen Formation	
Eastern Downs 2	Marburg Sandstone	
Eastern Downs 3	Helidon Sandstone	
Surat East 4	Precipice Sandstone	Precipice Sandstone

4.3 Baseline assessment

WorleyParsons completed an initial fieldwork program to support the Australia Pacific LNG application. This work was conducted from 10 June 2009 to 22 June 2009. Reconnaissance activities were focussed in the Talinga-Orana development area; however, assessment of the entire field extending from Dalby to Roma was completed. The scope of work included the following (where possible and appropriate):

- Locating nominated wellbores and measuring their co-ordinates
- Measurement of standing water levels (if possible)
- Completing down-hole surveys (video camera and natural gamma) to confirm or determine bore construction details, well integrity and possible lithology
- Collecting water samples for either measurement of sensitive field parameters only, or field parameters and laboratory analysis
- Instrumentation of appropriate bores with permanent, automated water level monitoring devices.

A summary report for the fieldwork is provided as Appendix B. One round of monitoring has been completed since initiation of this EIS. Many of the wells (owned by DERM) possess long-term water level monitoring records and several sets of water quality sampling results. The plan is to use this information to develop a better understanding of the range of natural variability in water levels and water quality. Results of the ongoing monitoring will also be used to enhance the understanding of the regional groundwater conditions. Follow-up monitoring is planned for sometime during 2010.

4.4 Numerical groundwater modelling

A numerical finite element groundwater flow model (employing the FEFLOW modelling platform) was constructed and calibrated for the purposes of projecting changes to groundwater levels in various intervals as a consequence of groundwater pumping in support of CSG production. Initial simulations have been conducted throughout the period of CSG development and a recovery period post-operation for:

- The 'project case', representing the Australia Pacific LNG project only
- The 'cumulative case', representing all known CSG activities and water takings in the region.

For clarification, the intent of the 'cumulative case' approach, as required in the Terms of Reference, has been to:

- Provide a more reasonable assessment of potential effects from CSG development

- Assist in the development of a robust regional monitoring system by identifying key areas to establish monitoring infrastructure
- Provide the necessary data from the monitoring infrastructure to verify model results and/or better constrain model results
- Provide the necessary information to assess the need for management options in response to modelled projection and monitoring data.

It is noted that with reference to the 'cumulative case' model simulation, a very conservative approach to modelling groundwater level depressurisation associated with all operators was adopted on the basis of publically available information. A key assumption adopted was that the target groundwater level depressurisation occurred over a 15-year timeframe, with an overall total depressurisation duration of 25 years. A second key assumption adopted was that timing of CSG development coincided with that of Australia Pacific LNG. This assumption concerning development sequencing was necessary given the lack of publically available information concerning the development sequencing of other CSG operators, and is thus very conservative in that a relatively high level of groundwater drawdown interaction and amplification by different operators is simulated.

It is emphasised that these conservative assumptions were made due to the limited availability of information concerning the development schedules and operational conditions for other CSG operators in the region. If more definitive information becomes publically available, these inputs to the 'cumulative case' model can be accommodated appropriately.

A second point of clarification is that the projections for the 'project case' will generally represent an over-estimate of Australia Pacific LNG's contribution to the regional groundwater level drawdown in all aquifers. Specifically, the 'project case' model assumes that Australia Pacific LNG alone will produce groundwater at a rate required to achieve CSG depressurisation. This associated water production rate will in fact be an over-estimate in the 'project case' as it does not allow for the associated water production and accompanying regional groundwater level drawdown effects that will be caused by other CSG operators, in neighbouring fields, as they commence production.

4.5 Impact assessment and risk evaluation

On the basis of the conceptual hydrogeological model developed, and the initial numerical modelling conducted thus far, potential effects to the groundwater system were assessed with regards to the range of activities proposed for the project. For clarification, the activities associated with Australia Pacific LNG's operation that may have the potential to effect local and regional scale groundwater system have been evaluated according to the following categories:

- CSG and associated water production
- Associated CSG water management practices
- Construction and operation of CSG infrastructure

Risks associated with the outcomes of the impact assessment have also been evaluated from a hydrogeological perspective, according to the risk evaluation framework described in Volume 1, Chapter 4 Risk Evaluation Framework. The assignment of risk provided a platform from which groundwater management and mitigation measures were identified.

4.6 Monitoring and mitigation strategies

The monitoring and mitigation strategies for the Australia Pacific LNG Project have been based on the principles of adaptive management. Adaptive management is a structured, iterative process of optimal decision-making in the face of uncertainty, with a focus on reducing uncertainty over time via system monitoring and knowledge enhancement. The approach is based on the concept of the precautionary principle. In this way, decision-making can simultaneously maximise one or more resource objectives and information gathered can be used to improve future management actions (Holling 1978). Therefore, by applying the adaptive management process, as new groundwater quality and quantity knowledge is generated in the region, the conceptual hydrogeological model and associated numerical groundwater flow model can be updated at appropriate times. This will allow CSG operations and associated water management decisions to be adapted accordingly.

The indicative monitoring program provided in support of this application has been based on results obtained from the numerical groundwater flow model coupled with results obtained from the risk mapping exercise, development sequencing, and the initial baseline field program conducted in June 2009. All of these components have been utilised in the following manner:

- **Numerical model and risk mapping** – identification of locations in each aquifer with a higher potential for effects from CSG development
- **Development sequencing** – accommodation of timing of development to inform monitoring system design (including the assumed development sequencing of other operators)
- **Baseline sampling** – identification of pre-development water level and water quality conditions, thus informing future monitoring requirements (for example, implementation of a more extensive array of wells or analytical suite than would usually be analysed).

Locations, sequencing and parameters to monitor for have been recommended; however, changes are anticipated through the adaptive management process as more information becomes available.

5. The study area: regional setting

5.1 Physiography and drainage

The study area for the gas fields component of the Australia Pacific LNG Project and the cumulative effects assessment is located within the Surat Basin, Queensland.

The eastern extent of the study area is situated approximately 150km west of Brisbane, just to the east of Dalby, and extends more than 300km to the west, near Mitchell. The southern extent is approximated by the border between Queensland and New South Wales, and the northern boundary is approximately 100km north of Taroom, and is defined by the outcrop extent of the Jurassic-aged formations. The north-south dimension is approximately 400km at its greatest width. The town of Miles is roughly in the centre of the study area, and the main road access to the study area is the Warrego Highway.

The Great Dividing Range forms a swathe of higher ground around the eastern and northern margins of the study area, reaching elevations up to 900mAHD. The ground surface slopes gently to the south-west to elevations less than 200mAHD.

The Condamine River and associated tributaries have created an extensive, flat floodplain particularly around the town of Dalby where significant agricultural development occurs. The interfluves of the floodplain tend to be relatively flat and the associated soil is of reasonable agricultural quality. The northern margin is characterised by a series of cuestas where the more resistant sandstone formations outcrop and the more erodible formations, like shales and mudstone, form valleys (Exon 1976)

The regional drainage system is dominated by the Condamine River, which originates in the higher elevations along the eastern margin of the study area. This river first flows north-west to the town of Chinchilla and then turns towards the west and south-west. It is then joined by the Balonne River to the south of the town of Roma and drainage is almost entirely to the south-west, where it eventually joins the Darling River system. Conversely, rivers originating in the northern part of the study area (on the other side of the Great Dividing Range) flow northward and eastward, eventually discharging to the ocean.

5.2 Climate

5.2.1 Climatic conditions

The climate in the study area is generally sub-tropical with warm, wet summer months and cooler, drier winter months. The average annual temperature is approximately 20°C and the normal range of temperatures through the year spans from 0°C to 34°C. Monthly average maximum and minimum temperatures (Figure 5.1 and Figure 5.2) indicate that the town of Dalby, located in the south-eastern portion of the study area, experiences slightly lower temperatures than the rest of the study area.

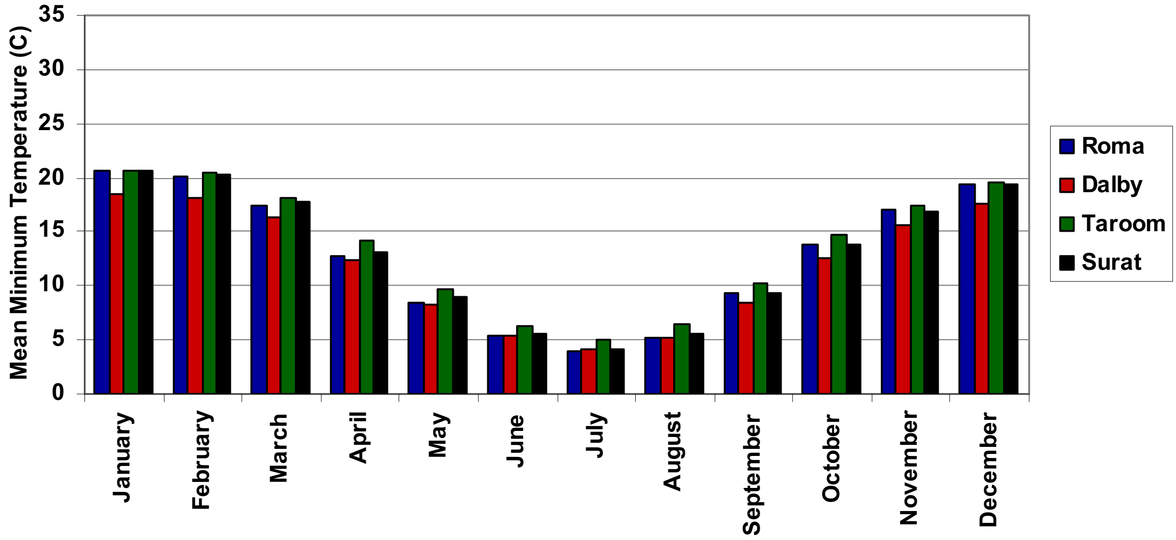


Figure 5.1 Average minimum monthly temperature

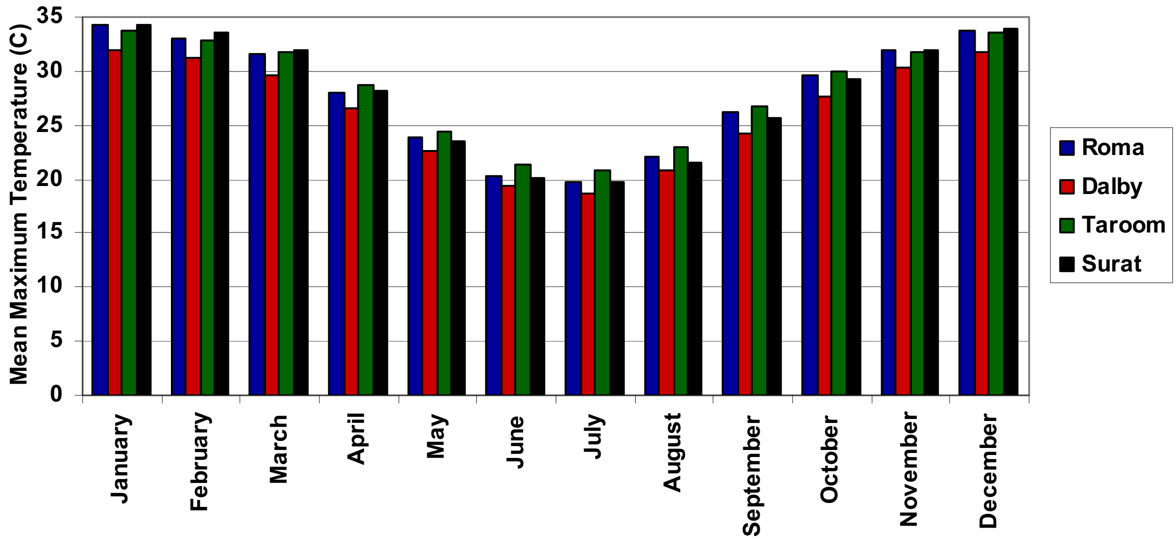


Figure 5.2 Average maximum monthly temperature

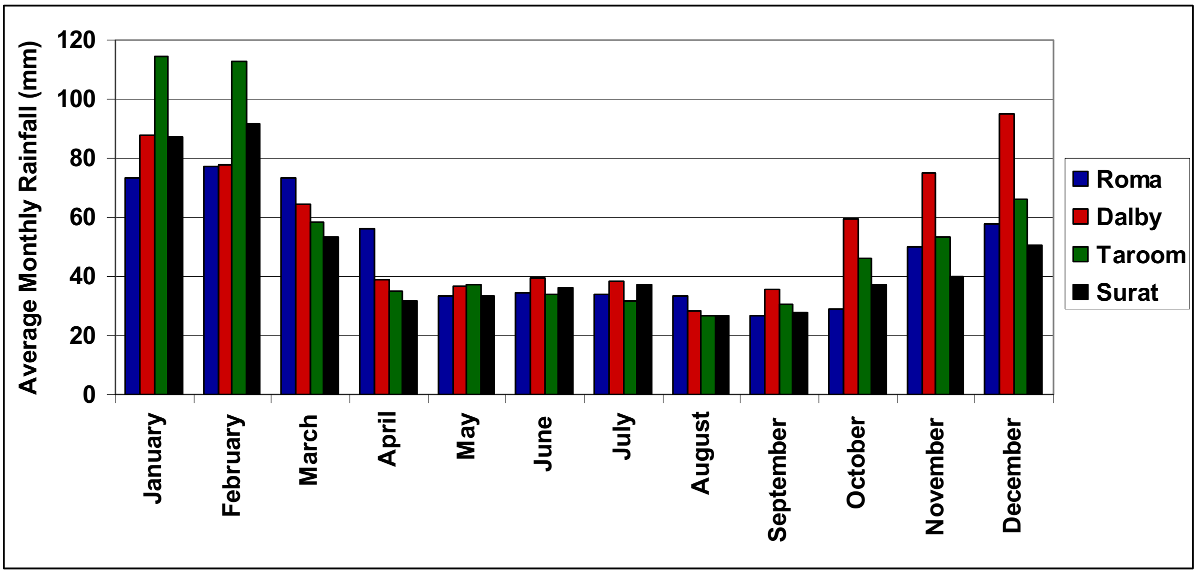


Figure 5.3 Average monthly rainfall in the study area

Figure 5.3 presents the average monthly rainfall for several towns located within the study area. It is evident that average annual rainfall increases from west (583mm/year in Roma) to east (676mm/year in Dalby) and south (575mm/year in Surat) to north (671 mm/year in Taroom). Most rainfall occurs between the months of October and March.

Rainfall mass residual curves have been prepared for each station based on the average monthly accumulation for the entire period of record (from the 1890s to the present). These have been calculated from daily data and presented in graphical form from 1960 to present (Figure 5.4). Where the slope of the curve is rising, this indicates a period of excess rainfall compared to the long-term average (that is, a wetter than average period). Conversely, where the slope of the curve is falling, this indicates a period of deficit rainfall compared to the long-term average (that is, drought conditions).

The rainfall mass residual curves indicate that since 1960, there have been periods of above-average and below-average rainfall:

- Above average rainfall was experienced at some stations in the early 1960s, between 1971 and 1984, and between approximately 1996 and 2000.
- Below average rainfall was experienced at some stations between 1963 and 1970; 1984 and 1996; and 2000 to present.

Compared to average annual rainfall, the average annual evaporation is between 1,800mm/year - 2,400mm/year. Hence, there is a significant rainfall deficit in the study area.

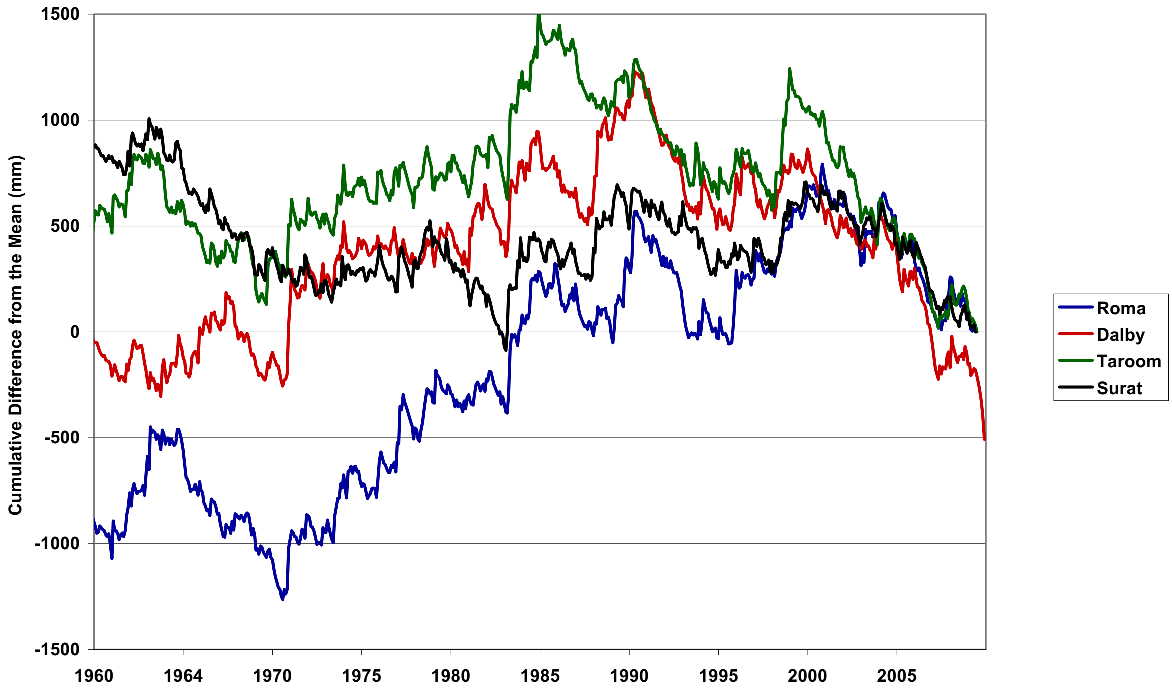


Figure 5.4 Rainfall residual mass curves

5.2.2 Climate variability

The Surat Basin is subject to varying climatic conditions which manifest themselves on a decadal time-scale. One such phenomenon that is known to affect conditions in Australia is the Interdecadal Pacific Oscillation, or IPO. The IPO is a multidecadal sea surface temperature pattern, similar to the El Niño Southern Oscillation (ENSO), but occurring over a longer period, and affecting rainfall patterns in Eastern Australia (Power et al.1999, Folland et al. 1999). The documented return period for positive and negative phases of the IPO (20 to 30 years) is much longer than the return period for ENSO phases (3 to 7 years).

It has been found that the IPO modulates the influence of the ENSO phenomenon in Australia, such that when the IPO is in a positive phase, there is a significant decrease in frequency of La Niña events and an increase in frequency of El Niño events. Thus, positive phases of the IPO are expected to result in extended periods of below average rainfall, with the inverse effect occurring during negative phases of the IPO.

Currently, the IPO is in a negative phase and has been trending in this direction since the apex of the last positive phase in the mid-1980s. As such, annual rainfall has been trending toward more normal conditions for the area. The expectation is that with an increasing development of an IPO-negative phase, above average rainfall conditions may begin to prevail in the region.

5.2.3 Potential implications of climate change

The world's climate is in a constant state of change. For Australia, average temperatures have been increasing like many other parts of the world, while rainfall patterns have been increasing in some areas and decreasing in others (Figure 5.5).

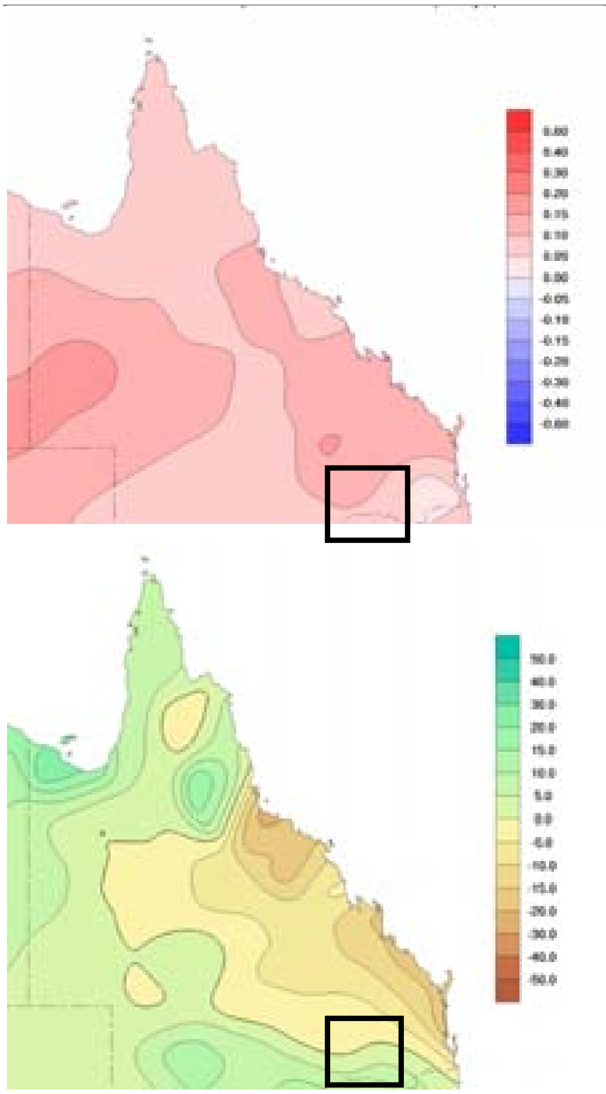


Figure 5.5 Trends in mean temperature (top) and precipitation (bottom) from 1910 to 2008 (BOM 2009)

Predictions of climate change (in particular temperature and precipitation) were accessed from CSIRO's technical document, *Climate Change in Australia (2007)* and the related website. The results are based on the Intergovernmental Panel on Climate Change fourth assessment report (IPCC, 2007). Projections shown are relative to the period 1980 to 1999 (referred to as the 1990 baseline for convenience), and provide an estimate of the average climate projected around the years 2030, 2050 and 2070, taking into account consistency among climate models. Individual years will show variation from this average. The 50th percentile (the mid-point of the spread of model results) provides a best estimate result and has been provided here for context. Emissions scenarios are from the IPCC Special Report on Emission Scenarios. The low emissions scenario is B1, medium emissions is A1B and high emission, fossil fuel intensive is A1FI (see Figure 5.6).

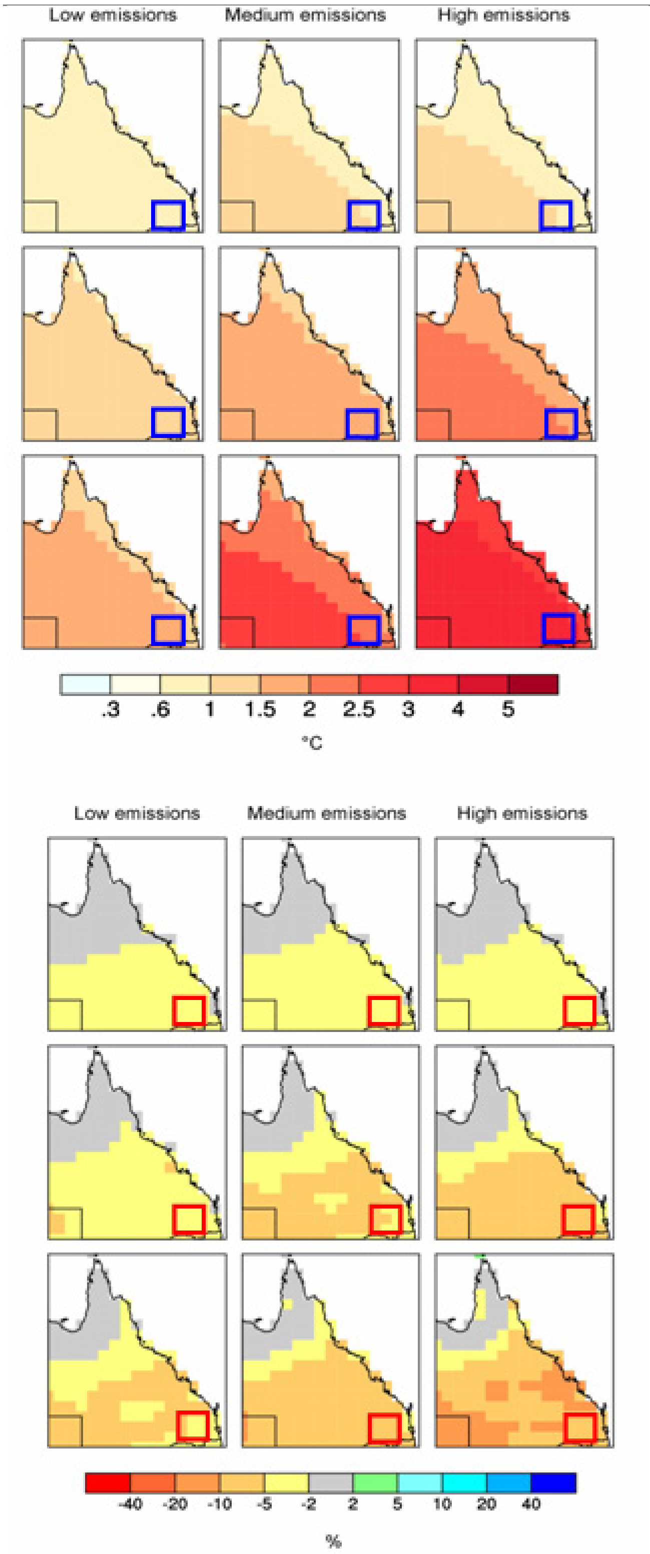


Figure 5.6 Predicted temperature (top) and rainfall (bottom) change at 2030, 2050 and 2070 (CSIRO 2007)

The working climate change scenario is based on results provided by Climate Change Scenarios for Initial Assessment of Risk in Accordance with Risk Management Guidance and amended with reference to *Climate Change in Australia (CSIRO 2007)*. Results generated for the St. George station located just outside the study area, west of Dalby and south-west of Surat, have been referenced in

this and other sections of the EIS. Based on these results, the following conditions are projected to occur between the present (2009) and 2070:

- A change in average annual temperature of roughly +1.3 to +4.4°C
- Variation in average annual precipitation from -3.5% to +17%
- A change in average annual potential evaporation of +5.6% to +16.

For the groundwater environment, recharge is a sensitive input parameter. Estimates of climate change effects on recharge to the Great Artesian Basin have been made in previous studies, such as BRS & NRM (2003), which are discussed further in Section 5.4.7. A decline in annual precipitation during the drier climate modes will directly result in a reduction in recharge to the Great Artesian Basin aquifers, and in particular shallower zones. A reduction in precipitation, combined with warmer temperatures, will adversely affect associated water levels in both the unconfined watertable aquifers and deeper confined aquifers.

Based on a percentage of precipitation, the recharge estimates (provided in Section 5.4.7) represent less than 1% up to about 6% of annual precipitation.

5.3 Geology

The Surat Basin is an elongate basin containing up to 2500m of continentally-derived sediment deposited in a series of four fining-upward cycles during the Jurassic Period. This depositional sequence is followed by transgressive marine deposits formed during the Cretaceous Period (Henning, 2005). The deepest part of the Basin corresponds to the north-south oriented Taroom Trough which is over 9000m deep within the regional study area. The sediments of the Permo-Triassic Bowen Basin unconformably underlie the Surat Basin sediments in the Taroom Trough.

Figure 5.7 Extent and sub-basins of the Great Artesian Basin (from NRW 2006)

The majority of the Bowen Basin lies to the north of the Surat Basin (Figure 5.7) and deposition of sediments within the Surat Basin extend beyond the Taroom Trough, even in the lowermost formations (Exon 1976). The Surat Basin is one of the three major sub-basins comprising the Great Artesian Basin, the others being the Eromanga Basin and the Carpenteria Basin. Sediments of the Surat Basin inter-finger with sediments of the Eromanga Basin across the Nebine Ridge, which forms the western boundary of the regional study area. The Nebine Ridge is bounded on the east side by the New England Fold Belt, but sediments in this area inter-finger with the Clarence-Moreton Basin across the Kumbarilla Ridge (near Dalby), and in the south by the Central West Folded Belt. The northern margin of the basin has been exposed and eroded (Exon 1976) due to orogenic uplift during the Tertiary Period.

5.3.1 Major formations

The main geological formations making up the sequence of sedimentary formations contained within the Surat Basin are described below. A stratigraphic column is presented in Figure 5.8 (showing major aquifer intervals in blue and confining units in grey) and conceptual regional cross-sections are illustrated in Appendix A, Map 3 to Appendix A, Map 5. For the purposes of this EIS, the base of the stratigraphic section is designated by the base of the Precipice Sandstone.

The Precipice Sandstone consists of quartzitic sandstone throughout and is coarser-grained nearer its base (DME 1997). The outcrop of the Precipice Sandstone defines the northern boundary of the Surat

Basin where it forms a sinuous east-west band. This unit extends to the Auburn Complex in the north-east and terminates against the Texas High and the St. George/Bollon Slope in the south-east and south-west, respectively. It eventually transitions into the Helidon Sandstone in the Clarence-Morton Basin and continues into the Eromanga Basin across the Nebine Ridge. It is thickest in the Mimosa Syncline adjacent to the Chinchilla-Goondiwindi and Moonie Faults (Cadman et al., 1998). Deposition of the Precipice Sandstone marks the start of a widespread period of predominantly continental-fluvial deposition. This sandstone unit rests un-conformably on rocks ranging from Devonian to Triassic age (Exon 1976), and although greater in extent than the Taroom Trough is not ubiquitous across the Surat Basin (DME 1997). Underlying the Precipice Sandstone is the Wandoan Formation, a fluvial deposit of sandstone, siltstone, shale and conglomerate, followed by the Moolayember Formation.

The Evergreen Formation resides above the Precipice Sandstone and forms a conformable confining layer. In part, it lies unconformably over the Bowen Basin sequence (DME 1997). The formation is mainly comprised of siltstone; however, there is a dominance of shale and sandstone in some horizons, such as in the western part of the Surat Basin (that is, the Boxvale Sandstone Member). The Westgrove Ironstone Member, directly overlying the Boxvale Sandstone or its equivalent, is a persistent marker horizon extending across most of the Surat Basin. With the exception of the two members, the Evergreen Formation is reasonably consistent in its fine-grained lithology and low permeability. The depositional environment of this unit was fluvial and marginal to shallow marine (that is, continental shelf). The maximum thickness of the formation is on the order of 300m (DME 1997). The boundary between the Evergreen Formation and the underlying Precipice Sandstone can be difficult to determine as the upper part of the Precipice Sandstone tends to be fine-grained.

The Hutton Sandstone resides above the Evergreen Formation. This sandstone unit outcrops to the north of Injune, through the Mimosa Syncline, and on the eastern margin of the basin where it grades into the Marburg Sandstone of the Clarence-Morton Basin across the Kumbarilla Ridge. The Hutton Sandstone was deposited by meandering streams, and is predominantly comprised of coarser-grained sediments with lesser amounts of siltstone and mudstone. It is generally between 120m and 180m thick and is more variable (60m to 240m) along the eastern margin of the Surat Basin. This unit conformably overlies the Evergreen Formation (Exon 1976) and is the most extensive Jurassic-aged unit in the Great Artesian Basin (DME 1997)

The Eurombah Formation lies conformably in contact with the Hutton Sandstone and the overlying Walloon Coal Measures. This confining unit is thickest, at approximately 100m, in the north part of the study area near Injune, and thins to the west, south and east until it diminishes completely (Exon 1976; Scott et al. 2004). DME (1997) included the Eurombah Formation in the Walloon Coal Measures based in its lithological descriptions as it is not possible to always differentiate in geophysical logs. Scott et al. (2004 and 2007) include the Eurombah Formation in the Durabilla Formation, which includes mudstone of the Taroom Coal Measures.

The Walloon Coal Measures are a thick sequence of sediments deposited in a low energy environment and extend across the Clarence-Moreton and Surat basins, and almost to the Nebine Ridge. The coal measures consist of light grey mudstone, siltstone, fine-grained sandstone and relatively thin seams of coal reaching up to a maximum thickness of approximately 500m (DME 1997) and at depths in excess of 1600m. The deposits dip to the south and west and outcrop, albeit poorly, across the northern and south-east edges of the Surat Basin, but outcrop extensively in the Clarence-Moreton Basin (Exon 1976). Coal deposits are concentrated in the north-eastern margin of the basin.

The Walloon Coal Measures can be readily subdivided into three sub-units (from bottom up):

- Taroom Coal Measures

- Tangalooma Sandstone
- Juandah Coal Measures.

Scott et al. (2004) suggest a fourth sub-unit at the base, the Durabilla Formation, which includes the Eurombah Formation.

Within the Walloon Coal Measures are accumulations of comparatively thick, laminated sandstone in bedded sequence. Six coal intervals have been identified in the Juandah Coal Measures (from the base up: Argyle, Iona, Wambo, Nangram, Macalister and Kogan) and three coal seams have been identified in the Taroom Coal Measures (from the base up: Condamine, Bulwer and Auburn). The Juandah Coal Measures are informally divided into and upper and lower units, with the divide occurring between the Macalister and Nangram seams. The Macalister and Bulwer seams are thick and relatively clean; however, the remaining coal seams comprise numerous thin stringers separated by thin to thick bands of mudstone, siltstone or sandstone (Scott et al. 2004). In parts of the north-eastern portion of the Surat Basin, the Kogan seam was completely eroded prior to the deposition of the Springbok Sandstone, with the sandstone lying immediately above and in connection with the Macalister Seam (Scott et al. 2007). The Birkhead Formation, recognisable in the western part of the Surat Basin, is laterally continuous with this coal-bearing interval (Exon 1976). The Walloon Coal Measures unconformably underlie the Springbok Sandstone (Scott et al. 2004).

The Springbok Sandstone outcrops on the northern and eastern sides of the Surat Basin; however, its occurrence in outcrop is poor. The unit predominantly comprises sandstone with minor interbedded siltstone and mudstone. Calcite cement is common in some intervals. This unit was deposited mainly by streams, and the fining-upward sequence suggests a decrease in stream energy over time. The Springbok Sandstone is thickest in the eastern part of the Surat Basin, reaching up to 200m. The equivalent of this unit is the Adori Sandstone in the Eromanga Basin. It also inter-fingers with the Pilliga Sandstone, which is predominantly in New South Wales (Exon 1976).

Confining the Springbok Sandstone from above is the Westbourne Formation. This formation comprises alternating sequences of mudstone and lithic sandstone with minor siltstone and coal in the upper portions, and thinly-bedded siltstone and low permeability sandstone in the lower portions. The Westbourne Formation reaches a thickness of over 250m in the eastern portion of the study area, and was deposited in a low energy fluvial and marginal-marine environment. These sediments outcrop at the surface in the northern part of the Surat Basin (Exon 1976).

The grouping of the Eurombah Formation, Walloon Coal Measures, Springbok Sandstone and Westbourne Formation is often referred to as the Injune Creek Group. In total, this grouping of formations can reach up to 1000m in aggregate thickness.

Above the Westbourne Formation is the Gubberamunda Sandstone, which consists of fine- to coarse-grained sandstone with minor interbedded siltstone and mudstone. Although the finer-grained sediments are minor in occurrence, they can form up to half of the total unit thickness. This sandstone unit was deposited by braided and meandering streams, and is up to 200m thick in the centre of the basin but is generally around 100m thick or less on the basin margins. The unit outcrops in the north of the basin from the western margin of the study area to the area around Roma (Grey 1972).

Next in the stratigraphic sequence is the Orallo Formation, which comprises thinly-bedded siltstone and mudstone, and thickly-bedded calcareous sandstone deposits laid down in a fluvial stream setting. Fossil wood and minor coal accumulations are common. This formation has been mapped in the northern part of the basin, but its low resistance to weathering makes identification of outcrop difficult. This unit rests in conformable contact with the underlying Gubberamunda Sandstone.

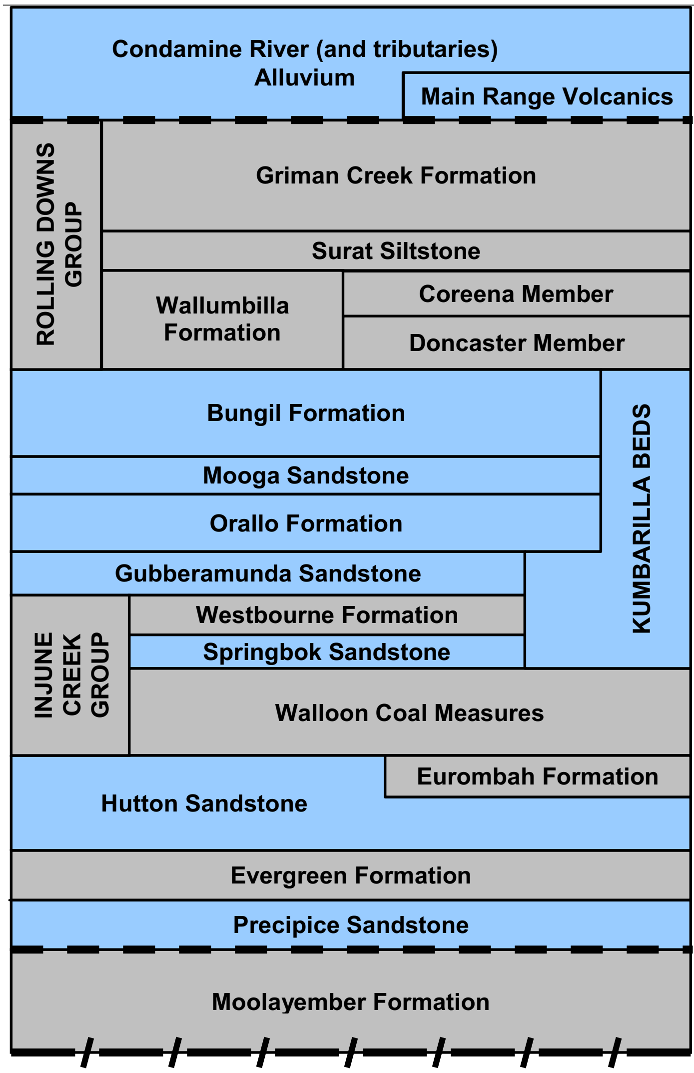


Figure 5.8 Stratigraphic column of the Surat Basin (after Radke et al. 2000)

The Hooray Sandstone is only present in the far western part of the Surat Basin (west of Mitchell), and outcrops in the north-western part of the study area. In the Surat Basin it is approximately 120m thick and mainly consists of sandstone deposited in an alluvial environment. It is generally the lateral equivalent of the Mooga Sandstone, Orallo Formation and Gubberamunda Sandstone in the Surat Basin. The upper part is also the equivalent of the Cadna-owie Formation (Exon 1976).

The Mooga Sandstone conformably overlies the Orallo Formation and outcrops in the northern part of the basin. It is rarely over 100m thick near the basin margins, but reaches thicknesses up to 200m in the central part of the basin. Similar to the Hooray Sandstone, it was deposited in a fluvial environment and predominantly comprises sandstone near the margins (braided streams), but siltstone and mudstone become more common in the central part of the basin (meandering streams).

The Bungil Formation resides above the Mooga Sandstone and mainly consists of fine-grained sandstone, siltstone and mudstone in about equal proportions. This unit was deposited in a near-shore environment. The formation has been mapped where outcrops can be positively identified in the northern and north-eastern parts of the Surat Basin; however, in the south-east it has been included in the Kumbarilla Beds. The Bungil Formation is consistent with the Cadna-owie Formation in the Eromanga Basin (Exon 1976).

The grouping of formations called the Kumbarilla Beds represents sediments of the Springbok Sandstone, Westbourne Formation, Gubberamunda Sandstone, Orallo Formation, Mooga Sandstone and Bungil Formation at locations where they outcrop. Although these formations can be differentiated in the subsurface, extensive weathering in outcrop areas on the eastern margin of the basin makes mapping of the individual units impractical (Exon 1976, Habermehl 1980).

The Wallumbilla Formation, conformably underlying the Surat Siltstone, is divided into two members:

- Doncaster Member
- Uppermost Coreena Member.

The Doncaster Member predominantly consists of mudstone (blue-grey or glauconitic) with subordinate siltstone and sandstone beds, and is characterised by inter-laminated fine- and coarse-grained mudstone in the Surat Basin. The Wallumbilla Formation outcrops in a discontinuous arc from the town of Morven in the far west of the study area, to the town of Miles in the middle of the study area, and extends into the Eromanga Basin. This formation has been found to be regionally extensive (Exon 1976).

The Coreena Member comprises interbedded mudstone and siltstone, grading into sandstone, deposited in an environment ranging from shallow marine to lagoonal / swamp. The Coreena Member is generally about 100m thick, and is thickest in the east where it has been found to reach in excess of 150m.

Conformably overlying the Wallumbilla Formation is the Surat Siltstone, which predominantly consists of interbedded siltstones and mudstones (Gray 1972). This formation is generally finer-grained than the underlying Coreena Member of the Wallumbilla Formation and forms scattered outcrops in the west of the basin (Exon 1976). An average thickness of approximately 110m is documented (Gray 1972).

Above the Surat Siltstone unit is the Griman Creek Formation. This unit was deposited during a marine regression sequence and primarily consists of micaceous sandstone and siltstone. It is only found in the Surat Basin and is predominantly identified in the area covered by the Surat 1:250,000 Geological Map Sheet (Thomas and Reiser 1971). The unit has been found to reach thicknesses of up to 350m (Gray 1972).

The Wallumbilla Formation, Surat Siltstone and Griman Creek Formation are often grouped together due to their finer-grained character, and are referred to as the Rolling Downs Group (Habermehl 1980).

The final sequence of sediments comprises the units of Cainozoic age. About one-quarter of the study area is covered by fluvial deposits, most of which have been deposited by the Condamine-Balonne River system. They are predominantly alluvial in origin, although they do include some accumulations of lacustrine (lake) deposits. Lithologies include variable amounts of consolidated sandstone, conglomerate, siltstone and mudstone, as well as unconsolidated deposits of sand, silt and clay. The sediments associated with the Condamine River to the east of Roma are generally in the range of 20m to 60m thick, but may reach up to 100m where the rivers have eroded deeper valleys in the relatively un-resistant Walloon Coal Measures sediments. The thickest accumulations of Cainozoic-aged sediments are found in the south-west portion of the study area, associated with the Balonne River system (Exon 1976).

Accumulations of basalt exist along the eastern margin and northern portions of the Surat Basin. The accumulations of basalt in the east form the western extent of the Main Range Volcanics, which flowed down from high ground that forms the eastern margin of the study area. Most of the volcanic

flows have been eroded away, leaving basalt capped mesas that may or may not be covered by more recent alluvium (Exon 1976).

5.3.2 Geological structures

The Surat Basin comprises several large-scale synclinal structures overlying the Bowen Basin and associated bedrock geology (Henning, 2005). The most easily recognised of these is the Mimosa Syncline, which comprises the sedimentary sequence of the Bowen and Surat Basins overlying the Taroom Trough.

The Taroom Trough is a half-graben structure, bounded on its eastern margin by a series of basement thrust faults known as the Burunga-Leichardt and Goondiwindi fault zones. The downthrown blocks are located in the western part of the regional study area, and the maximum displacement on the faults is approximately 2000m in the north, but is less than 1000m in the south.

A relatively small fault, located at the southern extent of the Burunga-Leichardt Fault is the Undulla Fault, which is down-thrown to the east, creating a south to south-westerly plunging basement high (or horst block) known as the Undulla Nose. Between the fault zones and the Kumbarilla Ridge in the east of the study area is the Chinchilla-Goondiwindi Slope, and between the western extent of the trough and the Nebine Ridge is the St. George/Bollon slope. Both slopes dip toward the Taroom Trough at less than 1° (Exon 1976).

The structural features of the Bowen Basin are generally reflected, but subdued, in the Surat Basin. By the beginning of deposition of the Precipice Sandstone (the lowermost formation of the Surat Basin sequence), the dips are only about half as steep as those in the deeper sediments and the basin is much broader and shallower than the Taroom Trough. The deepest part of the Taroom Trough (hence the Surat Basin) extends southward near Meandarra where it is approximately 2100m deep. Displacement on major faults within the trough is generally less than 200m at the start of deposition of the Surat Basin sequence, and less than 100m by the end of deposition of the Rolling Downs Group (Exon 1976). The total thickness of the Walloon Coal Measures and coal beds thin across the Undulla Nose, suggesting that this feature was still a structural high at the time of deposition (Scott et al. 2004).

5.4 Hydrogeology

5.4.1 Major aquifers and aquitards

Hydrogeologically speaking, the Surat Basin may be described as a multi-layered confined aquifer system, and is one of the major sub-basins of the Great Artesian Basin. The sedimentary sequence predominantly comprises fluvially-deposited sandstone units interspersed with marginal-marine mudstone and siltstone units. The sandstone units generally form aquifers, with intake beds to the Great Artesian Basin occurring on the northern margin of the basin where they are exposed. The units of marine origin generally form the intervening confining beds, or aquitard units. Most of the aquifer units either inter-finger with units in the Eromanga Basin (for example, the Gubberamunda, Orallo and Mooga Sandstones), or extend across the Nebine Ridge (for example, Rolling Downs Group and Hutton Sandstone).

Table 5.1 Hydrostratigraphic units defined for the Australia Pacific LNG EIS

Age	Hydrostratigraphic unit	Geological units	Aquifer / confining unit
Cainozoic	Cainozoic Units	Alluvium	Aquifer (watertable)

Age	Hydrostratigraphic unit	Geological units	Aquifer / confining unit
		Colluvium	
		Chinchilla Sands	
		Main Range Volcanics	
Cretaceous	Rolling Downs Group	Griman Creek Formation	Confining unit
		Surat Siltstone	
		Wallumbilla Formation	
	BMO Grouping	Bungil Formation	Aquifer
		Mooga Sandstone	
Jurassic		Orallo Formation	
	Gubberamunda Sandstone	Gubberamunda Sandstone	Aquifer
		Kumbarilla Beds	
		Hooray Sandstone	
		Southlands Formation	
	Westbourne Formation	Westbourne Formation	Confining unit
	Springbok Sandstone	Springbok Sandstone	Aquifer
		Pilliga Sandstone	
	Walloon Coal Measures	Upper Walloons Formation*	Confining unit
		Macalister Coal Seams	Aquifer (coal seams)/ confining unit (siltstones, mudstones)
		Juandah Sandstone	Aquifer
		Lower Juandah Coal Measures	Aquifer (coal seams)/ confining unit (siltstones, mudstones)
		Tangalooma Sandstone	Aquifer
		Taroom Coal Measures	Aquifer (coal seams)/ confining unit (siltstones, mudstones)
	Eurombah Formation	Eurombah Formation	Confining unit
	Hutton Sandstone	Hutton Sandstone	Aquifer
		Marburg Sandstone	
	Evergreen Formation	Upper Evergreen Shale	Confining unit
		Lower Evergreen Shale	

Age	Hydrostratigraphic unit	Geological units	Aquifer / confining unit
		Basal Evergreen Sandstone	
		Boxvale Sandstone	
	Precipice Sandstone	Precipice Sandstone	Aquifer
Triassic	Pre-precipice formations (model base)	Bowen Basin Sequence and Basement	Confining unit

* The upper Walloons Formation is defined as that part of the Walloon Coal Measure between its upper surface and the top of the Macalister coal seam.

Although a large number of lithostratigraphic units have been identified in the Surat Basin sequence, many adjacent units were deposited in similar environments and therefore possess similar lithologies. They are also broadly uniform in their geometry, internal structure and texture, and hence are considered to be similar hydrogeologically. For modelling purposes, the lithostratigraphic sequence has been simplified into a smaller number of hydrogeological units on the basis of broad consistencies. This method of grouping is consistent with other regional studies of the Great Artesian Basin (for example Habermehl 1980). It is recognised that locally, within individual lithostratigraphic units, this simple convention may not hold true.

The hydrostratigraphic units defined for this study, their constituent geologic units and their hydrogeological designation are summarised in Table 5.1. The siltstone and mudstone-dominated interval above the uppermost coal seam in the Walloon Coal Measures, but below the Springbok Sandstone, has been identified as the Upper Walloons Formation. Notably, the Kumbarilla Beds, which is the outcrop equivalent in the eastern part of the study area of the Bungil Formation, Mooga Sandstone, Orallo Formation, Gubberamunda Sandstone, Westbourne Formation and Springbok Sandstone, has been included in the Gubberamunda Sandstone hydrostratigraphic unit to provide a conservative approach during numerical modelling. Several units have been subdivided during development of the conceptual geological model to allow for intra-formational changes in hydraulic properties.

Outcrop areas of the hydrostratigraphic units are shown on Appendix A, Map 2, and cross-sections of the hydrostratigraphic units are provided as Appendix A, Map 3 to Appendix A, Map 5.

5.4.2 Water levels and groundwater flow

Level trends

Water level hydrographs were prepared for selected DERM monitoring wells to assess temporal changes, both seasonally and over the longer-term. Given that a large number of DERM wells have a long hydrographic record, those selected for analysis were firstly located in higher risk areas defined by the aquifer vulnerability and risk mapping, and secondly on the availability of water level data (length of record and regularity of measurements). A total of 45 hydrographs were prepared, which include bores completed in the Cainozoic Units, Bungil/Mooga/Orallo (BMO) aquifer grouping, Gubberamunda Sandstone and Walloon Coal Measures (Appendix A, Map 6). The cumulative difference from the mean rainfall curves derived from the closest meteorological station (Dalby or Taroom) has been used to provide a comparison between rainfall trends and water level trends.

A linear regression was applied to water level data post-2000 for each bore record to assess water level trends since the most recent extended period of below average rainfall, and within the timescale

of the commencement of CSG development in the area. The water level trends for each bore and statistics of the record length are provided in Table 5.2. A discussion for each major hydrostratigraphic formation is provided below, with selected bore hydrographs provided in Figure 5.9.

Cainozoic Units

The majority of the Cainozoic Units' monitoring bores are located to the south-west of Chinchilla in the Condamine River floodplain. Water level fluctuations have generally shown a strong correlation between the rainfall trend and the water level trend. For example, during times of below average rainfall, the water levels tend to decline. With the exception of two selected monitoring bores (42231311 and possibly 42231260), all others show declining water levels since the year 2000 with the area of greatest decline occurring west of Toowoomba.

The hydrograph for Bore 42231260 indicates that, since the mid 1990s, a strong seasonal trend has developed with declining levels occurring during the summer months and recovery during the winter months. The overall long-term trend in the hydrograph (since 1981) is a downward one.

The hydrograph for Bore 42231311 shows a number of periods during which rapid water level decline occurred, followed by a slow recovery (analogous to that of a pumping test recovery curve). This occurs over a number of months or years. The periods of decline correspond to relatively short periods when rainfall was much less than average (with the cumulative difference from the mean curve on a steeply downward trend). The GWBD indicates that the bore is screened in clay, which would result in a rapid drawdown and slow recovery when purged and/or sampled. The water level in the bore has been in a period of recovery since the summer of 2002.

Barnett and Muller (2008) indicate the development of a large cone of depression in the area between 1961 and 2001 associated with groundwater extraction from the Condamine River Alluvium south of Dalby. This is consistent with the declining water levels observed in both bore hydrographs.

Table 5.2 Water level monitoring statistics for selected DERM monitoring wells

RN	Start of record	End of record	Total number of measurements	Number of measurements post-2000	Trend post-2000 (mm/year)*
Cainozoic Units					
42230004	1970	2009	202	28	-0.4
42230057	1966	2008	176	30	-0.6
42230119	1967	2008	162	28	-0.3
42230155	1965	2008	186	16	-0.4
42230201	1981	2008	88	44	0.0
42230203	1966	2008	300	18	-0.4
42230205	1966	2008	150	36	-0.5
42230208	1966	2008	153	13	-0.2
42230209	1966	2009	142	39	-0.1
42230294	1968	2008	173	37	-0.3
42231051	1976	2008	109	47	0.0
42231052	1976	2008	143	43	-1.0
42231177	1979	2008	101	25	-0.5
42231194	1978	2006	295	31	-1.7
42231259	1981	2009	103	45	-0.3
42231260	1981	2008	99	47	0.9
42231307	1986	2008	152	43	-0.8
42231309	1986	2008	149	10	-1.0
42231311	1986	2008	87	10	0.9
42231317	1986	2008	80	9	-0.7
42231318	1986	2008	81	9	-0.3
42231360	1988	2008	83	3	-2.3
42231362	1988	2008	81	34	-2.4
42231369	1987	2008	105	35	-1.1
42231373	1987	2008	106	34	-1.1
42231383	1988	2007	115	22	-0.8
42231400	1990	2008	132	34	-0.5

42231414	1990	2008	103	13	-0.3
42231463	1992	2008	81	30	-1.3
BMO Grouping					
13030806	2003	2006	10	10	-0.6
Gubberamunda Sandstone					
13030808	2003	2006	10	43	-0.3
13030809	2003	2006	10	39	-0.2
Walloon Coal Measures					
13030812	2003	2006	9	42	0.0
13030813	2003	2006	9	41	-0.1
13030814	2003	2006	9	32	0.8
42230204	1966	2008	151	40	-0.2
42231062	1976	2008	137	31	-0.8
42231070	1976	2006	104	24	6.4
42231254	1980	2008	103	29	-0.5
42231256	1980	2008	94	43	-0.1
42231257	1980	2008	93	44	-0.3
42231258	1980	2007	70	16	-2.4
42231340	1989	2008	88	9	1.2
42231357	1988	2004	65	31	0.2
42231358	1989	2008	80	39	-1.9

* a negative (-) value indicates a declining water level

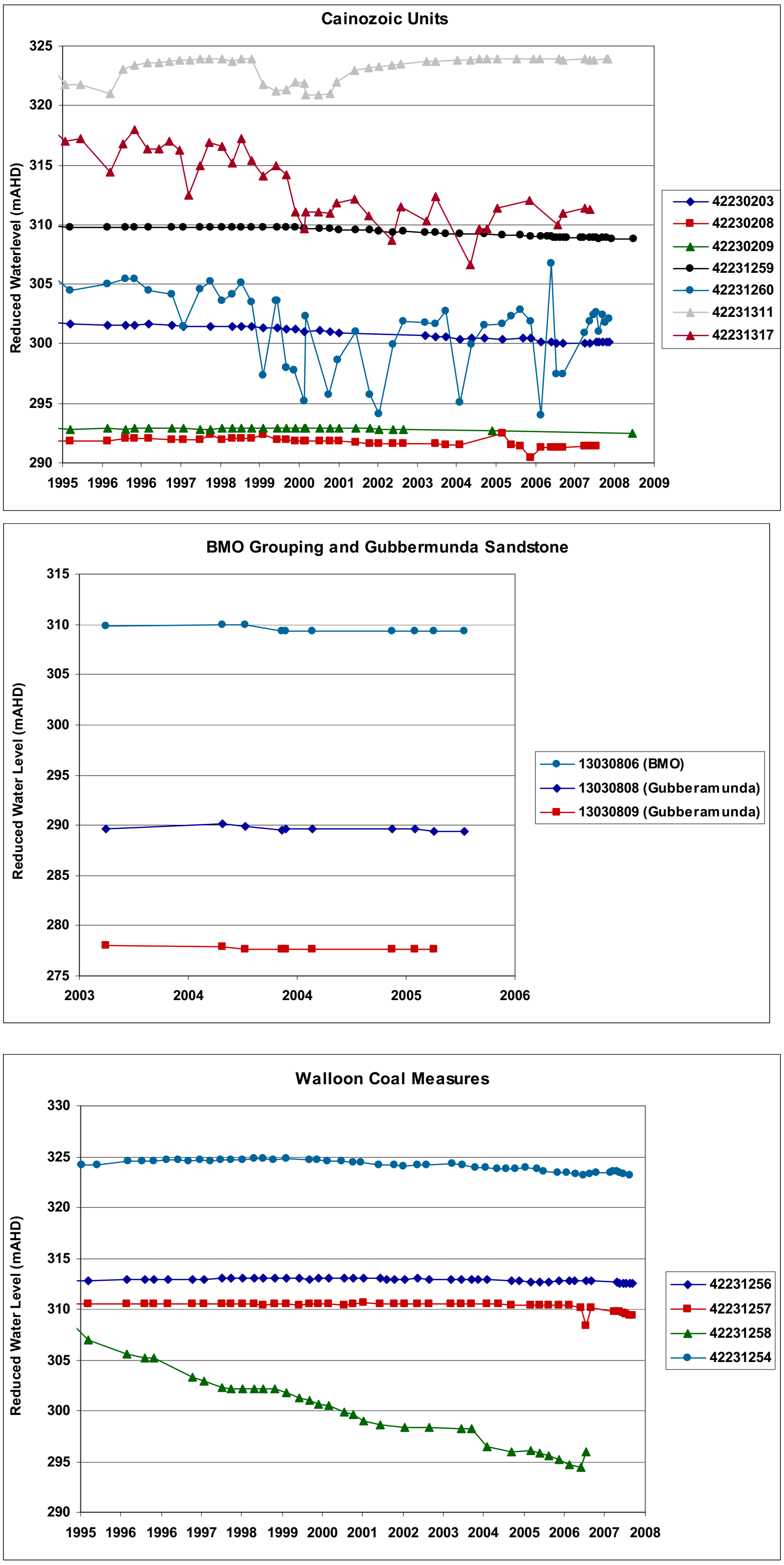


Figure 5.9 Selected groundwater monitoring bore water level hydrographs

BMO Grouping

A hydrograph for one BMO monitoring bore (13030806) was obtained for review. This particular bore is located to the north-west of Miles, where the Orallo Formation outcrops. The record for the bore is

short (2003 to 2006) and shows a 0.6m decline in water level in 2004, followed by stable conditions until 2006.

Gubberamunda Sandstone

Only two Gubberamunda Formation monitoring bores provided hydrographs for review, both located in the northern part of the Wolleebee Development Area where the formation outcrops. The records for these bores are relatively short (2003 to 2006), but both show a decline of approximately 0.4m in 2004. The water level in 13030809 was reasonably stable from 2004 to 2006, whereas the water level in 13030808 shows a further decline of 0.2m during the same period.

Walloon Coal Measures

A reasonable number of Walloon Coal Measures monitoring bores are located between Chinchilla and the eastern margin of the study area; however, to the west of Chinchilla, bore data is only available from wells located in the Injune Creek Group outcrops. The data range is also limited to the 2003 to 2006 period. Similarly to the Cainozoic water levels, hydrographs generally show a strong correlation with rainfall, with most water levels indicating a downward trend since 2000 (pre-dating CSG development in the area).

Bore 42231070 is located in the south-eastern corner of the study area. Quarterly water level readings in this well commenced in 1976, and the hydrograph record shows a strong correlation to rainfall. Regular water level monitoring ceased in 1997. Two readings in 2004/05 indicate water levels at a similar level compared to previous readings, suggesting that the correlation with rainfall may have continued; however, one measurement in 2007 shows the water level to be approximately 6m shallower. There is no indication in the GWBD as to why this may be, and there have been no readings since. It is postulated that this is either and erroneous reading or that the bore has failed, with the most recent water level indicative of interaction with a shallower water-bearing interval.

Bore 42231340 is located south-southwest of Dalby, and due west of Toowoomba. With the exception of a short period of water level decline between 1999 and 2003, the hydrograph for this well indicates increasing water levels since monitoring commenced in 1989.

Two other bores are in reasonably close proximity to Bore 42231340 (that is, 42231357 and 42231358). Water levels in Bore 42231357 correlate reasonably well with rainfall until about 1998 when an increased season fluctuation occurs. This is subsequently followed by a reasonably stable trend. Meanwhile, water levels in 42231358 show good correlation with rainfall, and a decline in water level of approximately 5m since 2000.

A cluster of Walloon Coal Measure monitoring bores (42231256, 4331257 and 42231258) in the subcrop area east of Dalby show good correlation to the longer term rainfall records, and exhibit declining trends since 2000. The most significant decline is noted for Bore 42231258, where the level has declined in excess of 10m since 1995. Drawdown effects from nearby irrigation bores are suspected.

Two of the bores in the Injune Creek Group outcrop, to the northwest of Miles, did not have sufficient data to determine a trend with any confidence. However, in the third bore, 13030814, the water level increased by approximately 1m between 2003 and 2006, indicative of recharge to that interval.

5.4.3 Hydraulic properties

A range of hydraulic parameters for the hydrostratigraphic units constituting the conceptual model have been compiled from exploration activities conducted by Origin Energy, various government

agencies and other consultants reports. Appendix B presents the available hydraulic data (namely, hydraulic conductivity, storativity, porosity and specific yield) for each hydrostratigraphic unit represented in the conceptual model. Where the availability of data permitted, lower (P_{10}), upper (P_{90}), and middle (P_{50}), percentiles are provided.

With reference to hydraulic conductivity, government-funded coal and gas exploration activities in the region have provided an extensive source of permeability data across the deeper geological units. This applies mainly to the Hutton Sandstone, Evergreen Formation and Precipice Sandstone. Similarly, Origin Energy's CSG exploration activities within their lease areas have provided hundreds of permeability measurements within the three coal seam units represented in the numerical model (that is, the Taroom, Jundah and Macalister). The availability of permeability data facilitated an assessment of lateral horizontal hydraulic conductivity distribution (following conversion from permeability values) within each coal seam unit, which has been represented in the numerical model.

The coal seam permeability data do exhibit regional trends in the lateral direction. For instance, coal seam permeability in the Undulla Nose region (a large south to south-westerly plunging anticline) averages 154 millidarcies. In contrast, coal seams in proximity to the major faults in the region (Leichhardt and Moonie faults) and in the shallower regions (less than 250m in depth) average six millidarcies and 43 millidarcies, respectively (Scott et al. 2004). The presence of the coal seams over the structurally-elevated Undulla Nose is responsible for the development of a well-defined cleat system and associated fractures during coalification, thus enhancing local permeability. In contrast, coal seam cleats and fractures associated with large-scale faulting or at shallower depths possess more mineral infilling, contributing to comparatively lower permeability characteristics (Scott et al. 2004).

Despite the volume of data available, there remain some gaps, particularly with reference to the confining units which have not been subjected to permeability testing. Furthermore, the permeability values available at the time of writing are representative of a particular sediment type, isolated to a particular interval and at a particular depth during drill stem testing (that is, a very small representation of a larger-scale system). The numerical model, however, requires each hydraulic conductivity value to be representative (or averaged) across an entire interval constituting a model layer. This is an obvious simplification of actual conditions.

In an attempt to address the challenges related to limited availability of hydraulic conductivity data, selected geophysical logs were reviewed to determine a relationship between gamma ray counts (in American Petroleum Industry (API) units) and measured permeability values. The inferred relationship is illustrated in Figure 5.10. Up to fifteen complete gamma ray logs were assessed from various locations across the study area. In doing so, a relationship between API value and measured permeability was derived. This relationship was then used to infer average hydraulic conductivity values across other geological units for which permeability measurements were lacking. Subsequently, hydraulic conductivity values were calculated (as the geometric mean) for each geological unit represented in the conceptual model. These inferred values are documented in Table 6.1 for each unit deeper than the Bungil Formation. The range in measured and inferred hydraulic parameter properties presented in Table 6.1 was adopted in the initial construction of the numerical groundwater model. In turn, the model calibration exercise (documented in Section 6.2.1) assisted in identifying upper, lower and best estimate values for hydraulic parameters related to each geological unit represented in the model.

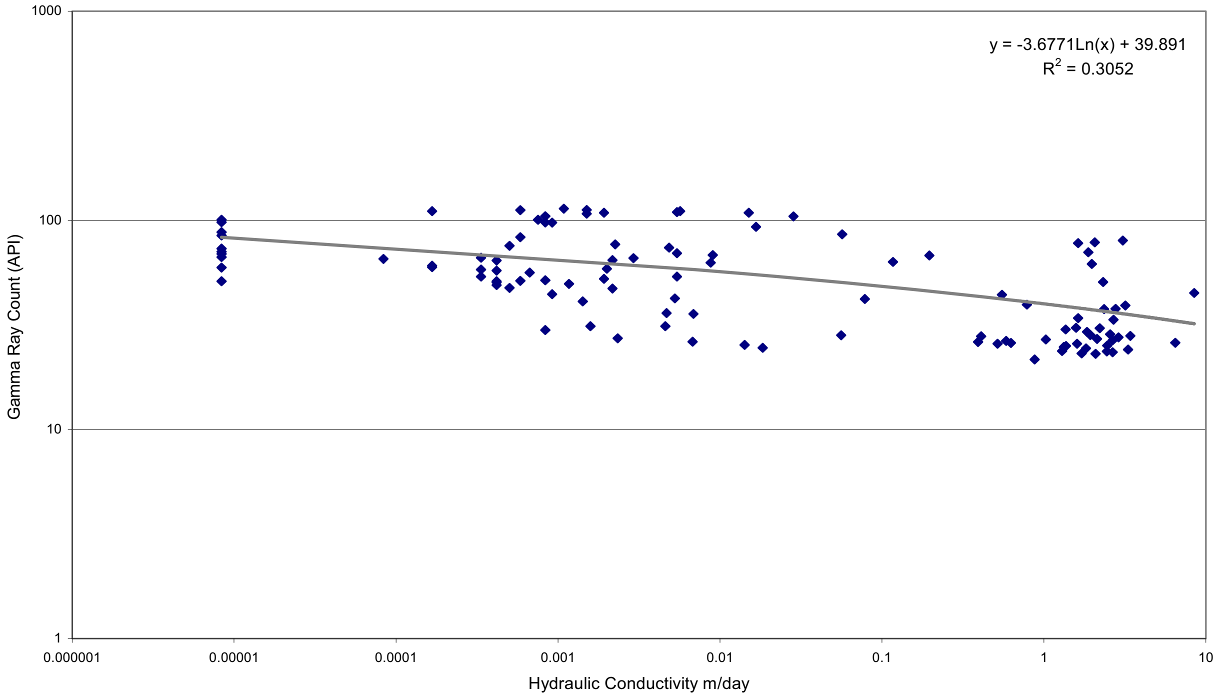


Figure 5.10 Relationship between gamma ray counts and hydraulic conductivity (in m/day)

5.4.4 Regional flow patterns

With the exception of data for the Cainozoic Units and Gubberamunda Sandstone, it was found that water level data in the other intervals was too clustered, and predominantly located around subcrop areas, to prepare meaningful potentiometric surface maps. While a large amount of data was available for the Walloon Coal Measures in the development areas, based on drill stem testing results, there was a paucity of data in the deeper parts of the basin to provide good control on potentiometric surface mapping. As such, statements on groundwater flow patterns are limited to the Cainozoic Units and Gubberamunda Sandstone intervals. However, the same general flow patterns are anticipated for the other units.

Appendix A, Map 7 and Appendix A, Map 8 present potentiometric surfaces for the Cainozoic Units and Gubberamunda Sandstone, contoured directly from reduced bore water level data. In the Cainozoic Units, it is apparent that a groundwater divide exists in the study area, oriented approximately north-west to south-east along the axis of Australia Pacific LNG's leases and corresponding to the Great Dividing Range. Hence, the regional-scale groundwater elevation represents a subdue reflection of topography. It is expected that regional groundwater flow in the Cainozoic Units will be to the south-west (that is, basinward) in the vicinity of the CSG fields; however, locally it may be towards watercourses where it might contribute to baseflow, such as in the Condamine River. Conversely, recharge to the groundwater system via stream losses may equally occur along some reaches of the Condamine River (Barnett and Muller 2008, Lane, 1979).

Review of the potentiometric surface generated for the Gubberamunda Sandstone (Appendix A, Map 8) indicates that groundwater generally flows towards the south and south-west; however, this is somewhat influenced by the data distribution.

Based on the equation:

$$\bar{v} = \frac{K}{n}\frac{\Delta h}{\Delta l}$$

Where $\bar{v}$ = average linear velocity,

K = hydraulic conductivity,

n = porosity, and

$\frac{\Delta h}{\Delta l}$ = hydraulic gradient, regionally calculated to be approximately 0.0005 (from Appendix A, Map 8)

and assuming an hydraulic conductivity range of 0.25m/day to 4m/day, and a porosity of 15%, the average linear groundwater flow velocity in the Gubberamunda Sandstone in the study area is calculated to be anywhere from 0.35m per year up to 5m per year. This corresponds with groundwater flow velocities calculated by Habermehl (1980) for the main Lower Cretaceous-Jurassic aquifers (corresponding to the Cadna-owie or BMO/Gubberamunda) along the eastern margins of the basin, where he calculated values on the order of 1m to 5m per year.

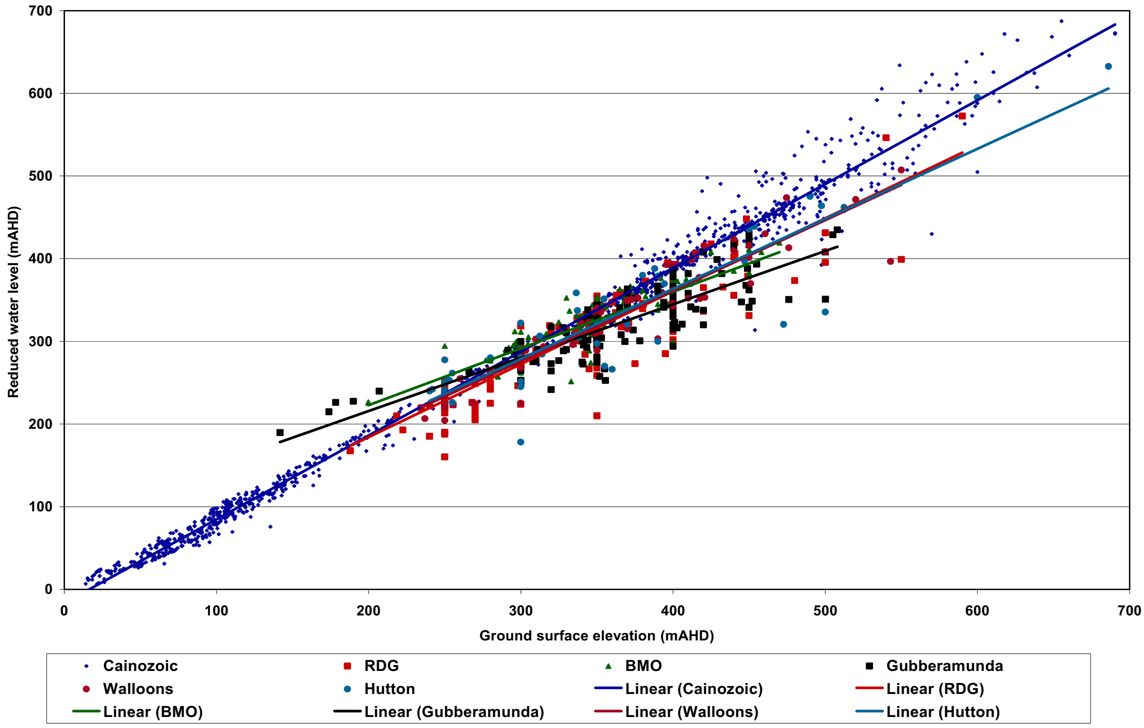


Figure 5.11 Relationship between ground surface elevation and reduced water level

Sufficient data exists for most aquifer units to define a relationship between the reduced water level (RWL) and the ground surface elevation. This comparison indicates that groundwater elevation is a subdued reflection of topography. Linear regressions between the ground surface elevation and the reduced water level are presented in Figure 5.11. The equations of the regression lines are provided in Table 5.3. Since the linear regressions suggest a relationship between topography and water level, it is expected that groundwater flow would be basin-ward in all units and to the southwest of the Great Dividing Range. In the northerly part of the study area, groundwater flow may be towards the north and east. This is consistent with the dominant anticipated groundwater flow patterns of the Great Artesian Basin (Habermehl 1980).

Table 5.3 Statistics for linear regression between ground surface elevation and reduced water levels

Unit	No. data points	Correlation co-efficient (R^2)	Trend line equation
Cainozoic	1218	0.99	y = 1.01x -16.74
Rolling Downs Group	195	0.84	y = 0.88x + 7.47
BMO Aquifer	295	0.68	y = 0.65x + 97.87
Gubberamunda	142	0.73	y = 0.65x + 86.32
Westbourne	21	0.62	y = 0.67x + 72.28
Springbok	6	0.73	y = 0.83x + 29.33
Walloons	87	0.86	y = 0.82x + 27.96
Eurombah	1	ID	ID
Hutton	43	0.82	y = 0.85x + 24.48
Evergreen	4	ID	ID
Precipice	2	ID	ID
Model Base	0	ID	ID

Note: ID = insufficient data

5.4.5 Inter-aquifer flow

Lack of sufficient water level data from nested bore locations (that is, wells completed in different formations and different depths at or near the same location) has precluded an in-depth assessment of the vertical potential for groundwater movement between discrete aquifers. However, based on the linear regressions conducted to assess lateral groundwater flow patterns (Figure 5.11), it is anticipated that vertical hydraulic gradients will vary across the study area. Habermehl (1980, 2002) suggests that vertical movement between the aquifers is limited by the low vertical hydraulic conductivities of the confining beds (usually two or more orders of magnitude lower than the lateral values); however, despite the low hydraulic conductivities, the inter-aquifer leakage is estimated to constitute a significant portion of the water balance of the Great Artesian Basin (Habermehl, 2002).

Henning (2005) identifies that where aquifers are connected by faults, there is the potential for groundwater movement; however, fault gouge or secondary mineral precipitation in the faults can effectively create a seal and limit significant movement of groundwater between aquifers.

Lane (1979) suggests that where the Walloon Coal Measures subcrop beneath the Condamine River alluvium, groundwater flow is generally from the coal measures into the alluvium. Downstream of Dalby, the vertical gradient has been determined to be from the alluvial deposits to the Marburg Sandstone (Lane, 1979)

Vertical movement of groundwater can also occur through incorrectly sealed bore annuli or compromised bores. The lack of detailed potentiometric mapping does not allow this aspect to be assessed; however, this potential pathway is discussed in greater detail in Section 6.2.5.

5.4.6 Hydrochemistry

A comprehensive review of the groundwater quality conditions in the various regional aquifers is provided in Appendix D. A summary of the key findings is provided below:

- Over 11,000 chemistry records, belonging to seven hydrostratigraphic units of the Surat Basin, have been assessed for the purposes of characterising the groundwater regime within the study area for the gas fields component of the Australia Pacific LNG's Project. The information has also been used to assess relevant environmental values. The groundwater salinity statistics (expressed as total dissolved solids, or TDS, in mg/L) and dominant hydrochemical facies of each hydrostratigraphic unit are summarised in Table 5.4.

Table 5.4 Groundwater salinity and hydrochemical facies summary

Hydro-stratigraphic unit	Salinity (total dissolved solids mg/L)						Dominant hydrochemical facies
	Count	20th percentile	80th percentile	Median	Mean	Standard deviation	
Cainozoic Units	1489	469	1810	891	1509	2332	Na-Mg-Ca-Cl-HCO_3 and Na-Cl-HCO_3
BMO Formation	228	745	2588	1153	1970	2285	Na-HCO_3-Cl
Gubberamunda Sandstone	100	590	1646	980	1673	1974	Na-HCO_3-Cl
Springbok Sandstone	8	533	1615	575	948	598	Na-HCO_3-Cl
Walloon Coal Measures	162	591	3564	1463	2547	3044	Na-Cl-HCO_3, Na-HCO_3-Cl and Na-Cl
Hutton Sandstone	234	568	2357	1033	1596	1598	Na-HCO_3-Cl and Na-Cl-HCO_3
Precipice Sandstone	23	127	1652	171	769	1096	Na-HCO_3 and Na-Cl-HCO_3

- Most aquifer or water-bearing units in the project area contain groundwater that is marginally alkaline with median salinities recorded below 1200mg/L TDS. Groundwater salinity trends in any one hydrostratigraphic unit are generally highly variable, on a regional scale. In contrast, groundwater in the Walloon Coal Measures yields the highest median salinity - in excess of 1400 mg/L.
- Groundwater chemistry within the shallow Cainozoic Units aquifer system is largely heterogeneous, possibly as a consequence of shallow groundwater processes such as local recharge and discharge systems, evapo-transpiration, rock-water interactions and possibly irrigation induced salinity.
- Groundwater salinities in the Gubberamunda Sandstone, Springbok Sandstone, Hutton Sandstone and Precipice Sandstone aquifers are typically very low in proximity to direct

recharge sources in and around Injune and Taroom, to the north of Australia Pacific LNG's development areas.

- Groundwater quality in the deeper confined aquifers generally deteriorates across Australia Pacific LNG's development areas (between Roma and Toowoomba). Processes that may be contributing to the deteriorating groundwater quality in this region include: ion diffusion from overlying or underlying aquitards with marginal marine depositional histories, ion-exchange, leaching of soluble constituents from the host rocks, mixing of different water types, and/or water-rock interactions along flow paths (Radke et al. 2000, Herczeg et al. 1991).
- In most hydrostratigraphic units the dominant water type is Na-HCO_3-Cl (or a close variant). The dominance of bicarbonate (and its common derivative from soil zone CO_2 as a result of plant respiration and oxidation of organic matter) may be a consequence of the proximity of the recharge zones to the north and northwest of Australia Pacific LNG's development areas. Additionally, its presence may be linked to other weathering reactions occurring deeper in the subsurface. Equally, bicarbonate concentrations may also be elevated as a consequence of the dissolution of carbonates by oxygenated recharge waters, mixing of different water types and/or precipitation/dissolution of minerals (Radke et al. 2000, Herczeg et al. 1991). The dominance of Na is likely related to the weathering of Na-bearing silicate minerals, cation exchange and conversion of Na-Smectite to Kaolinite and release of Na to solution (Radke et al. 2000). The geochemical signature may, however, be overprinted to some extent by the diffusion of Cl (and other soluble ions) from overlying or underlying aquitards with marginal marine depositional histories (Radke et al. 2000).

5.4.7 Recharge and discharge processes

Recharge to the groundwater regime in the Surat Basin predominantly occurs through infiltration of rainfall to intake beds exposed in outcrops or subcrops within the elevated northern and eastern margins of the area (BRS & NRM 2003). Infiltration of rainfall may occur directly into the outcropping sandstone aquifers, through contributions from losing reaches of creeks or rivers, or by percolation through unconsolidated sediments which overlie the aquifers, thus facilitating localised recharge (BRS & NRM 2003, Habermehl 2002). The regional extent of the intake beds (or outcrop areas) for each hydrostratigraphic unit is illustrated in Appendix A, Map 2.

The Great Artesian Basin groundwater flow models, GABSIM and GABHYD, developed by the Bureau of Rural Sciences (BRS), indicate that approximately 1% of the current rainfall over the intake beds infiltrates the aquifers as recharge (GABCC 2000).

In the BRS & NRM (2003) study, recharge processes to Queensland's Great Artesian Basin intake beds were differentiated according to the following mechanisms:

- Localised recharge
- Preferred pathway flow
- Diffuse recharge.

In general, preferred pathway flow (represented mainly by bedding plane partings and thin porous bands) was determined to be the dominant recharge process. Localised recharge zones are limited in area, being restricted to the occurrence of alluvium unless the weathered surface of the sandstone has been eroded by a stream and the aquifer is hydraulically-loaded by pooled water. Although the area of influence of diffuse recharge of rainfall was determined to be substantial (i.e. virtually the entire Queensland Great Artesian Basin intake beds), the rates were estimated to be an order of magnitude

lower than the preferred pathway or localised recharge mechanisms. The ranges of recharge rates for each process evaluated are reported as follows:

- Diffuse rainfall: 0.03mm/year to 2.4mm/year
- Preferred pathway flow: 0.5mm/year to 28.2mm/year
- River leakage (i.e. localised recharge): up to 30mm/year.

With regards to recharge processes in the Condamine River alluvial region, outcomes of injection trials conducted by Lane (1979) concluded that rainfall, surface runoff and floodwaters amount to a negligible contribution to the aquifer storage in this unconfined aquifer. Rather, the alluvial aquifer system is recharged predominantly through inflow from streams and bedrock systems (Lane 1979).

Various environmental isotope and hydrogeological studies conducted in the Great Artesian Basin have verified the increase in residence times between recharge zones and along downgradient flow pathways towards the centre of the Basin (for example, Airey et al. 1979, Calf and Habermehl 1984, Herczeg et al. 1991, Radke et al. 2000). In particular, the basin-wide spatial patterns of stable oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) isotopes and the general conformity of values with the global meteoric water line (Airey et al. 1979) demonstrate that the groundwater signatures are exclusively those of rainfall in the recharge areas. This supports the assumption of continuing recharge from geological to modern times. Age-dating work summarized in the BRS & NRW (2003) confirms this, with groundwater ages ranging from recent up to approximately 26,000 years.

Natural discharge from the confined aquifers in the Basin occurs by the following means (Habermehl 2002, BRS & NRM 2003):

- Concentrated outflow from springs
- Baseflow to rivers
- Vertical upward leakage from the Lower Cretaceous-Jurassic age aquifers towards the Cretaceous age aquifers and upwards to the regional watertable
- Subsurface outflow into neighbouring basins.

Artificial discharge occurs by means of free or controlled artesian flow and pumped abstraction from water bores installed in the aquifers. Diffuse discharge from the artesian aquifers through the confining beds towards the ground surface is known to occur in the marginal areas where the confining beds are relatively thin, potentiometric surfaces are high and water tables shallow (Woods et al., 1990).

Most springs in the Great Artesian Basin are concentrated in groups and are distributed over relatively small areas. The occurrence of springs in and around the study area is discussed in Section 5.4.9. Many of these springs are associated with structural features or resulting pathways, such as faults, folds, monoclines and intersecting lineaments. These tend to occur at the abutment of aquifers against lower permeability bedrock or where confining beds thin near discharge margins. Rates of discharge from the springs are generally low, averaging less than 1L/s (Habermehl 1982).

Prior to intensive development, the Great Artesian Basin existed in a steady-state condition with a natural equilibrium between recharge and discharge processes. Following intensive groundwater abstraction for agricultural and municipal development, natural discharge in the Basin diminished with a diminution of flow from springs in the south-central, south-western and northern regions (Habermehl 2002).

The large-scale lowering of potentiometric surfaces in various intervals (by groundwater abstraction) has contributed to a steepening of the hydraulic gradient, and in turn, higher rates of recharge water

entering the Basin. Past modelling has estimated an increase in recharge rates from 2200ML/day to 3000ML/day since the beginning of development (Habermehl 1980).

Anthropogenic influences on the Great Artesian Basin have broadly contributed to a new steady-state regime in which total recharge and discharge are approaching equilibrium and the sum of the discharges and vertical leakage are nearly equivalent to the recharge.

5.4.8 Groundwater – surface water interactions

The Australia Pacific LNG study area is principally located in the Condamine-Balonne River Catchment. The Condamine River (situated to the south and south-west of the study area) flows in a north-westerly direction and joins the Balonne River downstream of Surat, which flows west and south-west. It then flows into the Culgoa River and other related drainage features – Bokhara, Ballandool and Narran rivers, all of which flow to the south-west.

Groundwater and surface water connectivity relationships in the Condamine-Balonne River Catchment were assessed as part of the CSIRO Murray Darling Basin Sustainability Yields Project (CSIRO 2008). The analytical desk-top assessment (initiated during the drier-than-average conditions of March 2006) indicated that the northern branch of the Condamine River and the Oakley Creek tributary were generally disconnected from the underlying Cainozoic-age aquifer system, with river losses of between 0.4ML/day/km to 1.8ML/day/km. The large-scale groundwater extraction since the late 1960s has contributed to a large drop in water levels within the alluvial aquifer to the east of the North Branch and south-east of the town of Dalby, and is believed to be the primary cause of the disconnection of groundwater from the river system (CSIRO 2008).

From Tummaville to the Chinchilla Weir (in the Orana North development area), the main branch of the Condamine River is ‘losing’ water at medium (0.37ML/day/km to 0.44ML/day/km) to high (1.3ML/day/km) rates (CSIRO 2008). These rates are supported by the infiltration trials conducted by Lane (1979). In his 1979 study, Lane considered that maximum river loss rates during low flow conditions in the Condamine River occurred between Ellangowan and the Pittsworth-Millmerran Road. As a result of his infiltration trials, Lane (1979) estimated the infiltration rates in this area to vary from 0.1ML/day/km to 0.3ML/day/km. Downstream of this point, Lane reported that the presence of interbedded clay strata reduced the inflitration rate.

It was also emphasised by Huxley (1983) that during recharge events, a recharge mound builds up along the Condamine River. When river levels fall, following a rainfall event, discharge can take place back into the river. It was estimated by Huxley (1983) that downstream of Macalister where groundwater levels (at the time of his study) were near or above streambed level, approximately 1980ML/annum was discharged to the river from the shallow groundwater systems.

According to the CSIRO (2008) study, surface water storage at Chinchilla Weir has altered conditions to ‘gaining’ immediately downstream of the weir at rates of between 0.05ML/day/km to 0.11ML/day/km. These gaining conditions may extend seasonally to the Balonne River at the Weribone stream gauge (422213A), approximately 10km west of Surat. Further downstream, the Balonne-Culgoa River is ‘losing’ water at low (0.02ML/day/km) to medium (0.13ML/day/km to 0.27ML/day/km) rates (CSIRO 2008).

The tributaries of the Condamine-Balonne River system in and around the study area are ephemeral. During rainfall events, flow in the creeks and streams partially recharges the underlying alluvial deposits. Under the right conditions, groundwater in these deposits subsequently constitutes baseflow to the surface water courses once the flow in the creeks and streams diminish. The ephemeral nature

of these tributaries implies that the effective storage in the alluvial deposits is limited, with insufficient storage to supply baseflow over the entire dry season.

There are several nationally significant wetlands located on the lower Balonne River system. The Ramsar listed Narran Lake Nature Reserve (which includes Back and Clear Lakes) located in New South Wales, approximately 350km south-west of the CSG development area, is part of the large terminal wetland system of the Narran River at the end of the Condamine system flowing out of Queensland (CSIRO 2008). This system of lakes is notable as a site for large-scale waterfowl breeding during periodic flooding.

The hydrology of the lakes is dominated by flow from the Narran River, local rainfall (which can inundate large areas of low-lying lignum) and evaporation. The influence of groundwater in the Narran Lake wetlands is uncertain and has recently been identified as a knowledge gap requiring further investigation. In any event, the lakes are situated well outside the area of influence of the Australia Pacific LNG operations with regards to potential groundwater level drawdown influences within the shallow aquifers.

There are various river reaches in the study area that potentially receive baseflow from the outcropping aquifer systems of the Great Artesian Basin. According to the AGE (2005) desk-top study, the following river and creek systems may have the potential to contain reaches that receive baseflow from the following Great Artesian Basin intervals:

- The Kumbarilla Beds (Gubberamunda Sandstone equivalent) west of Dalby: Dogwood Creek, Condamine River, Wamboo Creek, Moonie River, Western Creek, Murri Murri Creek and MacIntyre Brook
- The Mooga Sandstone north and northeast of Roma: Bungil Creek and Yuleback Creek
- The Gubberamunda Sandstone north of Roma: Bungil Creek
- The Hutton Sandstone north and northeast of Injune: Hutton Creek and Dawson River
- The Precipice Sandstone northeast of Injune: Hutton Creek.

To date, the baseflow contribution rates to these river and creek systems have not been assessed.

5.4.9 Springs and groundwater dependent ecosystems

Springs and areas of seepage are abundant in the marginal regions of the Great Artesian Basin, particularly in the southern, south-western and northern areas. Most springs are concentrated in groups and are distributed over relatively small areas (GABCC 1998). Many springs occurring in the Great Artesian Basin are recognised as having unique cultural and ecological values.

'Groundwater dependant ecosystems' (GDEs) are common in areas where springs occur and are classified as ecosystems which have their species composition and their natural ecological processes determined by groundwater (ANZECC 2000). According to Hatton and Evans (1998) and Clifton and Evans (2001), six broad functional groups of groundwater dependant ecosystems are noted:

- Terrestrial vegetation
- River baseflow systems
- Estuarine and near shore marine
- Aquifer systems
- Cave systems

- Wetlands.

The function (that is, health) of groundwater dependant ecosystems is generally defined by four hydrogeological parameters: 1) groundwater flux; 2) groundwater level; 3) groundwater pressure; and 4) groundwater quality, with dependence being a function of one or all of these factors.

In general, springs associated with the Great Artesian Basin are characterised into 12 'supergroups'. Each supergroup comprises smaller groups of springs and spring complexes. The Australia Pacific LNG study area is located within the Springsure supergroup of the Brigalow Belt Complex (EPA 2005, Fensham et al. 2004, Fensham et al. 2007). The location of known springs in proximity to the study area (as sourced from the DERM wetlands mapping database) is illustrated in Appendix A, Map 9.

The community of native species dependent on the natural discharge of groundwater from the Great Artesian Basin is listed as an endangered community under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). A number of species are also listed under the *Queensland Nature Conservation Act* (1992) or the IUCN Redlist (DEWHA 2001, EPA 2005), of which two species of plant, *Myriophyllum artesium* (artesian milfoil) and *Eriocaulon carsonii* (salt pipewort), are known to occur within the Springsure supergroup (DEWHA 2001). For further information concerning these species and the outcomes of the dry season field surveys, refer to Volume 5, Chapter 20 Aquatic Biology.

Recharge springs[1] with high conservation values occur approximately 25km north and northeast of the Roma township. These are located within outcropping areas of the Gubberamunda Sandstone (Queensland Department of Natural Resources 2005). Numerous high value discharge and recharge spring complexes, associated with the Hutton Sandstone and Precipice Sandstone units, also occur in proximity to the towns of Taroom and Injune, at least 50km north and north-west of the Combabula and Ramyard development areas (Queensland Department of Natural Resources 2005).

The discharge spring complexes located near the Taroom township are supplied by artesian water from the Precipice Sandstone unit, rising to the surface through joints and fractures in the sandstone, and are known locally as 'boggomosses' (GABCC 1998). These spring complexes provide wetland habitat in an area that is subject to prolonged drought conditions. A total of 203 vascular plant taxa have been identified in the boggomosses (GABCC 1998).

For clarification, only those communities associated with discharge springs are listed under national legislation. The Springsure supergroup is located within a groundwater recharge area and consists of both recharge and discharge springs (DEWHA 2001). DEWHA 2001 stipulates that an assessment of each individual spring is required to determine its origin (that is, discharge or recharge) and, in turn, whether it is associated with the listed ecological community.

In other areas not dominated by the presence of active springs or spring-complexes, the greatest potential for groundwater dependency is likely to be within shallow alluvial sequences associated with drainage lines. In these areas, the water table is likely to be permanently shallow and higher than the maximum rooting depth of established vegetation. This excludes grass species which represent the predominant cover in most low-lying areas. The level of groundwater dependency in these areas is therefore likely to be low (opportunistic at best) with species potentially utilising groundwater in the saturated zone only during drought conditions where surface water flux is uncommon. Given the local

[1] A spring where water is absorbed into sandstone sediments that outcrop on the margins of the Great Artesian Basin and discharge water locally after relatively short residence times.

climatic conditions and drainage characteristics of these areas, surface water runoff and infiltrated rainfall are likely to represent the primary source of water flux required to satisfy plant requirements.

Established vegetation on non-alluvial sequences may also potentially utilise groundwater opportunistically during dry periods. However, the potential level of dependency is likely to be less than that required for vegetation in the vicinity of drainage lines, as shallow groundwater in non-alluvial sequences tends to represent interface drainage, which only persists after high intensity rainfall events.

5.5 Existing environmental values

A comprehensive review of the environmental values of groundwater resources within the study area is provided in the stand-alone hydrochemistry report presented in Appendix D. A summary of key findings is provided below.

The environmental values of groundwater have been assessed in accordance with the Environmental Protection (Water) Policy 2009 (EPP 2009). As stipulated in these policy documents, the following environmental values are to be enhanced or protected:

- Biological integrity of an unmodified, highly-valued or modified aquatic ecosystem
- Suitability for primary, secondary and visual recreational use
- Suitability for minimal treatment before supply of drinking water
- Suitability for agriculture use
- Suitability for aquaculture use
- Suitability for producing aquatic food for human consumption
- Suitability for industrial use
- Cultural and spiritual values of the water.

A discussion of each environmental value is provided below in the context of the study area, including the relevant guideline values adopted.

Biological integrity of an unmodified, highly-valued or modified aquatic ecosystem: Groundwater in most hydrostratigraphic units of the Surat Basin contains elevated levels of trace elements (including zinc and copper), and in some instances nitrate, which exceed the ANZECC 2000 guideline Trigger Levels for Freshwater Ecosystems (at 95% protection). Accordingly, any controlled, or uncontrolled, discharge of associated CSG water may potentially affect the biological integrity of any receiving surface water system. However, discharge of (untreated) associated CSG water to surface water systems will not occur during any period of operation, and hence, such impacts are not expected.

Where surface water and groundwater systems are hydraulically connected, there may be a potential for impacts on groundwater to indirectly affect the environmental values of connected surface water systems. As such, appropriate monitoring, management and mitigation measures will be required in all aspects of the Project’s operations to minimise the potential for groundwater and any connected surface water systems to be affected.

Notably, stygofauna, a type of groundwater dependant ecosystem, are classified as any fauna that live within a groundwater (aquifer) system. Stygofauna commonly include aquatic groundwater invertebrates (that is, fish, worms, snails, arachnids, mites and insects), though terrestrial air-breathing subterranean animals may also be included in this classification. These species tend to reside within

freshwater aquifers and within the pore spaces of limestone, calcrete or laterite, marine caves and along coast lines.

Stygofauna have been the subject of extensive investigation in countries such as the USA, France, Slovenia and numerous other European countries, due to the presence and accessibility of favourable habitat (that is, cave systems) and the large diversity and numbers of fauna identified. In contrast, Australian stygofauna species are relatively poorly investigated and understood.

The nature of the geology and shallow groundwater systems in the study area (that is, absence of limestone, marine caves, combined with the variable groundwater salinity) is unlikely to be conducive to large-scale populations of stygofauna species.

Suitability for primary, secondary and visual recreational use: The environmental values associated with recreational use are more applicable to surface water than groundwater. However, where surface water and groundwater systems are hydraulically connected, there may be potential for any affected groundwater to indirectly impact upon the recreational values of surface water systems. As such, appropriate monitoring, management and mitigation measures will be required in all aspects of the Project's operation to minimise the potential for groundwater and any connected surface water systems to be affected.

Suitability for minimal treatment before supply as drinking water: Groundwater salinities within the regional study area are commonly in excess of 500mg/L total dissolved solids, which represents the upper limit for the Australian Drinking Water Guidelines (2004) based on taste. Elevated salinities, together with concentrations of other elements (including iron and boron) that regularly exceed guideline values, are likely to preclude the use of groundwater as a source of drinking water without some form of dilution (with lower salinity water) and/or treatment.

On a regional scale, groundwater is accessed at various locations from the Cainozoic-age Condamine-Alluvium, Mooga Sandstone, Gubberamunda Sandstone, Hutton Sandstone and Precipice Sandstone for town water supply purposes. In most instances, the groundwater is not used as a continuous supply, but for drought relief purposes only. If accessed, the groundwater is generally shandied with lower salinity surface water to reduce the mineralisation to an acceptable level for drinking water purposes and treated accordingly prior to consumption.

Suitability for use in agriculture, aquaculture, and production of aquatic food for human consumption: The majority of registered bores present in the study area access groundwater for irrigation and stock watering purposes, indicating that the quality is likely suitable for these uses.

With reference to irrigation, appropriate groundwater salinities will be largely governed by the crop, soil type and irrigation regime. While groundwater salinities in the region may be suitable or marginally elevated for irrigation purposes, shandying with fresher surface waters may provide an opportunity to expand the potential irrigation uses.

The available groundwater quality data for the region indicates that the groundwater resources are likely to be suitable for stock watering purposes. Similarly, the groundwater is likely to be appropriate for aquaculture and production of aquatic food for human consumption.

Suitability for industrial use: Groundwater resources within, and in proximity to, the study area are expected to be suitable for a range of industrial uses including cooling water, process water, utility water and wash water. Each industry will have specific quality requirements and constraints that will determine the suitability of employing the treated or untreated groundwater resource.

Cultural and spiritual values of the water: This hydrogeological assessment has not identified any groundwater resources recognised for their cultural or spiritual value. Artesian conditions may give rise

to local scale, permanent water pools and/or springs. Such features may have important cultural significance, and if present, will require careful investigation as part of the CSG planning process.

With reference to the groundwater regime in the study area, the following environmental values are considered to be of particular relevance:

- Biological integrity of aquatic ecosystems – given the effect of groundwater discharge to surface water bodies or groundwater dependent ecosystems.
- Suitability for minimal treatment before supply as drinking water – if groundwater is to be accessed for domestic use or town water.
- Suitability for use in agriculture – in cases where groundwater is accessed for irrigation
- Suitability for use in agriculture – in cases where groundwater is accessed for livestock watering
- Suitability for industrial use.

Accordingly, the guidelines adopted in evaluating these environmental values of the groundwater regime are presented in Table 5.5.

Table 5.5 Adopted groundwater quality guidelines

Environmental value	Adopted guidelines
Biological integrity of aquatic ecosystems	ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality Trigger Levels for Freshwater Ecosystems – 95% protection level of species
Suitability for minimal treatment before supply as drinking water	NHMRC 2004 Australian Drinking Water Guidelines
Suitability for use in agriculture (irrigation)	ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality Short-term Trigger Values (STV) and Long-term Trigger Values (LTV) in Irrigation Water
Suitability for use in agriculture (livestock watering)	ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality Livestock Drinking Water Guidelines (Beef Cattle and Sheep)
Suitability for industrial use	Required quality conditions for intended use

5.6 Existing groundwater users

A search of DERM's WERD database returned a total of 877 groundwater extraction licenses within the vicinity of the gas fields. The locations of these licenses are shown on Appendix A, Map 10. Because of the simplification of the data (so that only the first bore associated with the license was mapped), it is recognised that the distribution of the licenses may actually differ; however, the general pattern of bore distribution is expected to remain similar.

Bores that do not require a license (such as those used for domestic and stock use only) and other unregistered bores may also exist in the study area, but have not been identified on Appendix A, Map 9, although stock and domestic bore locations are shown on Appendix A, Map 10.

Water extraction associated with petroleum and gas activities, including associated CSG production water, do not need to be licensed under the Water Act, and hence were not included in the WERD search results. Origin Energy CSG Ltd. has one groundwater extraction license (58579N).

Figure 5.12 to Figure 5.14 show how the licenses have been distributed between the various hydrostratigraphic units, and the different uses. Licensed allocations for the study area equate to approximately 125000ML/a and are associated with over 1700 water bores. The majority of the bores, both in terms of licensed volume and number of licenses, are permitted to extract groundwater from the relatively shallow Cainozoic Units (inclusive of the Condamine River Alluvium, the alluvium of tributaries to the Condamine River, and the Main Range Volcanics) which sit above and are not included in the aquifers of the Great Artesian Basin. Approximately 99500ML/a (80%) of licenses in the vicinity of the proposed gas fields are allocated to the Cainozoic Units, and most are located in and around the town of Dalby in the eastern part of the study area (Appendix A, Map 9). There is currently a moratorium on applications for new licenses in the Condamine River Catchment, specifically relating to the alluvium of the Condamine River and its tributaries, the Main Range Volcanics and the Chinchilla Sands (Queensland NRW 2008).

Within the vicinity of the Australia Pacific LNG gas fields, the majority of the licensed groundwater use is for agricultural purposes, with irrigation representing about 33% of allocations and intensive stock use representing 10%. The remaining allocations are for industrial use (26%), commercial use (17%), town water supply (10%) and 4% is for other or unidentified uses.

It is important to note that the allocation figures above do not include volumes of water used for livestock watering and domestic purposes, which do not require a license. Stock and domestic water constitutes the greatest use of groundwater from the Great Artesian Basin aquifers within the Surat Basin, both in terms of estimated volumes (currently estimated at approximately 81500ML/a compared with licensed allocations of approximately 25000ML/a) and number of bores (approximately 6480 bores - Queensland Department of Natural Resources 2005). The largest number of stock and domestic bores access water from the Hutton Sandstone hydrostratigraphic unit (30%) which includes the Marburg Sandstone, whereas in terms of volumes extracted, the greatest use is from the Gubberamunda Sandstone hydrostratigraphic unit (30%). Approximately 27% of bores access the Walloon Coal Measures. A breakdown of the distribution of bores and estimated usage for each aquifer unit is provided in Figure 5.15 and Figure 5.16, respectively.

Locations of the stock and domestic bores are shown on Appendix A, Map 11. Stock and domestic groundwater use from the Cainozoic Units has been estimated to be approximately 10000ML/a.

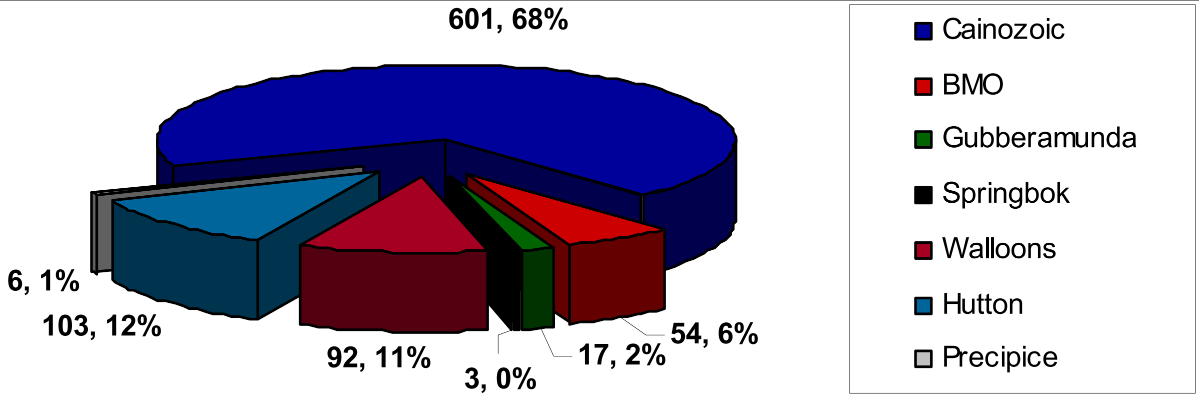


Figure 5.12 Distribution (number and % of total allocation) of licences by hydrostratigraphic unit in the vicinity of the gas fields

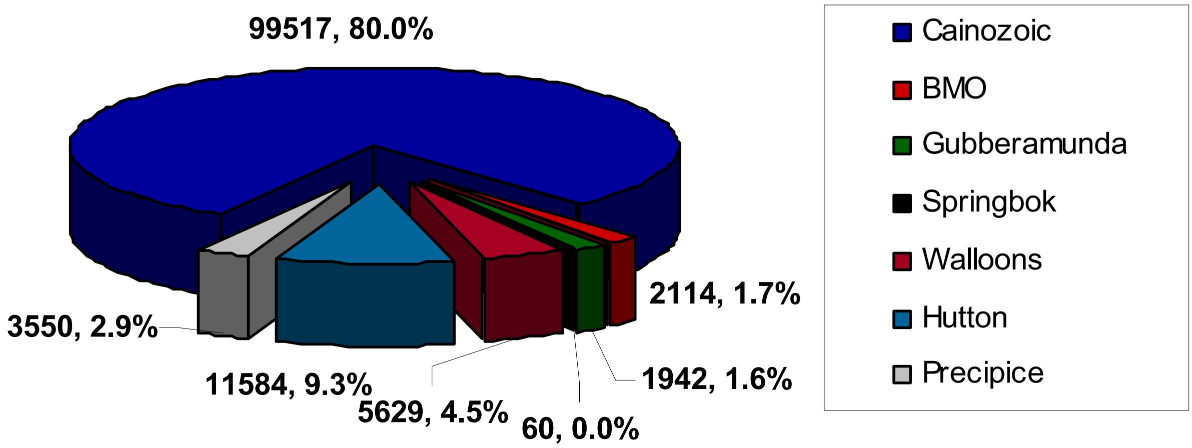


Figure 5.13 Distribution (number and % of total allocation) of allocated volume by hydrostratigraphic unit in the vicinity of the gas fields

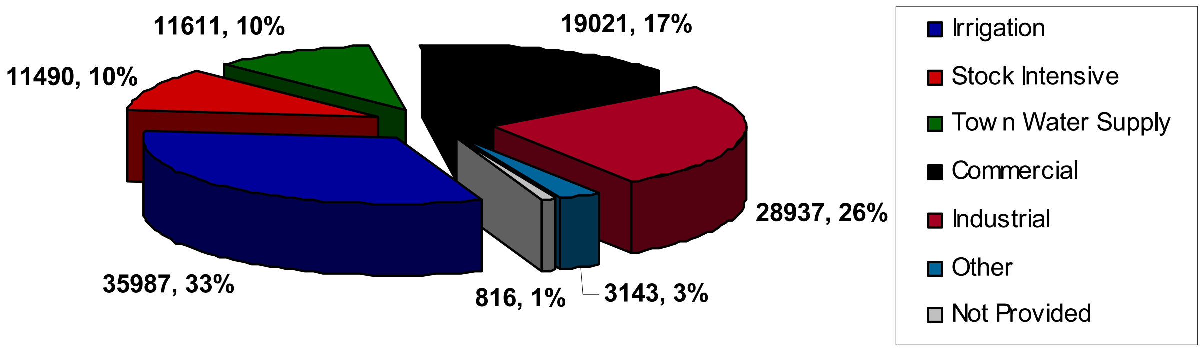


Figure 5.14 Distribution (number and % of total) of licenced volume by use in the vicinity of the gas fields

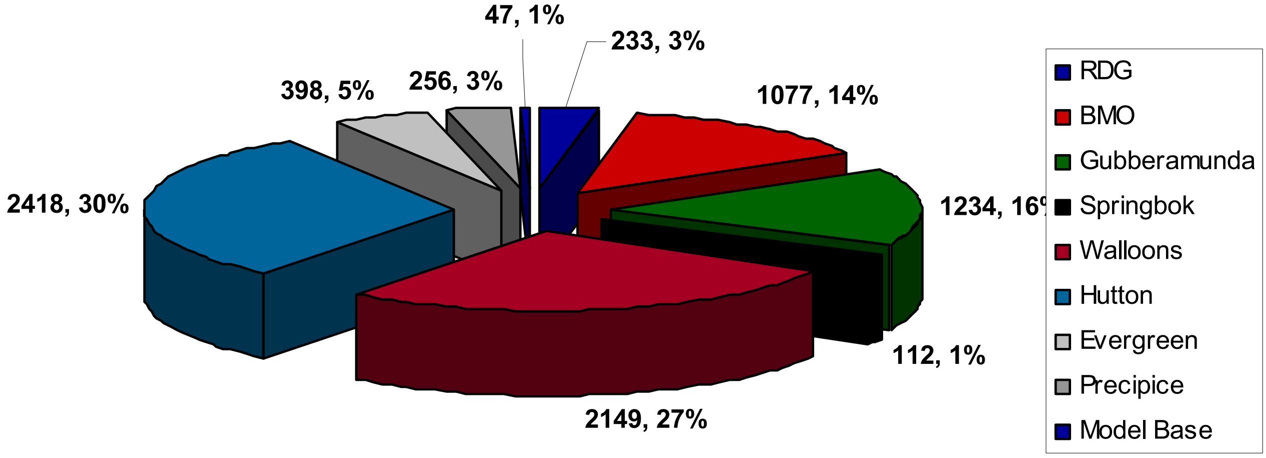


Figure 5.15 Distribution (number and % of total) of stock and domestic bores by hydrostratigraphic unit in the Surat Basin

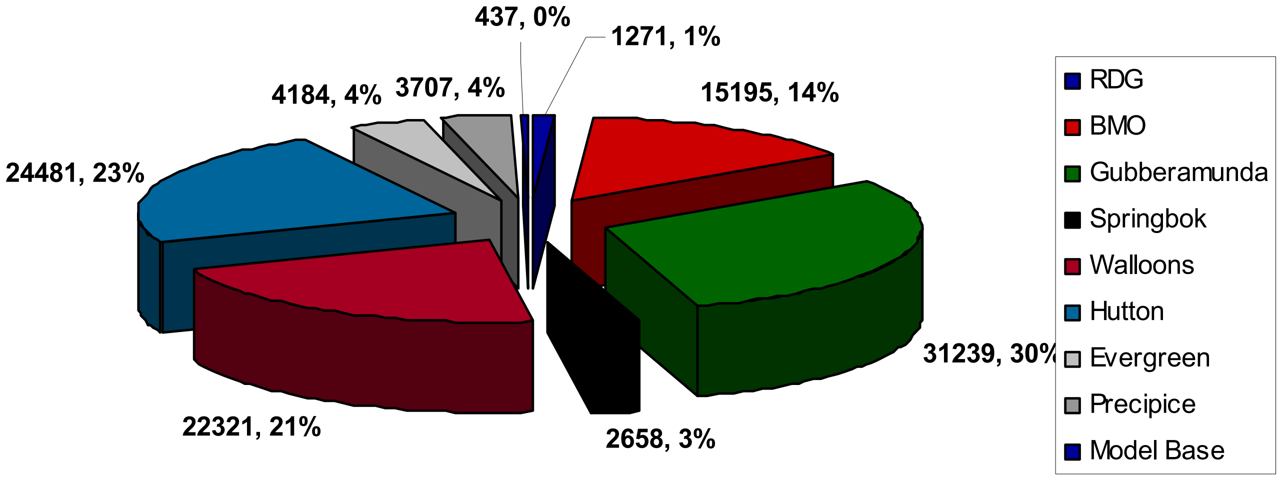


Figure 5.16 Distribution (number and % of total) of estimated groundwater use by stock and domestic bores for each hydrostratigraphic unit in the Surat Basin

5.7 Summary of hydrogeological conceptualisation

The Surat Basin is and elongate basin and contains a sequence of alternating terrestrial and marginal marine deposits. These deposits reach a maximum thickness of approximately 2500m. The terrestrial units tend to be sandstone-dominated and form regional aquifers, whereas the marine sequences are siltstone- and mudstone-dominated and form regionally extensive aquitards. Although the Surat Basin is geologically bound by the Kumbarilla Ridge in the east and the Nebine Ridge in the west, it is hydrogeologically connected to the Clarence-Morton and Eromanga basins (in the east and west, respectively) and is one of the major constituent basins of the Great Artesian Basin.

The hydrostratigraphic units (aquifers and aquitards) are broadly flat-lying; however, uplift and erosion along the eastern and northern margin of the basin has resulted in a south-westerly tilt to the units, exposing most of them along the northern boundary of the basin. These subcropping and outcropping areas represent the intake beds for recharge to the Great Artesian Basin aquifers.

Recharge comes predominantly by way of summer rainfall, either by direct infiltration into the outcropping areas, or indirectly via leakage from streams and/or from overlying aquifers. Water levels in the Cainozoic Units, in particular, respond directly to rainfall recharge, and heavy use. This,

combined with extended periods of below average rainfall over the last few years, has resulted in declining water levels over time.

The regional groundwater flow direction is to the south-west, and is generally a subdued reflection of topography. Locally, groundwater flow may be towards surface water features, where these intersect subcropping or outcropping units. In the Cainozoic Units groundwater flow may follow the valley of the Condamine River. Estimated flow velocities range from 0.35 metres per year to 5 meters per year.

Most aquifer units in the study area contain groundwater of meteoric origin and are marginally alkaline with median salinities below 1200mg/L as TDS. The dominant water type is generally Na-HCO_3-Cl (or a close variant). The highest median groundwater salinity (greater than 1400mg/L) is associated with the Walloon Coal Measures.

CSG extraction in the Surat Basin is targeted within the Walloon Coal Measures in the north-eastern margin of the basin. This mudstone- and siltstone-dominated unit subcrops in the vicinity of the Warrego Highway and reaches depths in excess of 1600m below ground surface (mbgs). Thicknesses of these deposits can be in excess of 500m. There are nine major coal seams within the Walloons interval, which are separated by mudstones, siltstones and occasional sandstones. The seams generally comprise intervals of numerous thin coal stringers within bands of sandstone or siltstone, although two of the seams are thick (up to metres) with relatively little intervening rock.

There is an aquifer (Springbok Sandstone) immediately, and unconformably, overlying the Walloon Coal Measures, and an aquitard (Eurombah Formation) immediately underlying. The unconformity between the Walloon Coal Measures and the Springbok Sandstone provides the potential for hydraulic connection with the sandstone aquifer in some locations. The finer-grained Upper Walloons interval between the Macalister coal seam and the Springbok Sandstone provides some hydraulic separation in the remaining areas.

To facilitate CSG extraction, the hydrostatic pressure in the coal seams must be reduced to approximately 50psi in the coal seams, which is achieved by extracting groundwater (associated water) via production wells. This represents a groundwater level of about 35 m above the top coal seam. Extracting the groundwater propagates a cone of depression which results in a decrease in hydrostatic pressures in the coal measures away from the gas fields in space and time. Such effects may also propagate vertically through the confining aquitard layers to overlying and underlying aquifers. This effect can potentially be exacerbated, both in terms of magnitude of effect and the speed at which it happens, by poorly constructed or compromised wellbores that penetrate the coal measures and other aquifer units.

The low resistance to weathering of the Walloon Coal Measures has resulted in its erosion, and up to 100m of Cainozoic-aged alluvial sediments have been deposited overtop by the Condamine River and its tributaries. In the area between Dalby and Chinchilla, where the Walloon Coal Measures subcrop and where this subcrop area is close to the CSG fields, groundwater from the Cainozoic Units is heavily utilised for irrigation. As the pressure reduction in the coal measures may propagate to the subcrop areas during CSG production, the increased vertical gradient between the coal measures and the alluvium may result in increased downward leakage of groundwater, further exacerbating the declining water levels in the Cainozoic Units and potentially decreasing groundwater availability to irrigators.

The majority of the bores, both in terms of extraction/allocation volumes and number of licenses, pump groundwater from the Cainozoic Units (inclusive of the Condamine River Alluvium, the alluvium of tributaries to the Condamine River, and the Main Range Volcanics). Most of these bores are located in and around the town of Dalby in the eastern part of the study area. The majority of groundwater use is

allocated for agricultural purposes (irrigation and stock intensive – 43%) followed by industrial water use (26%). Ten percent of the groundwater allocation is for town water supply. The amount of water used for stock and domestic purposes exceeds that of the licensed allocations.

These, and other, potential impacts of CSG development on the groundwater regime and connected entities will be assessed in Section 6.

6. Environmental impact assessment

6.1 Introduction

Various activities associated with Australia Pacific LNG's proposed operations have the potential to impact upon the groundwater system within the study area. On the basis of the conceptual hydrogeological model developed, and the initial numerical modelling completed to date, potential impacts on the groundwater system have been assessed with regards to the range of activities proposed for the Project.

For clarification, the activities associated with Australia Pacific LNG's operations that may have the potential to impact upon the local and regional-scale groundwater systems are evaluated below according to the following categories:

- CSG and associated water production; 'project case' and 'cumulative case' (Section 6.2)
- Associated CSG water management practices (Section 6.3)
- Construction and operation of CSG infrastructure and installation and abstraction from water supply bores in non-CSG production aquifers (Section 6.4)

Risks associated with the impact assessment have also been evaluated from a hydrogeological perspective, according to the risk evaluation framework approach described in Section 4.5. The evaluation of potential impacts and the accompanying risk assessment is documented below with respect to each of the proposed activities associated with the gas fields' element of the Australia Pacific LNG Project.

6.2 CSG and associated water production – Project and cumulative case

6.2.1 Numerical modelling approach

Introduction

The production of coal seam gas will require the reduction of hydrostatic pressure in the target coal seams of the Walloon Coal Measures. This depressurisation activity will occur at different times, at different places and at different rates of water withdrawal throughout the life of the Project.

In general terms, associated water production during CSG operation will influence the hydraulic equilibrium conditions of the target coal seams, artificially lowering the potentiometric surface of the water-bearing unit within the area of influence of CSG production. To address this more fully, a numerical, finite element groundwater flow model was constructed and calibrated for the purposes of projecting changes to the potentiometric surface in various intervals as a consequence of groundwater pumping for CSG production. Simulations have been conducted throughout the period of CSG development for the 'project case' and the 'cumulative case', and for a recovery period post-operation. A summary of the construction, calibration and operation of the numerical model is provided below.

Discussion of the initial groundwater model results, with reference to the projected hydrogeological implications of CSG development during the 'project case' and 'cumulative case', is provided in this chapter. The potential implications to regional-scale groundwater levels are presented in Section 6.2.2 for both the 'project case' and 'cumulative case'. The implications of associated water development to

groundwater storage and groundwater quality are also discussed in Section 6.2.3 and Section 6.2.4, respectively.

Outputs from the initial modelling exercise provide an opportunity to assess the potential impacts associated with proposed CSG production and associated groundwater level drawdown. The following potential impacts have been evaluated (as presented in Section 6.2.5) on the basis of the outcomes from the initial 'project case' and 'cumulative case' model:

- Potential impacts to landholder bore yields and water quality
- Potential impacts to groundwater – surface water interactions
- Potential impacts to springs and groundwater dependent ecosystems
- Potential for gas migration and associated risks
- Potential well bore pathways and associated risks
- Potential for gas seeps and associated risks
- Potential for aquifer compaction and land subsidence

Model development

The numerical computer code selected for model development was FEFLOW® (Finite Element subsurface FLOW) model version 5.4, developed by the WASY GmbH Institute for Water Resources Planning and Systems Research (Diersch 2005). The model domain was selected to address regional-scale three-dimensional groundwater flow conditions encompassing all known CSG tenements in the Jurassic-age coal measures. Numerical model construction was based on the conceptual hydrogeological model developed and described in Chapter 5.

The extent of the groundwater model domain is illustrated in Appendix A, Map 12. The Great Dividing Range forms the eastern and northern margins, with the exception of the Taroom region where the model incorporates the upper reaches of the Dawson River. The southern extent of the model domain corresponds to an approximate groundwater flow path coinciding with the Moonie River drainage system and the border between Queensland and New South Wales. The western boundary of the model domain generally coincides with the location of the Nebine Ridge, and likewise, corresponds to a north-south groundwater flow path that coincides with the Balonne River drainage system. The Precipice Sandstone is the lowermost aquifer in the Surat Basin and forms the base of drainage in the groundwater model.

The 11 principal hydrostratigraphic units (described in Section 5.4.1) were represented by 22 model layers comprised of finite element prisms (Table 6.1). The thickness of the hydrostratigraphic units are known to vary spatially across the model domain, based on top structure and isopach maps prepared as part of the conceptual model development. This variability has been incorporated into the model. The DEM used to define the top layer of the model was represented by part of a global 30 Arc-second elevation dataset acquired from the United States Geological Survey.

The 172740km^2 model domain was initially discretised with approximately 12km-sized triangular finite elements. The regional mesh was then refined to approximately 6km-sized elements within a 70km buffer around the CSG tenements (approximately corresponding to the anticipated extent of cumulative drawdown from CSG depressurisation). Three kilometre-sized elements were then applied to the CSG tenements themselves to provide the resolution needed to resolve more local effects.

Hydraulic parameters

Key hydraulic parameters requiring input to the each model layer include hydraulic conductivity, specific storage and specific yield. Whilst preliminary estimates of lateral hydraulic conductivity were adopted according to measured/converted and inferred values (Section 5.4.3), the final hydraulic conductivity values were generally derived during model calibration. One exception was the lateral hydraulic conductivity values for the Walloon coal seams represented by model layers 8, 12 and 16. The hydraulic conductivity values for these layers relied exclusively on drill stem test (DST) measurements of in-situ permeability.

Typical vertical to horizontal hydraulic conductivity (anisotropy) ratios for the geological units in the Surat Basin are likely to range from extremes of 1:10, for the least bedded or laminated rock-types (that is, massively bedded sandstones) to 1:1000 for the highly bedded and laminated rock-types (that is, mudstone and shale). Anisotropy ratios of 1:30 and 1:300 were adopted in the numerical model for the various aquifers and aquitards, respectively. The uniform specific storage value adopted in the model was based on a pumping test conducted in the Precipice aquifer, while a representative specific yield values was accessed from literature. Both parameters were not modified during model calibration due to their lack of sensitivity on calibration results.

The calibrated hydraulic properties adopted in the initial model are presented in Table 6.1.

Boundary conditions

Natural hydrogeologic boundaries were selected to define the edges of the model domain. A no-flow boundary condition was applied along most of the model domain perimeter in all model layers, with the exception of the Cainozoic Units at the downstream end of the Condamine and Moonie River drainage systems. The base of the model was represented by the underlying Moolayember Formation which was considered as a 'no flow boundary' given its fine-grained nature and resulting low permeability.

Groundwater recharge was applied at the top of the model domain (layer 1). Several detailed groundwater recharge studies have been undertaken in for the Great Artesian Basin intake beds and the Upper Condamine alluvium. These studies have indicated the following:

- Little or no groundwater recharge from precipitation to the alluvium deposits in the Upper Condamine area.
- Most of the Mooga Sandstone has estimated recharge rates less than 0.5 mm/yr, except between Wallumbilla and Roma where it is mostly in the range of 1mm/yr to 1.5 mm/yr, rising to 2.5mm/yr near Bungil Creek.
- Estimated recharge rates in the Gubberamunda Sandstone are between 1mm/yr and 2 mm/yr, with some localised areas up to 3mm/yr to 4 mm/yr.
- The majority of the Hutton Sandstone is indicated to have recharge rates of 2mm/yr to 4 mm/y, exceeding 10mm/yr in some places. The Hutton Sandstone generally displays a recharge gradient from 3mm/yr down-dip to 7mrn/yr up-dip.

The spatial distribution of groundwater recharge rates employed in the model is generally in good agreement with the findings from relevant studies.

The major surface water drainages – the Condamine, Moonie, Balonne and Dawson Rivers and their tributaries – were defined by applying FEFLOW mass-transfer boundaries. Such boundary conditions rely on the model to estimate exchange rates between the surface water and groundwater systems, according to a conductance term and the difference between calculated groundwater levels and user-

specified river or stream stage (that is, vertical gradient between the groundwater and the surface water).

Groundwater Use (Pumping)

Groundwater diversions from existing water bores were represented in the model. A total of 13213 water bores were identified for the study area, with 5253 of those bores associated with the Cainozoic Units (mainly the Upper Condamine areas) and the remainder with the Great Artesian Basin (BMO Grouping, Gubberamunda Sandstone, Springbok Sandstone, Walloon Coal Measures, Hutton Sandstone and Precipice Sandstone). The 13213 actual bores were aggregated to a total of 1509 pumping locations, accurately representing total groundwater diversion and spatial variability in water use in the Great Artesian Basin aquifers and Upper Condamine area.

Table 6.1 Hydrostratigraphic units and hydraulic properties represented in numerical model layers

Hydrostratigraphic unit	Classification	Model layer	Hydraulic Properties			
			Horizontal hydraulic conductivity (m/d)	Anisotropy (Kh/Kv)	Specific storage (1/m)	Specific yield
Cainozoic and Alluvium Units	Aquifer	1	0.22 (Cainozoic); 5.00 (Alluvium)	30	0.000004	0.03
Rolling Downs Group (RDG)	Aquitard	2	0.05	300	0.000004	0.03
Bungil/Mooga/Orallo (BMO)	Aquifer	3	0.12	30	0.000004	0.03
Gubberamunda Sandstone	Aquifer	4	0.31	30	0.000004	0.03
Westbourne Formation	Aquitard	5	0.0056	300	0.000004	0.03
Springbok Sandstone	Aquifer	6	0.28	30	0.000004	0.03
Walloon (Upper Unit)	Aquifer-Aquitard	7	0.00044	300	0.000004	N/A
Walloon (Macalister Coal Seam)	Aquifer	8	0.0025 (0.000024 to 0.54)	30	0.000004	N/A
Walloon (Macalister Mudstones)	Aquitard	9	0.00015	300	0.000004	N/A
Walloon (Upper Juandah Sandstones)	Aquifer	10	0.14	30	0.000004	N/A
Walloon (Lower Juandah Mudstones)	Aquitard	11	0.00015	300	0.000004	N/A
Walloon (Lower Juandah Coal Seam)	Aquifer	12	0.0064 (0.000015 to 0.43)	30	0.000004	N/A

Hydrostratigraphic unit	Classification	Model layer	Hydraulic Properties			
			Horizontal hydraulic conductivity (m/d)	Anisotropy (Kh/Kv)	Specific storage (1/m)	Specific yield
Walloon (Lower Juandah Mudstones)	Aquitard	13	0.00015	300	0.000004	N/A
Walloon (Tangalooma Sandstones)	Aquifer	14	0.14	30	0.000004	N/A
Walloon (Taroom Mudstones)	Aquitard	15	0.00015	300	0.000004	N/A
Walloon (Taroom Coal Seam)	Aquifer	16	0.0074 (0.0000019 to 4.0)	30	0.000004	N/A
Walloon (Taroom Mudstones)	Aquitard	17	0.00015	300	0.000004	N/A
Eurombah Formation	Aquitard	18	0.00062	300	0.000004	N/A
Upper Hutton Sandstone	Aquifer	19	2.4	30	0.000004	N/A
Lower Hutton Sandstone	Aquifer	20	0.12	30	0.000004	N/A
Evergreen Formation	Aquitard	21	0.00065	300	0.000004	N/A
Precipice Sandstone	Aquifer	22	3.1	30	0.000004	N/A
Moolayember Formation	Aquitard	Model Base	0.0025	300	0.000004	N/A

Model calibration and sensitivity analyses

The groundwater model was initially calibrated to pre-development (steady-state) conditions using measured water levels obtained from regional bores. The calibration to pre-development conditions utilised the following datasets:

- Static groundwater levels for 893 DERM monitoring bores
- Static water levels at 134 locations in the Walloon Coal Measures, as provided by Origin Energy
- Estimated stream loss contribution to overall groundwater recharge for the Upper Condamine system
- Estimated recharge rates for Great Artesian Basin aquifers.

In addition to this steady-state calibration, transient model runs were conducted to calibrate the model to CSG water production forecasts provided by Origin Energy.

The overall calibration statistics for the static water level data reflect a good steady-state calibration, returning a model error of 6%. The model was also able to reasonably capture estimated stream losses (leakage) to groundwater in the Upper Condamine area.

A comparison of model simulated associated water production rates and the Origin Energy water production forecast indicates reasonable correspondence from project commencement (2009) until 2025. Beyond this initial period, the two independent water production forecasts deviate. The general trend in CSG well production profiles is for a gradual decline in water production beyond 2025 as gas production increases. The FEFLOW predicted water forecast continues to rise until 2030-2035 before declining. Some of this discrepancy appears to be related to the reservoir engineering assumption on hydraulic isolation of coal seams (i.e. no groundwater inflows from surrounding formations to the coal seams during depressurisation is assumed), which is not fully supported by the FEFLOW analysis. Alternatively, FEFLOW may not be able to fully capture the decline in water production associated with gas flow (i.e. dual phase flow), although this process was replicated conceptually by reducing coal seam permeability by a factor 100 during depressurisation.

To characterise uncertainty in the groundwater flow model predictions, sensitivity analysis was performed to assess potential lower and upper limits to simulated drawdown effects from CSG production. Minimum and maximum hydraulic conductivity values (lateral and vertical), recharge rates and stream conductance were derived by dividing and multiplying calibrated values by a factor of four.

Simulation of groundwater depressurisation

Two sets of model simulations were conducted as part of the current study:

- ‘Project case’ – evaluation of the proposed Australia Pacific LNG CSG development alone
- ‘Cumulative case’ – hypothetical evaluation of the proposed Australia Pacific LNG CSG development plus other CSG developments including those by Arrow Energy, Queensland Gas Company and Santos.

Each of these cases was simulated with the calibrated model, and with the lower and upper limit models, for a total of six simulations.

With reference to the ‘project case’ model simulation, groundwater level drawdown associated with groundwater extraction during CSG production was modelled by imposing a declining constant head boundary condition in the three individual coal seams represented by layers 8, 12 and 16 in the

groundwater model. Broadly, the decline in coal seam hydraulic head pressure over time, together with the total duration of depressurisation and gas production, is primarily dependent upon the permeability and depth of the coal seams and its initial hydraulic head. To capture variations in these factors across Australia Pacific LNG's development areas, 'depressurisation type curves' were generated according to the Theis solution (Theis 1935), with a final target pressure for the top of the coal reservoir of 50psi, corresponding to a fluid level of approximately 35m. These type curves, in combination with the proposed Australia Pacific LNG development schedule and the elevation data for the top of Macalister Coal Seam (that is, assumed top of coal reservoir), were employed to project the spatial and temporal variations in hydraulic heads of the coal seam units (at five-year intervals).

The 'project case' model simulations were operated at one-year time steps for each five-year interval commencing in 2009 and extending until 2069, with final simulated heads for the end of each five-year interval constituting the initial heads for the next. Recovery of the groundwater system following the end of CSG development in 2069 was simulated at ten-year time steps for a 1000 year period (that is, until 3069).

With reference to the 'cumulative case' model simulations, a conservative approach to modelling groundwater level drawdown associated with other operators was adopted on the basis of publically available information. A key assumption adopted was that depressurisation to 50psi occurred over a 15-year timeframe, with a total depressurisation duration of 25 years. Furthermore, as publically available information concerning the development sequencing of other CSG operators is currently lacking, a second key assumption adopted was that timing of CSG development generally coincided with that of Australia Pacific LNG (i.e., from 2009 to 2069, with peak development occurring around 2030 to 2040). This assumption concerning development sequencing is quite conservative in that a relatively high level of groundwater drawdown interaction and amplification by different operators is simulated. The 'cumulative case' simulations started in 2005, to enable representation of CSG activities that have occurred in the Surat Basin to date.

Model limitations

The initial groundwater flow model developed in support of this EIS is subject to the following key limitations:

- Dual phase (gas and water) flow and the resulting effect on effective hydraulic conductivity of the coal seams in the vicinity of the depressurisation centres (well fields) was only conceptually accounted for in the initial numerical model
- The model construction was based on available geologic and hydrogeologic data and existing literature, and may only reflect a partial understanding of the complex hydrogeology of the Surat Basin, particularly along the axis of the Taroom Trough/Mimosa Syncline where stratigraphic data is sparse
- The model provides a simplified representation of actual conditions, with average (bulk) hydraulic parameters assumed for most aquifers and aquitards
- The steady-state model calibration was largely based on static water level data, the quality of which is only moderate
- Lack of information on appropriate specific storage values for the Surat Basin aquitards is a key uncertainty in projections regarding magnitude and timing of groundwater level drawdown in overlying and underlying aquifers

- The constant head boundary approach to representing coal seam depressurisation represents a simplification of actual CSG operations in which pumping wells are employed to lower reservoir pressure
- Groundwater level drawdown predictions do not include the potential for hydraulic connectivity between aquifers due to fractures or other structural lineaments or any effect from poorly constructed well bores
- The model simulations do not consider any upward propagation of depressurisation from Permian-age coal deposits in the Bowen Basin
- Groundwater levels in the Great Artesian Basin aquifers and Upper Condamine alluvium were assumed to be in equilibrium with respect to current pumping from existing water users other than CSG operations (for example, town wells, domestic water use, agricultural water use). That is, existing water use was incorporated in the steady-state model calibration based on measured static water levels. While this assumption may be reasonable for most portions of the Surat Basin, it is known to be invalid for the Upper Condamine area where the groundwater resource is being actively mined.

6.2.2 Potential groundwater level drawdown

Groundwater level drawdown projections, as a consequence of associated water production during the Australia Pacific LNG operation, and all proposed CSG operators in the Surat Basin, are summarised below on the basis of the initial numerical modelling conducted for the ‘project case’ and ‘cumulative case’, respectively.

It is important to recognise that the projections for the ‘project case’ represent an over-estimate of Australia Pacific LNG’s contribution to the regional groundwater level drawdown in all aquifers. Specifically, the ‘project case’ model assumes that Australia Pacific LNG alone will produce groundwater at a rate required to achieve CSG depressurisation in the region. The water production rate associated with the Australia Pacific LNG project will in fact be an over-estimate as it does not allow for the associated water production and accompanying regional groundwater level drawdown that will be caused by other CSG operators, in neighbouring fields, as they commence CSG production.

Project case

The projected (best estimate) groundwater level response of associated water production from the Project’s gas fields (the ‘project case’) is presented in Appendix A. A description of the projected effects are provided in the proceeding sections.

The maps illustrate areas of drawdown greater than 5m in each hydrostratigraphic unit at model year 2049 for the Project’s gas fields development. Model year 2049 was chosen to illustrate projected drawdown as it generally represents the time of maximum magnitude of drawdown in the various aquifer units.

As documented in accompanying explanatory notes (Chapter 4) of Great Artesian Basin Resource Operation Plan (2007), a 5m groundwater dra

zwdown has been adopted for an evaluation criterion for the protection of existing groundwater entitlements. The same criterion has been applied in this impact assessment to evaluate potential effects to existing registered water bores.

Walloon Coal Measures

Broadly, the evolution of the modelled groundwater level drawdown in the coal seam units over the operational period corresponds to Australia Pacific LNG's proposed CSG development sequencing schedule. As associated water production in the three target coal seams is represented in the numerical model by a progressive lowering of the pressure heads to 35m above the Macalister Coal Seam, the groundwater level drawdown projections generally demonstrate a level of consistency with the elevation of this unit. For instance, the greatest groundwater level drawdown projection in the Taroom Coal Seam unit is projected to occur in the Carinya development area where the unit occurs at its lowest elevation (between -600m and -700m AHD) across the Australia Pacific LNG production area. In contrast, the Taroom Coal Seam unit is comparatively shallower in the Talinga and Orana North development areas (between 0m and 300m AHD). Within this development area, the groundwater level drawdown is projected to be substantially less.

During Australia Pacific LNG's operational period, the radial extent of the groundwater level drawdown in the coal seam units is projected to be limited to the development area and nearby surrounding areas, within 50km of the development area boundaries. Post-production, during the groundwater level recovery phase, the radial extent of the groundwater level drawdown is projected to broaden to less than 100km beyond the development area boundaries.

Underlying and overlying aquifers

As discussed in Section 5.4.5, under equilibrium conditions, groundwater flow is sub-horizontal, with limited flow occurring in the vertical direction. Specifically, groundwater flow is largely restricted by the natural alignment of the sedimentary particles parallel to the bedding plane, as is reflected in the high $K_{horizontal}$ to $K_{vertical}$ ratio assigned to the sedimentary units in the numerical model.

However, significant inter-aquifer flow may occur locally in areas of direct aquifer connectivity; for instance, in locations where intervening aquitards thin (particularly, around the margins of the basin) or as a consequence of structural controls (that is, in fault or fold zones where vertical dislocations promote vertical or sub-vertical hydraulic conduits). There is currently insufficient regional scale potentiometric data to evaluate vertical hydraulic gradients and the associated potential for cross-formational groundwater movement within the model domain.

In any case, lowering the potentiometric surface in the coal seams of the Walloon Coal Measures during CSG associated water production will alter the existing vertical gradients and create a pressure differential between the coal seams and overlying and underlying units. The pressure differential has the potential to transmit groundwater vertically from overlying and underlying aquifers towards the coal seams through intervening units (aquitards) or along open pathways. The magnitude of the groundwater transfer is governed by the pressure differential between the units and the ability of the intervening layer to transmit the groundwater vertically; a function of the unit's vertical hydraulic conductivity and thickness. The nature of the aquitards is such that time delays are commonly observed between the commencement of associated water production and the onset of groundwater level changes in overlying or underlying aquifers.

The projected groundwater level drawdown in response to the Australia Pacific LNG Project is summarised below, with regards to the following five major aquifer systems above and below the Walloon Coal Measures: overlying Springbok Sandstone, BMO Grouping/Gubberamunda Sandstone, Watertable interval, and underlying Hutton Sandstone and Precipice Sandstone.

Initial model results project that the Springbok Sandstone aquifer will likely experience the highest magnitude of groundwater level drawdown, outside the Walloon Coal Measures. On average, the

groundwater level drawdown is generally projected to be less than 15m across the development areas and their proximities. Localised areas, concentrated in the Gilbert Gully, Ramyard, Carinya, Condabri South and Condabri South and Condabri Central development areas, are projected to experience greater drawdowns due to the following key factors:

- The comparatively deep coal seam elevations in these areas and requirement for substantial groundwater drawdown to achieve CSG production
- The inferred consistent thinning of the underlying aquitard (Upper Walloons unit) separating the Springbok Sandstone aquifer and the upper CSG target; the Macalister Coal Seam.

The BMO Grouping and Gubberamunda Sandstone are projected to experience comparatively less drawdown (less than 3m on average), but in a localised areas may approach between 5m and 8m. This localised effect, which is projected to occur in the Carinya development area and areas to the south, generally corresponds to the comparatively larger drawdown projected in the deeper Springbok Sandstone aquifer.

Similarly, the watertable interval is projected to experience a comparatively low magnitude of groundwater drawdown, generally less than 2m. According to the initial numerical model results, very isolated groundwater drawdowns between 5m and 7m are projected east of Condabri Central and in Condabri South. These isolated areas correspond to the groundwater level drawdown in the deeper Gubberamunda Sandstone aquifer, and are representative of a localised area where the Rolling Downs Group aquitard (separating the Cainozoic Units and the underlying Gubberamunda Sandstone) is believed to be thin or possibly absent.

During associated water production, the radial extent of the groundwater level drawdown within these overlying aquifers is projected to remain within close proximity to the development area boundaries. Post-production, during the groundwater level recovery phase, the radial extent of the groundwater level drawdown is projected to expand.

Beneath the Walloons Coal Measures, and the intervening low permeability Eurombah Formation, the Hutton Sandstone is projected to experience very limited groundwater level drawdown of less than 2m, on average. During the associated production, the radial extent of the groundwater level drawdown in this aquifer is projected to remain in close proximity to the development areas. Post-production, during the groundwater level recovery phase, the radial extent of the groundwater level drawdown is projected to broaden beyond the development area boundaries.

Negligible upwards leakage of groundwater from the Precipice Sandstone aquifer, and hence drawdown of groundwater levels, is anticipated due to the limited magnitude of drawdown in the Hutton Sandstone and presence of the intervening the Evergreen Formation aquitard.

Cumulative case

In general, the extent of the groundwater level drawdown in the Walloon Coal Measures and overlying and underlying units projected in the 'cumulative case' simulations (relative to the 'project case') is expected to expand due to the greater volume of associated water production by all CSG operators. The projected magnitude of the groundwater drawdown in each unit is, however, generally anticipated to be of the same order as that for the 'project case'.

Walloon Coal Measures

The groundwater level drawdown projections generally demonstrate consistency with the elevation of the Walloons Coal Measures and are most significant in areas where the unit occurs at its lowest elevation, such as 50km west of Gilbert Gully (North), 10km west of Condabri South and 10km, 40km

and 100km south-west of the Carinya development area. These are the areas where considerable groundwater level drawdown is required to achieve CSG production.

During the CSG operational period, the projected radial extent of groundwater level drawdown in the coal seam units is projected to be limited to the cumulative development areas and nearby proximities, within 50km of the development area boundaries. Post-production, during the groundwater level recovery phase, the projected radial extent of the drawdown broadens to less than 100km beyond the cumulative development area boundaries.

Underlying and overlying aquifers

The Springbok Sandstone is projected to experience the highest groundwater level drawdown outside the Walloon Coal Measures. On average, the groundwater level drawdown is projected to be approximately 15m across the cumulative CSG development areas and their proximities. Localised areas of greater drawdown are projected, being generally concentrated in areas where both the coal seam elevations are comparatively deep and the Upper Walloons unit aquitard (separating the Springbok Sandstone and target coal seams) is inferred to be thin. These localised areas of elevated drawdown are projected to occur in the proximity of the Gilbert Gully, Ramyard, Carinya, Condabri South and Condabri Central development areas, between the Gilbert Gully and Kainama development areas and 100km southwest of the Pine Hills development area.

The BMO Grouping and Gubberamunda Sandstone are projected to experience comparatively less drawdown (less than 3m on average) but in localised areas may approach 10m. These localised drawdown effects generally correspond to larger drawdown in the Springbok Sandstone aquifer, and in some instances occur in areas where the intervening aquitard (i.e. Westbourne Formation) is inferred to thin. These localised areas of elevated drawdown are generally projected to occur in the Carinya development area and areas to the south, 100km southwest of the Pine Hills development area and north and northwest of the Gilbert Gully development area.

Similarly, the watertable interval is projected to experience a comparatively low magnitude of groundwater level drawdown, generally less than 2m. According to the initial numerical model results, localised areas of the watertable interval are projected to experience greater drawdown generally concentrated in the following areas:

- East of Condabri Central and in Condabri South
- North and northwest of the Gilbert Gully development area.

These isolated areas correspond to a projected groundwater level drawdown in the deeper Gubberamunda Sandstone aquifer, and are representative of localised zones where the Rolling Downs Group aquitard (separating the Cainozoic Units and the underlying Gubberamunda Sandstone) is inferred to be thin or possibly absent.

During associated water production, the radial extent of the groundwater level drawdown within these overlying aquifers is projected to remain within close proximity to the cumulative development area boundaries. Post-production, during the groundwater level recovery phase, the radial extent of the groundwater level drawdown is projected to expand.

The Hutton Sandstone is projected to experience groundwater level drawdown, particularly in areas where both the coal seam elevations are comparatively deep and the overlying aquitards (i.e. Taroom mudstones and Eurombah Formation) are believed to be thin. Groundwater level drawdowns are generally expected to be less than 10m.

Minimal upwards leakage of groundwater from the Precipice Sandstone aquifer is anticipated due to the presence of the intervening Hutton Sandstone aquifer and confining properties of the Evergreen Formation aquitard. Areas at higher risk of drawdown correspond to those regions with concentrated depressurisation in the overlying Hutton Sandstone and/or thinning of the overlying Evergreen Formation aquitard.

During CSG production, the radial extent of the groundwater level drawdown within the Hutton Sandstone and Precipice Sandstone aquifers is projected to be concentrated around the development areas. Post-production, during the groundwater level recovery phase, the radial extent of the groundwater level drawdown is projected to broaden beyond the cumulative development area boundaries

6.2.3 Potential implications for groundwater storage

Associated water production from the Project's gas fields (the 'project case') and all other existing and proposed CSG developments in the Surat Basin (the 'cumulative case'), will be represented primarily as a change in groundwater storage within the Walloon Coal Measures. Initial projections of the numerical groundwater model (as described in Section 6.2.2) indicate that a level of inter-aquifer leakage may occur as a consequence of the pressure differential created between the coal seams and the overlying and underlying units. Hence, while associated water production will primarily affect groundwater storage in the Walloon Coal Measures, the potential for inter-aquifer leakage is such that a small proportion of change to basin groundwater storage may occur in overlying and underlying aquifers. The intervening aquitard layers separating the coal measures and major aquifer formations and the dominant sub-horizontal nature of groundwater flow in the basin will ultimately restrict the potential for inter-aquifer leakage, and subsequently limit the extent to which groundwater storage in these major aquifer units may be affected.

6.2.4 Potential groundwater quality changes

Production of CSG and groundwater from the coal seams, in both the 'project case' and 'cumulative case', whilst potentially affecting groundwater levels and storages in underlying and overlying aquifers, is not expected to have a detrimental effect on groundwater quality in these units. As discussed in Section 6.2.2, the pressure differential created by associated water production from the Walloons Coal Measures has the potential to transmit groundwater vertically from overlying and underlying aquifers towards the coal seams through intervening aquitards. That is, all transfers of groundwater will occur from adjacent aquifers towards the coal seams. While the poorer quality groundwater in the Walloon Coal Measures is extracted during the CSG process, this water will not transmit to adjacent aquifers containing higher quality groundwater.

Furthermore, as groundwater quality in non-coal bearing aquifers is largely comparable (Section 5.4.6), any groundwater transfers induced by CSG production from one comparatively fresh unit to another is unlikely to compromise the regional quality of groundwater in Great Artesian Basin aquifers.

In conclusion, no significant regional-scale changes to groundwater quality in the Walloon Coal Measures or adjacent aquifers are expected to occur as a consequence of associated water production, either in the 'project case' or 'cumulative case'.

6.2.5 Potential impacts of CSG associated water production

Existing water bores

Depressurisation associated with CSG production will potentially affect water levels in existing bores licensed under the *Water Act (2000)*, and other stock and domestic bores which are not specifically licensed. These potential reductions in water levels may reduce the availability of water in those bores.

Initial groundwater modelling of the 'project case' projects that a number of bores in the BMO Grouping, Gubberamunda Sandstone and Springbok Sandstone aquifers may incur greater than 5m drawdown as a consequence of associated water production from the Project's gas fields. Those bores extracting water from the Walloon Coal Measures (licenced and stock and domestic), particularly those immediately to the east of the Orana development area and south-east of the Gilbert Gully development area (where the coal measures are at shallow depths), have the greatest potential to be affected. The bores accessing groundwater from the Hutton Sandstone and Precipice Sandstone aquifers are not expected to experience drawdowns greater than 5m as a consequence of associated water production from the Project's gas fields.

With respect to the initial 'cumulative case' model projections, a larger number of water bores may potentially be affected due to the comparatively larger drawdown footprint associated with cumulative development in the region. It is possible that drawdown impacts may affect bores in the Cainozoic Units, particularly in the high usage area between Dalby and Millmerran. The Condamine River Alluvial aquifer beneath this area is currently under heavy use in support of irrigation activities, which has reduced groundwater levels substantially in some of the Cainozoic aquifers. It is anticipated that the groundwater level drawdown associated with CSG activities will be significantly less than currently observed drawdowns in water supply bores accessing the Condamine Alluvium.

Streamflow

Groundwater and surface water connectivity relationships within the study area are summarised in Section 5.4.8. The discussion below is structured according to the potential implications for groundwater – surface interaction with reference to those aquifer systems that potentially supply baseflow to surface water systems.

In general, the major river systems of the Condamine-Balonne River Catchment are variably connected with the underlying Cainozoic Units. Levels of groundwater–surface water interaction are largely controlled by climatic (rainfall) conditions, surface water storages and the magnitude of groundwater extraction from the alluvial system. The tributaries of the catchment system in and around the study area are ephemeral and may receive limited baseflow from the adjacent alluvial sediments for short durations following rainfall events.

As described in Section 6.2.2, according to the initial 'project case' numerical model projections, the potential effects of the Project's CSG development on watertable intervals are indicated to be limited in extent. A number of these localised, shallow drawdown areas may have the potential to intersect major river systems of the Condamine-Balonne River Catchment. In particular, within and around Australia Pacific LNG's eastern and southern development areas, initial model projections indicate drawdown in the watertable aquifer (during and post-operation) in close proximity to the Condamine River, immediately downstream of the Condamine Weir. Such an affect to the watertable aquifer may have the potential to alter the groundwater – surface water interaction relationship of the Condamine River in this localised area. Operation of the weir itself is, however, likely to override any potential changes to the groundwater – surface water relationship in these localised areas.

Additional localised occurrences of drawdown in the watertable aquifer upstream of the Chinchilla Weir are projected in the initial 'cumulative case' model. Such drawdowns may alter the groundwater – surface water interaction rates between the Condamine River and underlying aquifers in these localised areas; however, on the basis of the limited extent of the projected drawdown such affects are expected to be minimal.

The initial 'project case' and 'cumulative case' numerical models project a minor effect to the Cainozoic Units aquifers in other localised regions across the study area. These localised areas largely occur in proximity to ephemeral streams and creeks, which only receive limited baseflow following rainfall events. Shallow groundwater level drawdown in these localised areas is not expected to have a significant effect to the limited baseflow occurring in these ephemeral systems.

There are various river reaches in the study area that potentially receive baseflow from the outcropping aquifer systems of the Great Artesian Basin. On the basis of the initial 'project case' and 'cumulative case' numerical model projections, there is considered to be a low potential that these river reaches will be affected.

Springs and groundwater dependent ecosystems

A description of the major recharge and discharge spring complexes and groundwater dependant ecosystems within the study area is presented in Section 5.4.9. Of particular relevance to the hydrogeological impact assessment are discharge spring complexes (and their dependent ecosystems) that have the potential to be affected by reduced groundwater flow as a consequence of local or regional scale drawdown.

During the CSG production phase, the drawdown in groundwater levels in the Great Artesian Basin aquifers, as a consequence of associated water production in the Walloon Coal Measures, is expected to be limited in extent to areas within, or just beyond, the boundaries of the proposed CSG operations. According to the DERM wetlands mapping database (Appendix A, Map 9) and other sources of publically available information (that is, Queensland Department of Natural Resources 2005), no "discharge" spring complexes are documented to occur in close proximity to the proposed CSG field development areas (pers. comm. R. Fensham, 18 February 2010). Therefore, these features are not expected to be at risk of groundwater level drawdown or reduced groundwater flow.

For a period of time post-operation, during the groundwater level recovery phase, the groundwater level drawdown cones in the affected Great Artesian Basin aquifers, whilst reducing in magnitude, are projected to broaden beyond the boundaries of the CSG development areas. According to the initial 'project case' and 'cumulative case' numerical model projections, associated water production may potentially have the following implications to spring complexes (and their dependent ecosystems) post-operation:

- With reference to the high-value spring complexes and their associated ecosystems that occur east of the town of Injune (in association with the outcrop areas of the Hutton Sandstone unit), there is a low risk that groundwater levels (and potentially the rate of vertical groundwater flows) will be affected by the Australia Pacific LNG operations.
- The high-value spring complexes and their associated ecosystems that occur near the town of Taroom (being supplied by artesian water from the Precipice Sandstone unit) are not expected to be at risk of reduced groundwater levels or vertical flows as a consequence of Australia Pacific LNG operations.

- The spring complexes that occur 25km north and northeast of the Roma, in outcropping areas of Gubberamunda Sandstone unit are not expected to be affected by any reduced groundwater levels that may occur in this area
- Various spring complexes may exist approximately 100km west of Roma. These spring complexes are recharge springs (pers. comm. R. Fensham, 18 February 2010) and are therefore not expected to be affected by any reduced groundwater levels that may occur in this area.

The initial 'project case' and 'cumulative case' numerical model projections (presented in Section 6.2.2) also indicate that groundwater levels within the shallow Cainozoic Units may potentially be affected, in localised areas, by associated water production activities during CSG development. As the level of groundwater dependency by ecosystems in these areas is likely to be low (Section 5.4.9), there is considered to be a very low risk that species (partially or opportunistically) dependent upon groundwater in the shallow watertable aquifers associated with drainage lines may be affected.

Gas migration

Although potential risks associated with gas migration and the Australia Pacific LNG project are considered to be low, it is an issue that has been observed internationally in other CSG developments and warrants further discussion.

Gases, including methane, may be present in the subsurface as a combination of one or more of the following phases:

- Adsorbed to the matrix material
- Dissolved phase *or*
- Free phase gas.

The gas phase is directly related to pressure and temperature conditions in the subsurface. Salinity of the groundwater and the presence of other gases (for example, carbon dioxide) also influence relative solubilities and saturation states. In undisturbed coal seams, the methane is predominantly in the adsorbed phase. Depressurisation of coal seams by pumping groundwater and reducing the hydraulic head allows the gas adsorbed to the coal cleats to desorb and migrate to the production well for extraction both in the dissolved phase and as free gas. CSG development in the United States of America demonstrated that gas migration from the onset of commercial extraction can be nearly instantaneous (Alberta Environment, 2009).

The primary driving forces of a free gas are pressure and buoyancy. That is, gas will move from zones of higher pressure to lower pressure and will tend to rise in water due to buoyancy. The greatest volume of movement (of gas or water) will occur along the pressure gradient though the pathway with the highest conductivity and cross sectional area (Darcy's Law). Thus, the majority of free and dissolved gas in the zone affected by depressurisation (the cone of depression) will move towards the production wells. However, at some distance from the edge of the gas field, where the effects of depressurisation are less, the force of buoyancy will overcome that of the pressure gradient. Because of the dip on the formations, the gas will tend to move away from the gas field, and in the up-dip direction. These gases might eventually make their way to shallower intervals and potentially discharge to the surface, either through wellbores or via natural geological pathways to surface seeps. Gas may also accumulate in overlying aquifers where there is an established pathway between the coal seams and the overlying aquifer. This has been identified in the Springbok Sandstone, where due to the unconformity between the coal measures and the Springbok Sandstone, the aquifer has

become gas-charged (Scott, et al. 2007). A schematic diagram of these concepts is provided as Figure 6.1.

Sampling and analysis for dissolved methane was completed during the Phase 1 groundwater monitoring program in June 2009. The results indicated the presence of methane in the Gubberamunda Sandstone at concentrations similar to those in the Walloon Coal Measures. Although the source of the methane in the Gubberamunda Sandstone is currently unknown (that is, local biogenesis or thermogenic), it highlights that there is methane in overlying aquifers. Methane concentrations in the monitoring wells screened in the Cainozoic Units were reported at, or below, method detection limits.

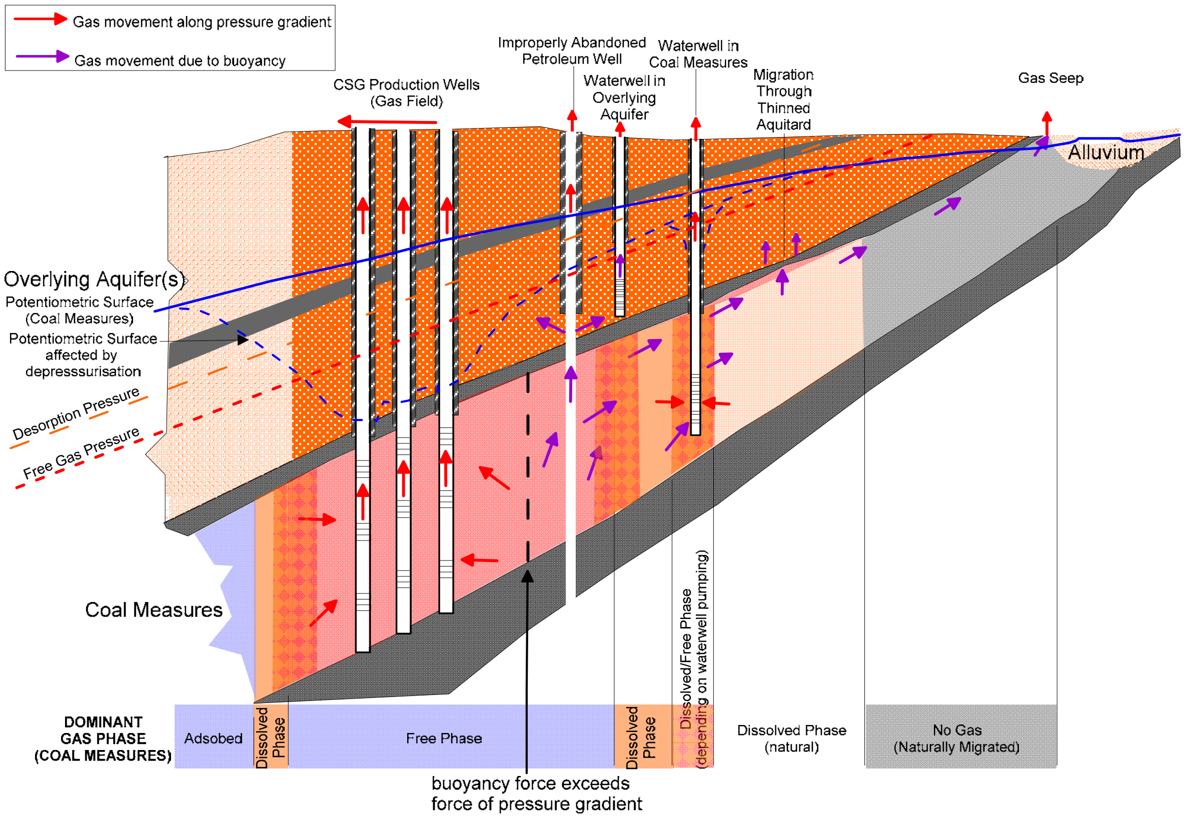


Figure 6.1 Conceptual diagram of gas migration

Gas migration through wellbore pathways

Chafin (1994) identified three main pathways for the migration of gas from deep reservoirs to near-surface environments. These were:

- Through rock pore spaces via diffusion
- Through natural fractures
- Through man-made conduits.

In the United States of America, man-made conduits were found to be the primary source of gas migration to the shallow-subsurface (Chafin 1994). This includes poorly constructed or wells, as well as other inappropriately abandoned or constructed petroleum or water bores.

Although CSG production and exploration wells, by their sheer number, constitute a high potential risk, this is recognised and is mitigated in Australia Pacific LNG's drilling program and wellbore design, as

discussed specifically in Section 6.4. The greatest risk is likely to be associated with existing and poorly constructed or abandoned petroleum wells and water bores. Several potential scenarios of wellbores providing preferential pathways for groundwater movement are shown schematically on Figure 6.1.

Existing water bores and abandoned wells (including petroleum wells) in the CSG gas fields and surrounding areas may act as preferential pathways for gas to migrate from the coal measures to the surface, either directly or via overlying aquifers. When the cone of depression reaches a well without a fully cemented annulus, the annulus could provide a conduit for the upward flow of desorbed gas. Such an example was observed during the Phase 1 monitoring program, where continuous gas bubbling was observed in an old petroleum exploration well (see Appendix B).

Pumped water bores pose a greater potential risk as the pressure reduction in the well during pumping may result in dissolved-phase gas transitioning to the free gas phase. Pumping may also draw free and dissolved gas towards the wellbore, thereby increasing gas concentrations and volumes in the local porewater. The headworks of CSG production wells are designed to accommodate free-phase gas safely; however, water bores generally do not. The build-up of gas in the bore column, a pump shed, or possibly an occupied building constitutes a potential health risk (asphyxiation) and safety risk (explosion). Methane is lighter than air so should it displace sufficient oxygen it may become an asphyxiant. Where methane concentrations range between 5% and 15% by volume of air, it may become explosive (Alberta Environment, 2009). High enough gas volumes in pumped water bores may also result in pump cavitation and damage (Fisher 2001). It should be noted that not only water bores accessing the Walloon Coal Measures pose a risk, Bores accessing overlying aquifers with sufficient gas concentrations do as well.

Viellenave et al. (2002) indicated that between and 10% and 55% of all domestic water wells in the Raton Basin and the Colorado portion of the San Juan Basin in the USA contained dissolved methane indicating a high risk of finding methane in non-CSG production wells in a gas field. Further investigation found that the methane in the San Juan Basin was of biogenic origin and not due to CSG development. These findings are similar to those of the Phase 1 field program mentioned above. Viellenave et al. (2002) suggested that understanding the origin of the gas (that is, biogenic or thermogenic) was the key to mitigating the risk associated with potential harm and litigation.

Poorly constructed or failed wellbores intersecting multiple aquifers have the potential to act as pathways for preferential flow of groundwater between aquifers by creating an artificial connection that bypasses intervening aquitard(s). The risk increases both with the depth of the wellbore, because it would intersect more aquifers, and with the age of the bore, due to the limited life-span of the materials which ultimately end in casing or annulus failure. Depending on the pressure differentials between the aquifers, an incorrectly constructed or failed well bore may provide a conduit for groundwater movement without pumping; however, the effects will be exacerbated with pumping (although the direction of movement may be changed due to an associated change in relative pressures).

A compromised wellbore does not necessarily need to intersect the Walloon Coal Measures to transmit pressure effects between aquifers if those effects are already transmitted to the aquifer in which the bore is constructed. For example, assume the deepest unit in which a water well is constructed is the Springbok Sandstone, and that this unit is affected by CSG extraction. If the wellbore provides a pathway between the Springbok Sandstone and the Cainozoic Units, say via a casing failure or open annulus, the pressure effects in the Springbok Sandstone will be transmitted to that shallower interval. Not only do compromised wellbores provide a pathway for the transmittal of

pressure effects, they also provide a potential pathway for the movement of gas from the Walloon Coal Measures to the surface. This is discussed further in Section 6.2.5.

It is noted that although a cement seal may be inserted in the annulus of well bore, it is possible for micro-channels to form in the cement, resulting in a poor bonding between the formation or casing. Micro-fractures may also develop in the formation immediately surrounding the borehole as a result of the drilling process, thereby providing potential pathways for gas migration (Alberta Environment, 2009).

Although there are approximately 2100 water bores in the Walloon Coal Measures, they are mostly located where the unit is shallow and distal to the Australia Pacific LNG tenements. The overall risk is predominantly limited to those water bores that are completed within the Walloons beneath the development areas.

Gas seeps

With the dipping geological beds and associated potential for up-dip migration of free-phase gas, a potential risk exists for gas migration from the Walloon Coal Measures as a result of Australia Pacific LNG activities.

Coal bed gas development commenced in the USA in the late 1970s in the San Juan Basin. Complaints arose shortly after development when gas bubbling was observed along the Animas River bank, where patches of crops died and gas caused pumps to cavitate in some wells. This led to ground-breaking studies into gas seepage (Fisher 1994); however, no study of this phenomenon has been undertaken in Queensland.

Gas migration, seepage and venting are natural phenomena where coal beds are close to the surface. All seeps vary in spatial and temporal expression depending on a wide range of natural environmental factors (for example, barometric pressure and decreased recharge due to drought - Viellenave et al. 2002). It is recognised that the geological setting of CSG development in the USA differs from that in the Surat Basin in that the USA developments tend to be shallower and located closer to higher density population centres.

Natural seeps were identified in the San Juan, Powder River, Black Warrior and Washakie Basins in the USA prior to the development of CSG extraction (Alberta Environment 2009). In the San Juan Basin, a large number of inconclusive investigations have been undertaken to determine whether CSG production has resulted in increased seepage rates. Investigations completed, as a result of litigation, in the Rawhide Village in the Powder River Basin found the gas seeps pre-dated local coal mining and CSG development (Viellenave et al. 2002).

Aquifer compression and potential land subsidence

The release of groundwater from storage in confined aquifers results in a level of compression of the aquifer skeleton. Compression of the aquifer skeleton can cause subsidence at the ground surface if the overlying rock material is not sufficiently competent to resist such movement. Differential land subsidence has the potential to compromise the geotechnical integrity of surface infrastructure and, in severe cases, can interfere with surface drainage patterns.

It is emphasised, however, that the risk of compression is overwhelmingly influenced by the type of aquifer (and its compressibility) and the magnitude of the pressure reduction, rather than the volume of groundwater removed. For instance, while subsidence due to groundwater extraction and pressure reduction can transpire, its occurrence is dominant in heavily-exploited unconsolidated aquifer systems comprising interbedded clay, sands and gravels. In these aquifers, much of the sedimentary

sequence consists of highly compressible clays which, when drained, contribute to the majority of compaction (Freeze and Cherry 1979).

In contrast, groundwater in the Great Artesian Basin is stored in consolidated, confined, porous sandstones aquifers that have limited compressibility. Although groundwater extraction in the Great Artesian Basin has resulted in reduced hydraulic pressures (by up to 100m), the comparatively low compressibility of the sandstone aquifers has limited the change in aquifer thickness to immeasurable levels of less than 0.1% of the entire aquifer thickness (Hillier 2000).

To assess the potential for aquifer compression and land subsidence associated with the 'project case' and 'cumulative case' CSG development, a simplified discussion of the process of aquifer compression and land subsidence is provided in the following text.

At the water table (in an unconfined aquifer), groundwater is released from storage by gravity drainage. However, in a confined aquifer, groundwater is released from storage due to a reduction in hydrostatic pressure within the pore spaces which accompanies the withdrawal of groundwater from the aquifer. The total load above an aquifer is supported by a combination of the skeletal framework of the aquifer and by the pressure exerted by the associated pore water. Withdrawal of groundwater from the aquifer (such as will occur in CSG production) results in a decline in the pore pressure and subsequently more of the load must be supported by the aquifer skeleton. As a result, the rock particles become distorted and the aquifer skeleton is compressed, leading to a reduction in effective porosity and overall volume. Additionally, the decreased water pressure causes the pore water to expand slightly. Both the compression of the skeleton and expansion of the pore water cause water to be expelled from the aquifer. The volume of water that a permeable unit expels from storage per unit surface area and unit change in the hydraulic head is termed the storage coefficient and can be defined as:

$$S = \rho g b \left(\alpha + n\beta\right)$$

Where:

S: Storage co-efficient (dimensionless ratio)

ρ: Mass density of water (kg/m^3)

g: Acceleration due to gravity (m/s^2)

b: Thickness of aquifer formation (m)

α: Coefficient of compressibility of the aquifer formation (m^2/N)

n: Porosity

β: Fluid compressibility (m^2/N)

To assess the potential deformation across geological units as a consequence of associated water production (and the lowering of pressure head), the following formula can be employed:

$$\partial b = -\alpha b \rho g \partial h$$

Where:

∂b: Level of compaction or change in thickness of the aquifer (m)

α: Coefficient of compressibility of the aquifer formation (m^2/N)

b: Thickness of aquifer formation (m)

ρ: Mass density of water (kg/m^3)

g: Acceleration due to gravity (m/s^2)

∂h: Change in pressure head (m)

A simplification of the compaction formula (substituting the storage coefficient) can be defined as follows (Edgar and Case 2000):

$$\partial b = S \partial h$$

Where:

∂b: Level of compaction or change in thickness of the aquifer (m)

S: Storage co-efficient (dimensionless ratio)

∂h: Change in pressure head (m)

The storage co-efficient (S) is the product of the specific storage (Ss) and the aquifer thickness and is a commonly determined value in aquifer testing. In the current study, the specific storage (Ss) for each hydrostratigraphic unit was derived as part of the numerical model calibration, while the change in pressure head value (∂h) was the primary output of the initial numerical modelling.

Employing the simplified compaction formula (provided previously) and the initial outcomes of the numerical model, the potential compaction of each hydrostratigraphic unit affected by associated water production during the 'project case' and 'cumulative case' CSG operations was estimated across the region at model year 2049. This year was selected as it is generally representative of the greatest potential for groundwater level drawdown in the Walloon Coal Measures. The total estimated compaction, as a consequence of the CSG operations, was projected by summing potential deformations in each hydrostratigraphic unit.

Broadly, the initial assessment indicates that potential for compaction across the region, as a consequence of the either the 'project case' or 'cumulative case' CSG operations, is conservatively considered to be less than 0.5m. The risk of compaction is generally correlated with the coal seam elevation and requirements for groundwater level drawdown. For instance, the greatest potential for compaction is considered to be associated with those areas possessing comparatively deep coal seams and greater magnitudes of drawdown (that is, west of Condabri, between Kainama and Gilbert Gully and west of Carinya development areas).

Importantly, all, or part of, this deformation is unlikely to be expressed at the surface (as land subsidence) as the shallower consolidated and competent rock, being largely unaffected by groundwater level drawdown, will to some extent operate as a bridge to prevent the downward movement of the minimally deformed underlying rock. On the basis of the initial assessment, the potential risk of land subsidence as a consequence of CSG production is considered low.

It is notable that potential also exists for differential geological deformation to promote additional fracturing and/or further opening of existing fractures in underlying or overlying units. Such an occurrence, particularly in the case of aquitard fracturing, could increase the potential for inter-aquifer flow between aquifers, possibly resulting in quality and drawdown implications. The potential risk of this occurring is considered low.

6.2.6 Risk evaluation

The risk assessment of potential hydrogeological impacts associated with Project's CSG associated water production during the Australia Pacific LNG Project, including the proposed control measures, is summarised in Table 6.2.

Table 6.2 Risk assessment of potential hydrogeological impacts - CSG associated water production during the Australia Pacific LNG Project

Potential risk	Possible cause(s)	Possible consequences	Existing controls	Risk ranking	Mitigation measures	Residual risk ranking
Loss or reduction of groundwater supply to bore owners	Associated water production from coal seams potentially resulting in drawdown effects in landholder bores.	Reduction in landholder bore pumping capacity and a requirement to 'make good' in accordance with the *PAG (Production and Safety) Act 2004*.	(1) Baseline and ongoing regional groundwater level and quality monitoring, particularly in areas identified with higher risk of effect from CSG activities (2) Employ CSG production well construction that minimises impact to overlying and underlying units.	Medium	(1) Provide water to landholder's affected by groundwater depressurisation in excess of trigger levels ('make good'). (2) Injection of water to reverse potential effects to groundwater storage in major aquifers.	Low
Potential reduction of baseflow to surface water systems and/or increase in stream losses	Associated water production from coal seams and risk of drawdown effects to watertable and confined aquifers adjacent to surface water systems with potential to affect groundwater - surface water connectivity.	Reduction of baseflow and/or increase of stream losses have the potential to affect surface water flows and the accompanying river ecology (particularly during periods of low flow).	(1) Baseline and ongoing regional groundwater level and quality monitoring, particularly in areas identified with higher risk of effect from CSG activities.	Low	(1) Early intervention (if required) to mitigate localised impacts (e.g. aquifer injection, supplementing stream flow, etc).	Low
Potential reduction of flows to springs and groundwater	Associated water production of the coal seams and potential	Reduction of flow to springs has the potential to affect the	(1) Baseline and ongoing regional groundwater level, flow and quality monitoring,	Low	(1) Early intervention (if required) to mitigate localised impacts (e.g.	Low

Potential risk	Possible cause(s)	Possible consequences	Existing controls	Risk ranking	Mitigation measures	Residual risk ranking
dependent ecosystems	to depressurise confined aquifers providing flow to important springs and accompanying GDEs ('project case').	integrity, health and habitat of GDEs.	particularly in areas identified with higher risk of effect from CSG activities.		supplementary supply, etc).	
Potential for groundwater induced salinity	Associated water production of the coal seams and potential to induce groundwater in from overlying/underling of aquifers of poorer salinity	Potential impacts to beneficial uses of the groundwater resource	(1) Australia Pacific LNG CSG production well design minimises potential for inter-aquifer leakage and pressure transmittal through pressure cementing of annuli and sacrificing of higher risk coal seams. (2) Baseline and ongoing regional groundwater level and quality monitoring, particularly in areas at elevated risk of being impacted.	Low	NA. Groundwater in overlying and underlying units is of better quality than coal seams.	Low
Gas migration	Potential migration of gas away from the gas fields, via wellbores and through geological pathways.	Gas migration and seepage to the surface may lead to vegetation die-back, human health and safety risks if gas builds up in concentration.	(1) Appropriate CSG well construction (2) Further investigation of potential gas seeps, and gas provenance in overlying aquifers. Baseline and ongoing monitoring, particularly in areas at higher risk of effect from CSG activities.	Medium	(1) Abandonment of inappropriately constructed wellbores. (2) Installation of hydraulic barriers to protect key units (e.g. injection or extraction wells).	Low

Potential risk	Possible cause(s)	Possible consequences	Existing controls	Risk ranking	Mitigation measures	Residual risk ranking
Artificial connection between aquifers via CSG wells	Potential transmittal of pressure reduction effects directly from Walloon Coal Measures to overlying and/or underlying aquifers due to improperly constructed CSG wells.	Increased drawdown in overlying and underlying aquifers, potentially resulting in decreased water bore yields, reduction in baseflow and spring flows, and gas migration to overlying aquifers.	(1) Australia Pacific LNG CSG production well design minimises potential for inter-aquifer leakage and pressure transmittal through pressure cementing of annuli.	Low	NA	Low
Artificial connection between aquifers via old wells	Potential for improper well construction (or abandonment) or casing failure possibly resulting in connection between individual aquifer units.	Increased drawdown in overlying and underlying aquifers, potentially resulting in decreased water bore yields, reduction in baseflow and spring flows, and gas migration to overlying aquifers.	(1) Risk assessment to identify potential pathways. Baseline and ongoing regional groundwater level and quality monitoring, particularly in higher risk areas.	Low	NA	Low
Potential for differential land subsidence	Aquifer compaction as a consequence of associated water production of the coal seams and possible expression at the surface as differential	Differential settlement has the potential to compromise the geotechnical integrity of surface and subsurface	(1) Baseline and ongoing regional groundwater level monitoring in areas at higher risk of drawdown. (2) If groundwater level monitoring detects significant drawdown in high risk areas,	Low	NA	Low

Potential risk	Possible cause(s)	Possible consequences	Existing controls	Risk ranking	Mitigation measures	Residual risk ranking
	land subsidence.	infrastructure, and in severe cases, surface drainage patterns.	land subsidence monitoring will be initiated. (2) Early detection of potential land subsidence impacts may require mitigation measures to be implemented.			

Note: NA = not applicable

6.3 CSG associated water and waste stream management

6.3.1 Management options

The management of CSG associated water on the Australia Pacific LNG Project (described in detail in Volume 5, Attachment 12 Adaptive Associated Water Management Plan) is broadly categorised according to:

- Short-term water management options (Phase 1), comprising approximately the initial three years of operation
- Ongoing water management options (Phase 2), beyond Phase 1 until project cessation.

For clarification, the preferred Phase 1 associated water management approach is anticipated to consist of the following:

- A centralised water collection system delivering water to a series of central locations
- Short-term CSG associated storage (feed) ponds to facilitate initial water treatment and operational flexibility
- An (integrated membrane system) water treatment facility to desalinate the water, utilising RO desalination technology, to a standard suitable for discharge into the surface water environment
- Opportunistic discharge of high-quality treated water to either regulated and/or unregulated watercourses. When and where watercourse discharge rates are insufficient to meet water production, a range of beneficial uses, including supply for irrigation and stock and potable, will be implemented
- Brine evaporation ponds to store and concentrate the salt reject stream from the water treatment process.

A range of water management options are currently being assessed for Phase 2 (fourth year of operation until project cessation) of the Australia Pacific LNG Project. Beneficial use options include (but are not limited to):

- Industrial users (e.g. proposed and existing mines and power stations) See Section 5.5
- Potable water supply (i.e. to local urban and rural communities)
- Existing and Australia Pacific LNG-owned and operated agricultural uses, potentially including: irrigation, feedlots and aqua-culture
- Injection back into Great Artesian Basin aquifers with ongoing investigations evaluating both a range of injection products and targets.

On account of the elevated salinity of the CSG production water, environmentally-acceptable options for direct use of the untreated water are very limited. Accordingly, any water management strategy will require the CSG water to be treated to an acceptable salinity level, enabling a wide range of beneficial uses, or low environmental impact discharge, in the event that beneficial use is not practical.

Most of the water disposal strategies being considered for Phase 2 of the Australia Pacific LNG Project will not have direct implications for the groundwater regime. One exception is the option of associated water injection into non-CSG aquifers of the Surat Basin (with appropriate pre-treatment or

blending with fresher water). The potential groundwater implications of employing an injection strategy are discussed in Section 6.3.2.

In association with the water management strategies being considered for the Australia Pacific LNG Project in Phase 1 and 2, various methods to dispose of the concentrated salt reject waste stream (brine) are being evaluated. The range of potential strategies includes (but is not limited to):

- On-sell of salt products
- Burial of crystallized salts in approved waste management facilities
- Injection of brine to suitably isolated and deep geological formations.

Brine injection, if pursued, will clearly have implications for the deeper groundwater regime. The potential groundwater implications of employing a waste injection strategy are discussed in the Section 6.3.2.

6.3.2 Potential impacts

This section addresses the following potential hydrogeological implications of the range of CSG associated water and waste stream management options being considered for the Australia Pacific LNG Project:

- Potential for the uncontrolled discharge of associated water from the feed ponds or waste water from the brine storage ponds and associated pipework and infrastructure at a magnitude that would cause significant environmental harm (Phase 1 and Phase 2)
- Potential shallow groundwater flow and quality implications of treated water discharge to regulated and unregulated watercourses (Phase 1 only)
- Potential groundwater flow and quality implications of the injection of (treated or blended) associated water to major aquifers in the Surat Basin (possible options for Phase 1 and Phase 2)
- Potential groundwater flow and quality implications of the injection of brine concentrate injection to isolated and deep geological formations (possible option for Phase 1 and Phase 2).

The hydrogeological implications of constructing and operating water management infrastructure (such as, water collection systems and WTFs) are evaluated in Section 6.4.

Potential for uncontrolled discharge of water and waste water from storage ponds and associated pipework and infrastructure

From a hydrogeological perspective, the primary risk associated with the feed and brine storage ponds is the uncontrolled discharge of water or waste water to the environment by way of:

- Seepage through the base of the storage ponds and/or pipework to the underlying aquifers
- Overtopping of the ponds during, or following, heavy rainfall and subsequent seepage to underlying aquifers or discharge to surface water courses.

Any uncontrolled seepage from the feed and brine storage ponds has the potential to affect the quality of the shallow groundwater and alter groundwater flow patterns by way of water table mounding. However, such risks will be managed through appropriate engineering design and construction procedures.

Key design criteria mitigating the uncontrolled discharge of water or wastewater from the ponds include the following:

- All feed ponds and brine storage ponds and associated pipework will be lined and constructed to conform to Queensland EPA and DERM guidelines (May 2009) and good engineering practices
- The ponds and associated pipework will be designed and constructed to the regulatory standard providing reliable service to the required design life
- The pond volumes will be sized to comply with relevant DERM and EPA guidelines in accordance with the determined hazard category.

With reference to other water/wastewater generated as part of the water treatment process:

- Stormwater will be managed via conventional stormwater handling infrastructure
- All associated water, plant wash down water and other wastes will be segregated from stormwater systems. All process area wash-down wastes will be captured and returned to the feed ponds for reprocessing and treatment
- Small volumes (<20m^3/year/facility) of oily wastewater will be generated by each WTF. The wastewater will be redirected to the Gas Plant oily water treatment systems and appropriately managed in accordance with regulatory requirements.

In summary, the appropriate engineering design and construction of the lined feed and brine storage ponds will mitigate the uncontrolled discharge of water or wastewater from the ponds and minimise the risk of affecting the groundwater quality and environmental values of underlying aquifers. Importantly, construction of the feed and brine ponds will be accompanied by a suitably-designed shallow groundwater monitoring network. The network will be regularly monitored for groundwater quality and levels, providing an opportunity for early detection and response in the event of an uncontrolled discharge of water or wastewater from any of the ponds associated with a WTF.

Chapter 8 contains further detail concerning the proposed approach to groundwater monitoring of feed and brine ponds.

Potential implications of treated water discharge to regulated and unregulated watercourses in Phase 1

As discussed in Section 6.3.1, the preferred treated water management approach in Phase 1 is, where practicable, to adopt the beneficial re-use of water. This re-use may be supplied for primarily agricultural water uses, combined with the opportunistic discharge of treated water to either regulated and/or unregulated watercourses.

Discharging high quality treated water to the Condamine River has the potential to temporarily alter the connectivity relationship of the river and groundwater systems. Section 5.4.8 documented the findings of the 2008 CSIRO Murray Darling Basin Sustainability Yields study concerning surface water – groundwater connectivity relationships in the Condamine-Balonne River Catchment for the drier than average conditions of March 2006. In proximity to the Condabri and Talinga development areas, the study reported that the Condamine River (during March 2006) has the potential to ‘gain’ at rates of between 0.05ML/day/km to 0.11ML/day/km, primarily as a consequence of the Chinchilla Weir surface water storage (CSIRO 2008). These baseflow rates (which are representative of one summer period) will fluctuate in correlation with seasonal rainfall and climatic patterns.

The extent to which the connectivity relationship between the Condamine River and adjacent alluvial aquifer system will be altered by the discharge of high quality treated water, will be dependent upon a range of existing conditions including: river and aquifer hydraulics, river bed and aquifer permeability, geomorphology and climate, along with the location, timing, duration, frequency and rate of water release.

Any changes to river and aquifer connectivity upon discharge of high quality treated water to the Condamine River will be temporary and localised at the discharge sites. The minor and temporary increase to flow rates in the Condamine River during discharge events may marginally reduce the river's baseflow component (i.e. rate of groundwater discharge). In turn, a marginal rise in groundwater levels adjacent to the river system on a local and temporary scale may ensue. Such changes are not expected to have any significant implications for groundwater quality or flow patterns in the adjacent alluvial aquifer system.

Discharging treated water to unregulated ephemeral watercourses, in proximity of the six proposed WTFs and the existing Talinga WTF, will have short-term implications for the local groundwater resource. During a discharge event to an ephemeral stream or creek, the underlying alluvial deposits will receive a level of recharge. Following cessation of discharge, the recharged groundwater may partially constitute baseflow to the ephemeral stream or creek for short periods. Any affects to the groundwater system, upon discharge to ephemeral watercourse, will be localised and temporary and more importantly, given the high quality of the treated discharge water, are not expected to cause detrimental impacts.

Use of treated water for agricultural uses will ultimately be dependent on the demand for the water, with higher demands projected for the drier seasons of autumn and winter. Such a strategy is not expected to cause any detrimental impacts to the shallow groundwater system. In particular, the use of high-quality treated water for irrigation purposes, in place of lower-quality surface water or groundwater resources, will ultimately contribute to a level of localised dilution of the shallow groundwater resources. Furthermore, utilising this readily available and good quality water resource will alleviate the demand and stress on already over-exploited surface water and groundwater resources and potentially alleviate/mitigate some soil salinisation problems.

Potential implications of associated water injection

The injection of raw or treated production water into selected aquifer systems of the Surat Basin is one strategy being considered to dispose of water generated during CSG production as part of the Australia Pacific LNG Project.

Importantly, a range of regulatory criteria or guidelines are advised in the implementation of any injection system. Key criteria include the following:

- **Injection pressure** - The injection pressure must be limited to prevent rupturing (fracturing) of overlying confining beds. The Australian Guidelines for Water Recycling (EPHC et al. 2008) stipulates that the injection pressure should not exceed the dry overburden pressure as determined from the base of the aquitard. In simple terms, the injection pressure is typically limited to 1.5 times the depth to the top of the aquifer.
- **Quality of source water** - In accordance with the Queensland Government's current CSG water management policy (Department of Infrastructure and Planning May 2009), the injection of production water of lesser quality into a reasonably exploitable aquifer is not currently permitted.

The criteria concerning injection pressures will constrain the injection capacity of the receiving aquifers and the potential configuration (number and spacing) of any injection well network. With reference to the second criteria (source water quality), the injection of untreated associated water with a median TDS concentration in excess of 1400mg/L (average of 2547mg/L - Table 5.4) is unlikely to be acceptable from the perspective of current policy. On a regional scale, groundwater salinity in the major aquifer (non-CSG) formations of the Surat Basin is generally below the expected salinity of the CSG associated water. Consequently a level of treatment or blending with fresher water may be required prior to the injection of associated water. In compliance with the current policy, the salinity of the injected water (i.e. source water) will be required to be comparable to the average regional salinity of the target aquifer. Analysis of other water quality parameters will also be required to comprehensively evaluate source water – groundwater chemical compatibility and requirements concerning pre-treatment and ongoing maintenance of a potential injection system.

Outcomes from initial pilot field trials (if pursued), coupled with numerical groundwater flow modelling (employing the existing modelling platform) and geochemical modelling of a potential injection system, will enable a thorough assessment of the viability and associated effects of an injection scheme. From an environmental perspective, potential impacts requiring consideration may include:

- Changes to groundwater levels and groundwater flow regimes in the target aquifer(s) and underlying and overlying units
- Potential for inter-aquifer flow (that is, leakage) across geological units
- Changes to local and regional scale groundwater quality in all affected aquifers
- Potential to compromise the integrity of the geological units (that is, hydro-fracturing, and mineral dissolution reactions)
- Implications for groundwater dependent ecosystems and surface water courses in the region
- Implications for groundwater users and other CSG operators in the region
- Potential to affect municipal supplies or industrial applications as a consequence of inconsistent groundwater supply or variable groundwater quality.

Importantly, an injection scheme operating in any of the non-CSG aquifers has the potential to deliver substantial social and environmental outcomes. Recharge to any of these aquifers will assist in countering currently declining groundwater levels and minimise the risk of further declines as a consequence of continued drought conditions, irrigation development and CSG production. Furthermore, injection of production water into the Hutton, Springbok and Gubberamunda Sandstones in particular, may assist in (by way of inter-aquifer flow) recharging the depleted coal seams and may address the risks associated with the ‘make good’ provisions stipulated by the *Petroleum and Gas (Production and Safety) Act 2004*.

Potential implications of brine concentrate injection

The injection of brine into suitably isolated and deep geological formations is one strategy being considered to dispose of the waste stream generated during the water treatment process associated with Australia Pacific LNG’s operations.

Preferred locations identified in the pre-feasibility phase would aim to fulfil the following criteria to minimise potential environmental risks and impacts:

- A geological horizon that is suitably isolated from potential drilling targets and groundwater development activities

- A hydrogeological horizon with no agricultural, economic or cultural value
- Lithology that has sufficient capacity to accommodate the required disposal rates of brine concentrate.

The implementation of any brine injection system will require comprehensive exploratory drilling and pilot injection trials. The field investigations would be accompanied by predictive density-coupled numerical modelling for temperature-dependent fluid density and fluid viscosity solute transport, along with geochemical modelling to evaluate the efficiencies and potential operational risks of a prospective system and, importantly, the potential environmental impacts.

6.3.3 Risk evaluation

The risk assessment of potential hydrogeological impacts associated with proposed CSG associated water and waste stream management during the Australia Pacific LNG Project, including the proposed control measures, is summarised in Table 6.3.

Table 6.3 Risk assessment of potential hydrogeological impacts - proposed CSG associated water and waste stream management during the Australia Pacific LNG Project

Potential risk	Possible cause(s)	Possible consequences	Existing controls	Risk ranking	Mitigation measures	Residual risk ranking
Potential for uncontrolled discharge of water and/or wastewater from storage ponds (Phase 1 or Phase 2)	Vertical seepage of water and/or wastewater through the base of the storage ponds to underlying aquifers and/or overtopping of the embankment and subsequent seepage to underlying aquifers.	Potential to locally impact the quality of the shallow groundwater and alter groundwater flow patterns by way of mounding.	(1) Leakage and overtopping risks will be managed through the appropriate engineering design and construction of the storage ponds. (2) Construction of the ponds will be accompanied by a suitably-designed shallow groundwater monitoring network. The network will be regularly monitored for groundwater quality and levels, providing an opportunity for early detection and response, in the event of an uncontrolled discharge of water or wastewater.	Low	NA	Low
Potential implications of high quality water discharge to the regulated and/or unregulated watercourses (Phase 1)	Short-term transfer of treated water to regulated and/or unregulated watercourses (during Phase 1) and potential to disturb the groundwater - surface water connectivity relationship.	Potential local and marginal reduction to the river or creek's baseflow component, possibly contributing to a minor rise in groundwater levels adjacent to the river or creek system on a local and temporary scale.	No controls required.	Low	NA	Low
Potential implications	Injection of treated or	Alterations to the	(1) If associated water injection is pursued,	Low (pending		Low (pending

Potential risk	Possible cause(s)	Possible consequences	Existing controls	Risk ranking	Mitigation measures	Residual risk ranking
of associated water injection	blended water and potential to affect the receiving hydrogeological regime.	hydrogeological regime could affect groundwater storages, groundwater levels, inter-aquifer flow, groundwater quality, integrity of geological units and have implications for GDEs, surface water courses, surrounding groundwater users and CSG operations.	pilot injection trials will be conducted to field test the injection capacity of targeted aquifer horizons and the geochemical compatibility of the source and in-situ water. A fundamental criterion to implementing any associated water injection system will be demonstrating that the associated impacts can be appropriately monitored and managed with an acceptable level of risk.	pilot injection trials)		pilot injection trials)
Potential implications of brine concentrate injection	Injection of brine concentrate into suitably-isolated and deep geological formations, and potential to affect the receiving hydrogeological regime.	Potential groundwater quality implications (that may affect groundwater user and environmental receptors) if the brine concentrate breaches the target geological formations.	(1) If brine water injection is pursued, comprehensive pilot injection trials will be conducted to field test the capacity and confining properties of targeted geological horizons. A fundamental criterion to implementing any brine injection system will be demonstrating that the associated impacts can be appropriately monitored and managed with an acceptable level of risk.	Low (pending pilot injection trials)		Low (pending pilot injection trials)

Note: NA = not applicable

6.4 CSG infrastructure activities

6.4.1 Issue identification

The proposed CSG infrastructure activities associated with the Australia Pacific LNG Project are presented in Table 6.4 along with the potential hydrogeological risks.

Table 6.4 Proposed CSG infrastructure activities and potential hydrogeological risks

Activity	Description	Potential hydrogeological risks
Installation of CSG wells	Larger drilling pad created, however following completion of the well, the majority of the drill pad rehabilitated.	Potential reduction to groundwater recharge. Potential pathways for the transmittal of pressure or the migration of gas to overlying/overlying units.
Construction of Gas Processing Facilities (GPFs)	GPFs will be established within the proposed development areas. Associated infrastructure: processing equipment, large gas engine generators and flare facilities.	Potential reduction to groundwater recharge. Potential for spills of chemicals, fuels, oils and wastes and associated effects to shallow groundwater.
Water Treatment Facilities (WTFs) and Water and Brine Transfer Networks	Typical water treatment facilities include water and brine ponds, pumps, maintenance sheds, and gas powered generators. Water transfer stations will be installed where the local terrain does not allow for gravitational flow. Buried pipes will transfer associated water produced from each wellhead separator to the nearest trunk line (larger buried lines). This gathering system will be constructed using reliable high density polyethylene pipe (HDPE). Open unlined drains will transfer water to feed and effluent ponds. The drains will either be cut into competent sandstone or otherwise be lined with 300mm of in-situ material mixed with gypsum and grasses established within the drains.	Potential reduction to groundwater recharge. Potential pipeline leaks, spills of chemicals, fuels, oils and wastes and associated effects to shallow groundwater.
Extraction of groundwater	Potable water supply for personnel purposes will be accessed from the groundwater bores at 50 m^3/day to 200m^3/day. Water for dust suppression and other non-potable uses will be accessed from the bores and supplemented by	Potential localised groundwater level drawdowns.

Activity	Description	Potential hydrogeological risks
	rainwater.	
Gas pipeline systems	All gas pipelines will be buried except within the fenced well site and GPF areas.	Potential pipeline leaks and associated effects to shallow groundwater.
Power and telecommunications	Power generation will be achieved through a variety of forms including generators, grid supply and micro-turbines for wellhead power. Telecommunications will be achieved through fibre optics, radio, microwave and mobile networks. Fibre optics will be co-located with the main gas transmission line.	Potential reduction to groundwater recharge.
Camps, offices and workshops	Camps, offices and workshops will be established in close proximity to the GPFs. Camps will include accommodation for up to 200 personnel and provision of parking areas, while offices will facilitate administration and operations. These areas for these facilities will be rehabilitated after the pipeline has been constructed. Workshops will provide minor maintenance activities throughout the active use of the pipeline.	Potential for spills of chemicals, fuels, oils and wastes and associated effects to shallow groundwater. Potential effects of sanitation systems and associated effects to shallow groundwater.
Access roads, storage areas and laydown areas	Existing carriageways will be used wherever possible for the transport of equipment, materials and personnel. Additional access roads will be established where necessary. Regional warehouse storage sites will store materials prior to JIT (Just In Time) delivery to the pipeline corridor. Pipe laydown areas will be established at centrally-located areas along the pipeline corridor or where possible the pipes will be directly strung along the pipeline route.	Potential reduction to groundwater recharge. Potential for spills of chemicals, fuels, oils and wastes and associated effects to shallow groundwater.

6.4.2 Potential impacts

The potential hydrogeological impacts of the proposed CSG infrastructure activities are described below.

Potential for loss of recharge

The shallow groundwater regime is vulnerable to loss of recharge through altered land use. Clearing of vegetation and alteration of landscape topography (such as levelling, resurfacing with impermeable materials or compaction associated with the development of CSG and pipeline infrastructure) can result reduced capability for groundwater recharge over these areas. However, the area potentially affected would be very small compared to the total gas field area. Additionally, the affected areas are

not directly connected with the surface water network; therefore, the water is still more likely to be conveyed as recharge at some point, rather than as surface runoff. The impacts of loss of recharge are therefore considered insignificant.

Potential for pipeline leaks

Leakage of water and gas pipelines within the gas field areas has the potential to affect the quality of groundwater locally.

Monitoring of gas and water gathering networks will be continuous using Supervisory Control and Data Acquisition (SCADA) systems to identify changes in pressure. Operating staff will monitor and maintain water drainage pipe networks through high point vents. Inspection of the water gathering pipe network should not be required as the HDPE material is expected to run through the life cycle of the entire system. As part of regular right-of-way inspections, potential disturbances to the pipe network from the above ground environment (such as erosion or vegetation) will be identified and addressed.

Potential for spills of chemicals, fuels, oils and wastes

Construction and operation of the proposed gas gathering network and processing facilities will generate small volumes of domestic and industrial wastes. All waste streams will be subject to the best practice philosophy of avoidance where possible, reduction or minimisation of the waste generated, followed by reuse, recycling and/or appropriate disposal. Detail management procedures for chemical use, as well as strategies to deal with risks of chemical handling and disposal are addressed in the Volume 3 Chapter 16 and the Project's Waste Management Plan.

With appropriate management of wastes, as proposed in the Waste Management Plan, the potential for groundwater impact is considered to be low.

Potential effects of sanitation systems

Sewage treatment will be achieved through the use of discrete package treatment facilities installed at the workforce accommodation areas. DERM requirements and/or guidelines will be adhered to as appropriate, as well as measures outlined in the CSG field Environmental Management Plan. The location of sewage treatment and areas of irrigation using treated effluent water will be selected to avoid impacts to groundwater and other potential receptors.

Potential localised groundwater level drawdown

Water supplies will be required for activities associated with the Project's drilling operations. This water will need to be of a better quality than the associated water produced during CSG production. Sources of this water, in order of preference, are:

- Treated water produced through the RO process
- Recycled water from other construction activities
- Commercial suppliers
- Surface water
- Groundwater
- Untreated associated water.

Although groundwater is not the preferred option, it is considered probable that it will constitute some portion of the requirements. Development areas where a groundwater-based water supply may be required include:

- Ramyard
- Pine Hills
- Combabula
- Dalwogan
- Reedy Creek
- Gilbert Gully.

Water bores have already been installed at Pine Hills and Ramyard fields. These bores were drilled and constructed by a licensed water bore driller and the construction records indicate that they were completed in accordance with the minimum construction requirements for waterbores in Australia (LWC 2003) and minimum standards for the construction of water bores that intersect the sediments of artesian basins in Queensland (NRM 2004). Notices of completion in accordance with Section 32 of the *Petroleum and Gas (Production and Safety) Regulation 2004* were submitted for the two new bores. Australia Pacific LNG also uses groundwater from a licensed water bore at the Rockwood property for potable supply in the Talinga development area for the Walloons Development Project.

Table 6.5 summarises the anticipated water requirements for different elements of the construction and operation of the gas fields and pipeline components of the Australia Pacific LNG Project. If these requirements were to be supplied using groundwater, there would be drawdown effects in the vicinity of the extraction bore. The magnitude and extent of these effects would be related to the rate of extraction and the hydraulic nature of the aquifer. If the aquifer is confined and of low hydraulic conductivity, the effects may be noticeable several kilometres from the pumping centre. However, if the hydraulic conductivity is high and the aquifer unconfined, the noticeable effects may be limited to several hundred metres.

Without specific information related to extraction rates, durations, and target aquifer geometry and hydraulic nature, it is not possible to assess potential impacts particularly to neighbouring landholder bores. Prior to the commencement of extraction, consideration would be given to the assessment of potential impacts based on site-specific information.

Table 6.5 Estimated water use during construction and operation

Use	Element	Estimated total volume (ML)	Average daily rate (ML/day)
Construction	Brine pond	620	1.7
	Gas plant	365	1
	Water treatment facility	365	1
	Water treatment storage	90	1
Hydrostatic testing	Australia Pacific LNG gas pipeline	100*	NA
	High pressure network	0.3 per km	NA
Dust Suppression	NA	87.6 per year during construction	0.25
Drilling	NA	0.6 per well	0.64
Camp	Potable	0.15	0.15

NA = not applicable

* Water used for hydrostatic testing will be re-used where practicable.

Potential wellbore pathways

To assess the potential for the Australia Pacific LNG CSG production wells to act as pathways for the transmitting pressure effects or gas to overlying units, a detailed assessment of the drilling and construction methods has been undertaken.

A breakdown of the main stages for the current Australia Pacific LNG practices in drilling and construction of CSG production wells follows. Figure 6.2 further summarises the production well construction and provides a schematic diagram thereof. It is recognised that the current practices may change in the future as additional research and development improves methods and efficiencies; however, it is expected that any changes to methods will maintain the integrity of seals between the coal measures and overlying and underlying aquifers.

Drilling and construction staging:

1. Install 14" surface casing to control washout at shallow depths and cellar to allow installation of blow out protector (BOP).
2. Rotary drill 12$^{1}/_{2}$" diameter to approximately 10% of the anticipated total depth of the bore (between 70m and 100m) using water-based mud system with biocide added.
3. Run in 12$^{5}/_{8}$" diameter surface casing (with centralisers).
4. Pressure cement from casing shoe to the surface.

   Water/mud circulated to clean out hole

   Measured volume of cement (greater than the calculated annular volume) pumped into the inside of the casing

   Hard rubber drillable plug inserted, and water pumped into the casing forcing the cement up the annulus and out the top of the hole at ground surface

   Pressure in the casing held until the cement hardens.
5. Rotary drill 8$^{3}/_{4}$" diameter to total depth (through rubber plug). If there is certainty that the Eurombah Formation is sufficiently thick that the Hutton Sandstone is not be penetrated (based on the logs of surrounding wells), the drilling will proceed to approximately 60m past the last coal seam, otherwise it will be stopped at a lesser depth.
6. Condition the hole and run wireline geophysics (typically natural gamma, calliper, density and resistivity).
7. Run in 7" diameter production casing (with centralisers) pre-perforated across depth of target coal seams. An external casing packer (ECP) with cement stage tool (CST) is installed at a minimum of 12m above the uppermost perforations. Cement baskets are installed directly below the ECP, as well as one above and one below the surface casing shoe. A cement basket is designed to minimise cement slump into the formation.
8. ECP is inflated.
9. Further pump pressure is applied to the inside of the casing to activate/open the CST. When the CST is open, cement is circulated down the casing through ports in the CST and into the casing annulus until the cement returns are noted at the surface.

Resistivity logs (wireline geophysics) are routinely run to assess the relative permeabilities of the formations. If the resistivity logs and drill cuttings indicate direct connection of the uppermost coal seam with the overlying Springbok Sandstone (that is, an unconformity), the uppermost coals may be sacrificed to minimise the pressure reduction impacts on the Springbok Sandstone. In this case, the ECP is set above the first target coal, thereby effectively sealing the annulus between the uppermost coals and the Springbok Sandstone.

Twice the calculated annular volume of cement is available prior to commencing the cementing of both the 9-5/8" and the 7" casing. If no cement returns to surface during cementing of the production casing (that is, if there is a loss of over 100% of the calculated annular volume), cement bond logs (CBLs) are run to confirm the integrity of the annular seal. The Minimum Construction Requirements for Water Bores in Australia (LWBC 2003) specifies a minimum annular thickness of 20mm for surface casing and 15mm for inner casing strings to be grouted. Although CSG well design is not prescribed by these requirements, the annular thicknesses for production well design proposed for the Australia Pacific LNG gas fields exceeds this minimum requirement for water bores. Australia Pacific LNG CSG well construction also exceeds the Minimum standards for the construction of water bores that intersect the sediments of artesian basins in Queensland (NRM 2004).

In addition, drill stem tests (DSTs) may be conducted in the 8 3/4" diameter hole to determine reservoir pressures and formation permeabilities. Target coal seams may also be under reamed to 121/2" diameter prior to running in and cementing 7" production casing. This removes formation damage in the wellbore (skin) to improve coal permeability in proximity to the wellbore, thus reducing drawdown effects.

Where it is necessary to abandon wells, the method is evaluated on a case-by-case basis, and a design is implemented that assures isolation of the aquifers.

Thus, the production well design effectively seals all overlying formations from the Walloon Coal Measures and from each other through complete pressure cementing of casing strings from the bottom of hole or packer to the surface. By not drilling through the underlying aquitard, pressure reduction effects to the underlying aquifers are controlled by the integrity of the aquitard, and the CSG production wells do not provide a preferential pathway. Potential risks associated with pressure transmittal and gas migration pathways through CSG production wells are thus effectively mitigated.

The use of water-based drilling fluids and biocide will limit the potential for impacting the aquifer water quality and the spread of bio-fouling bacteria through the aquifers.

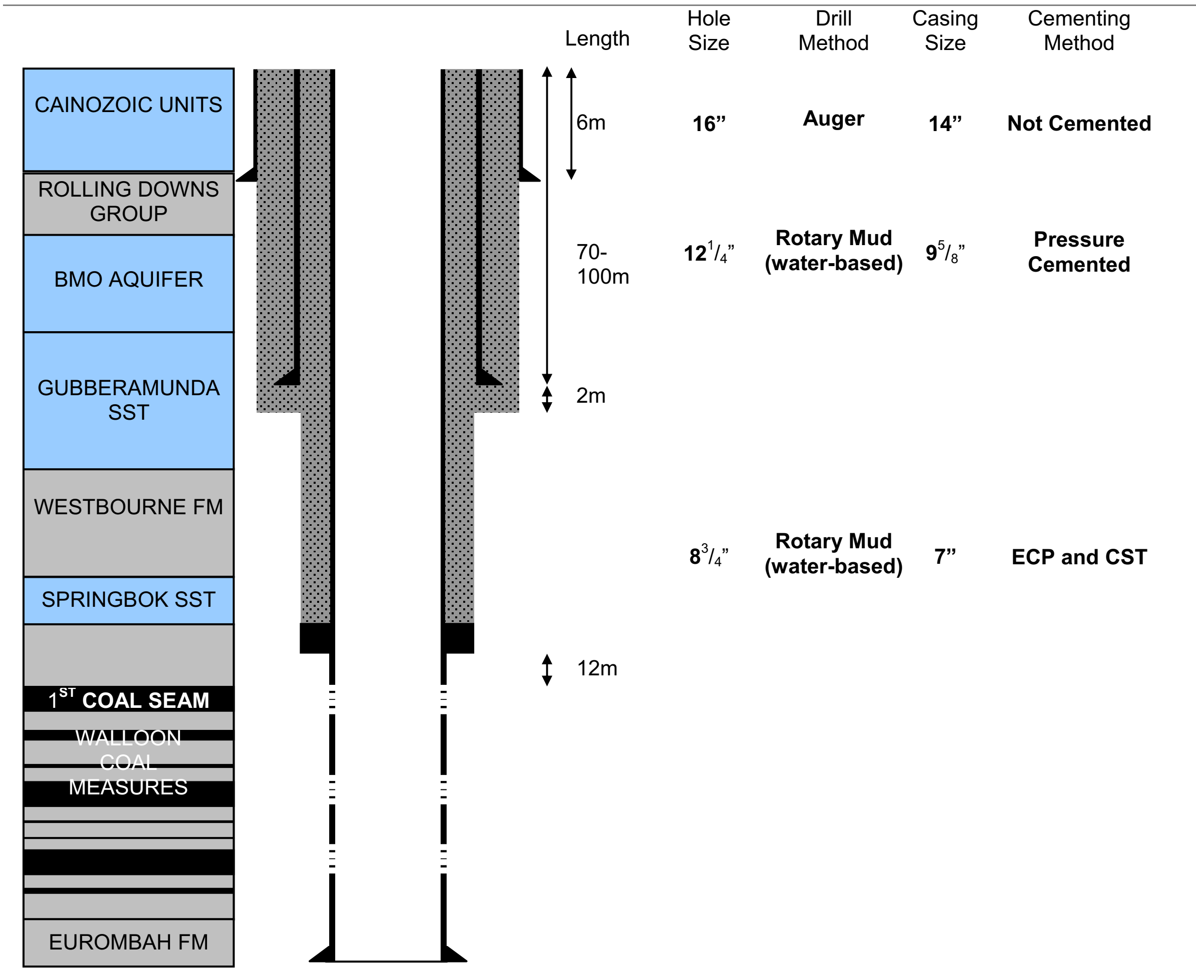


Figure 6.2 Schematic diagram and summary of current Australia Pacific LNG CSG production well construction

6.4.3 Risk evaluation

The risk assessment of the potential hydrogeological impacts associated with the proposed CSG infrastructure activities during the Australia Pacific LNG Project, including the proposed control measures, is summarised in Table 6.6.

Table 6.6 Risk assessment of potential hydrogeological impacts - proposed CSG infrastructure activities during the Australia Pacific LNG Project

Potential risk	Possible cause(s)	Possible consequences	Existing controls	Risk ranking	Mitigation measures	Residual risk ranking
Potential for reduction of groundwater recharge	Clearance of vegetation, levelling of land surfaces, construction of processing plants and buildings associated with the CSG development including impermeable surfaces.	Potential reduction in recharge of shallow aquifers and altered groundwater flow patterns.	(1) Reduction of recharge is minimised through limitation of clearance and disturbance, and rehabilitation of disturbed land including reinstatement of soil layers and revegetation.	Low	NA	Low
Potential for leakage of pipeline infrastructure and other gas and water transfer mechanisms	Poorly designed, installed or maintained pipeline and drainage systems.	Potential quality effects to shallow groundwater resources and recharge sources.	(1) The location of pipeline and related infrastructure has taken into account sensitive groundwater areas. (2) The pipeline and associated infrastructure has been designed to high standards and will be constructed using appropriate materials and methods. (3) The infrastructure will be regularly monitored internally and externally for faults to facilitate early detection and mitigation of leakage. Systems are also in place to mitigate any major leakages.	Low	NA	Low
Potential for chemical spillage or wastes to seep into shallow aquifers	Inappropriate handling, storage, or disposal of chemicals and/or associated waste materials.	Potential contamination of shallow groundwater resources and connected surface	(1) Suitable guidance in EMPs for waste and chemical management will be implemented to manage and mitigate potential risks to groundwater resources.	Low	NA	Low

Potential risk	Possible cause(s)	Possible consequences	Existing controls	Risk ranking	Mitigation measures	Residual risk ranking
		water systems.				
Potential for impacts to receptors from localised groundwater level drawdown and extraction	Localised drawdown effects relative to extraction volumes and local nature of the aquifer(s)	Reduction in landholder bore pumping capacity and a requirement to 'make good', in accordance with the *PAG (Production and Safety) Act 2004.*	NA	Low	(1) Supply water to landholders affected by groundwater level drawdown in excess of established trigger levels.	Low
Potential for creating wellbore pathways during drilling and construction	Incorrect well construction (or abandonment) or casing failure resulting in connection between individual aquifer units.	Increased drawdown in overlying and underlying aquifers, potentially resulting in decreased water bore yields, reduction in baseflow and spring flows, and gas migration to overlying aquifers.	Well bore design minimises potential for inter-aquifer leakage and pressure transmittal through pressure cementing of annuli.	Low	NA	Low
Potential for reduction of groundwater quality during drilling	Use of unsuitable drilling fluids.	Unsuitable drilling fluids may contaminate the aquifer(s).	Water-based, biodegradable drilling fluids will be used to minimise potential for contamination.	Low	NA	Low

Note: NA = not applicable

7. Monitoring and assessment

7.1 Objectives

Although groundwater quality issues may arise at various locations associated with construction or operational activities, these are quite localised and detectable by compliance monitoring systems. Additionally, the relatively slow groundwater flow rates and attenuation capacity of the natural system allows for action to be taken in instances where issues are detected. The objectives of the local scale (compliance) monitoring (hereafter referred to as 'local monitoring') are:

- Establishment of an appropriately located monitoring network, both in space and time
- Development of a high quality background dataset against which potential impacts can be assessed
- Timely identification of potential impacts from local-scale activities.

In contrast, effects from groundwater pumping (drawdown) to allow CSG extraction, or re-injection of associated water into the subsurface (pressure build-up), tend to manifest themselves across much larger areas, possibly extending over tens of kilometres. In that regard, development of an effective monitoring system to address the potential effects on regional receptors is very important. Understanding the potential pathways and effects to groundwater users and sensitive water bodies is critical in establishing the level of risk to the environment from such occurrences.

Therefore, the objectives of the regional groundwater monitoring program (hereafter referred to as 'regional monitoring') are to:

- Provide good regional coverage and establish baseline groundwater conditions in major aquifers
- Gain further understanding of aquifer interactions and how the groundwater system is connected to surface environments
- Verify and refine understanding of the regional hydrogeology
- Gain a better understanding of natural variability in the region
- Provide information to help better understand natural groundwater recharge and discharge in the region
- Assess for long-term trends and potential cumulative effects from current and future CSG development
- Detect any potential large-scale groundwater quality effects from CSG development
- Identify high risk areas that may require monitoring or additional monitoring
- Generate data against which projections made in the EIS can be verified
- Gather high quality data to develop target and threshold values for each key indicator parameter and each major aquifer in the development areas using an adaptive management process
- Communicate results of the groundwater monitoring program to government and community stakeholders.

7.2 Legislative and regulatory requirements

7.2.1 Regional monitoring

Under the *Petroleum and Gas (Production and Safety) Act 2004*, pre-existing water bores (under the Water Act – that is, water bores that were licensed for groundwater extraction prior to the start of approved petroleum testing or production) may be unduly affected by the exercise of a petroleum tenure holder's underground water rights if:

- There is a drop in water level in the bore beyond an established threshold for a given aquifer due to the exercise of the underground water rights; and
- The bore has an impaired capacity, which depending upon the use of the bore (domestic, stock or other use), means it is no longer able to provide a reasonable stock and/or domestic supply, or if there is a material reduction in the number of stock able to be watered from the bore or a material reduction in the pumping supply of an otherwise licensed bore (for example, industrial or town water supply).

If the bore is unduly affected by the exercise of the underground water rights, measures must be implemented to restore the supply of water to the owner of the bore (by either ensuring the bore no longer has impaired capacity or by providing an alternative supply of water) or the owner of the bore must be compensated. This is referred to as the 'make good' obligation under the *Petroleum and Gas (Production and Safety) Act 2004*. To understand when a licensed water bore is unduly affected, it is necessary to understand changes in groundwater conditions in the aquifers that may be affected by the petroleum activities.

In addition, the Act requires groundwater impact reports to be prepared and submitted. These reports must identify:

- Trigger thresholds for aquifers affected
- Details of the groundwater flow model used to predict the impacts (may be an exemption)
- Predicted impacts in terms of aquifer and areal extents
- Details of existing water bores predicted to be unduly affected by the petroleum activities, with an estimate of when each of these water bores may become unduly affected
- Details of a monitoring program to monitor the impact of the activities.

The tenure holder can request the trigger threshold for an aquifer from the Chief Executive, who must take into account the hydrogeology of the specific aquifer. No reference is made in the Act for the development of trigger thresholds to the timeframe over which pumping is conducted. DERM is working to define a suitable drawdown trigger level(s) for consideration by the CSG industry operating in the Surat Basin.

The Blueprint for Queensland's LNG Industry (DEEPI 2009) indicates that the government will, in relation to groundwater:

- Fully implement groundwater monitoring, assessment and reporting requirements under the Act
- Simplify the process for setting trigger levels
- Expand the application of the 'make good' obligation to include cumulative impacts and installation of future bores
- Develop a regional groundwater monitoring regime.

The proposed regional monitoring framework for the Australia Pacific LNG Project is consistent with the overarching goals of the Blueprint.

7.2.2 Local monitoring

Legislative and regulatory requirements related to water management, groundwater extraction and infrastructure activities are predominantly related to environmental authorities and licenses and associated compliance monitoring for the construction and operation of those infrastructure and activities.

The overarching legislation covering the groundwater monitoring associated with these activities includes the *Environment Protection Act 1994* and the Environmental Protection (Water) Policy 2009 (the Policy). The Act requires dams and ponds to be designed, constructed, operated and maintained in accordance with stated objectives. The policy requires accidental releases of process water to groundwater to be prevented, or if impracticable minimised, and the potential impacts thereof to be compared with baseline conditions. This therefore necessitates the establishment of a local monitoring network around such facilities.

7.3 Groundwater monitoring framework

The proposed groundwater monitoring framework (GMF) is based on the principles of performance assessment and an adaptive management system. Adaptive management, also known as adaptive resource management, is a structured, iterative process of optimal decision-making in the face of uncertainty with a focus on reducing uncertainty over time via system monitoring. The approach is based on the 'precautionary principle'. In this way, decision-making simultaneously maximises one or more resource objectives and gathers information needed to improve future management (Holling 1978). Therefore, using adaptive management, as new groundwater quality and quantity knowledge is generated, models can be updated and water management decisions adapted accordingly. This particular framework is therefore a living document and should be updated as required (for example, every four to five years).

The performance assessment system links regional groundwater outcomes, indicators and management actions in the groundwater management framework. This is consistent with Queensland government commitments in the Blueprint for Queensland's LNG Industry (DEEPI 2009). It is Australia Pacific LNG's intention to develop this GMF in consultation with DERM and other appropriate stakeholders.

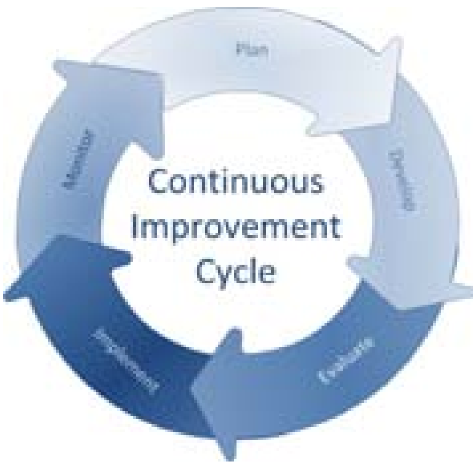


Figure 7.1 Adaptive management and continuous improvement process

A number of elements associated with the GMF are described below.

Outcome: the environmental state to be achieved. Outcomes need to reflect societal values and perceptions. They also need to relate to the long-term sustainability of a resource. Outcomes must be pragmatic, realistic and measurable (using relevant indicators).

Indicator: a measured variable or state of resource condition used to verify that established outcomes are being met.

Target: a desired condition for a given indicator to be maintained below. To develop a target, one must consider natural variability and background conditions for an aquifer with respect to both quality and quantity.

Threshold or limit: a value not to be exceeded, such that resource health and associated resources may be maintained (that is, significantly exceeding the established natural variability at a given location or an agreed-upon published criterion).

Monitoring, evaluation and reporting are required to ensure outcomes are being met. If not, there needs to be feedback into management actions to address the issues that are preventing the outcomes from being met. Adaptive management principles allow for adjustments in outcomes, indicators, target and thresholds as well as associated monitoring and reporting approaches.

7.4 Monitoring network design

7.4.1 Regional monitoring - locations and timing

As indicated previously, the intent of establishing a regional groundwater monitoring network is to provide groundwater level and chemical quality data to properly establish baseline conditions in the various aquifers in the area, against which future effects can be compared. To fulfil the goal of regional groundwater monitoring, strategic locations must be identified for relevant aquifers.

The primary consideration in selecting locations was given to the regional hydrogeological setting. Risk mapping was undertaken to identify those areas most at risk from CSG field development taking into account the intrinsic vulnerability of the aquifer under assessment and receptors of the risk (that is, existing licensed groundwater users and surface water features). A secondary consideration was the basic philosophy of utilizing existing infrastructure to attain a longer monitoring record. The hierarchy for this was:

1. DERM monitoring wells for which extensive monitoring records are already available. The water level records from the DERM wells are generally long enough to start identifying the range of natural variability and any underlying trends that may be present prior to the beginning of CSG development.
2. Origin Energy owned wells. These could be either existing water bores associated with Origin Energy owned properties in the development areas or retro-fitted CSG wells.
3. Privately owned wells for which the owner/landholder provided access rights.

It is important to note that the monitoring network described below is one potential possibility of how the network may be implemented. As additional information becomes available, it is likely the number of monitoring points and their actual locations will change.

With the exception of the Cainozoic Units, future monitoring will be initially focussed on the Springbok Sandstone and Hutton Sandstone, as these aquifers are the two with the greatest potential to be

affected by depressurisation in the Walloon Coal Measures (as shown by the results of numerical modelling – refer to Section 6.2.1). The intention, as part of the adaptive management process described above, is that if significant effects associated with CSG development are observed in these two units, that overlying or underlying aquifers would then be monitored. However, some monitoring has been, and further monitoring will likely be carried out within the Gubberamunda Sandstone and BMO Grouping of aquifers. As existing bores in the Precipice Sandstone have been identified, these too have been proposed for inclusion in the regional network.

Because the Walloon Coal Measures subcrop beneath the Cainozoic Units in the Chinchilla-Dalby area, the effects of pressure reduction have the potential to be more readily transmitted to the near-surface deposits than the Gubberamunda Sandstone, which has an intervening aquitard (Westbourne Formation). Furthermore, intensive groundwater use in this area and the presence of the Condamine River puts the Cainozoic Units at higher risk to drawdown effects, hence a further reason for monitoring of this unit in that area.

Current monitoring locations have been established in the Talinga and Orana development areas. Existing and potential monitoring bores for addition to the network have been identified and are also shown on Appendix A, Map 10. Table 7.1 summarises the number of locations currently proposed for each unit. Extending the network to incorporate all development areas should be undertaken in a manner similar to that for the established network around the Talinga and Orana development areas which is:

- Field reconnaissance to locate and verify the suitability of existing bores (DERM, industry and private)
- If suitable, sample the bores for field and/or laboratory chemical parameters
- Instrument appropriate bores with permanent water level monitoring devices.

Table 7.1 Indicative number of potential monitoring bores for each unit

Hydrostratigraphic unit	Indicative no. of proposed monitoring bores (approximate)
Cainozoic Units	20
BMO Grouping/ Gubberamunda Sandstone	20
Springbok Sandstone	15
Walloon Coal Measures	15
Hutton Sandstone	15
Precipice Sandstone	5

It is likely that several of the proposed bore locations will be found to be unsuitable on the basis of land access, bore condition or validity of existing data. Where necessary, if suitable existing bores are not identified, new dedicated monitoring bores may need to be installed, maintaining focus on the Springbok Sandstone and Hutton Sandstone. Adjoining aquifers would be included if drawdown effects are observed.

Monitoring bores that need to be installed should, where practical, be drilled and constructed on existing drill pads to minimise impacts associated with the land disturbance and drilling activities. The

added benefit of this is the potential for connection to the production monitoring system, allowing real-time automatic data downloads of water level information through the SCADA system.

Where practical, additional monitoring locations will be brought into the regional network 12 months in advance of development progressing to allow the establishment of baseline conditions and assessment of the range of water level fluctuations prior to commencement of development. The currently proposed program is shown in Table 7.2.

Table 7.2 Timing for commencement of monitoring

Development area	First wells online	Latest year of commencement of monitoring	Commencement initiated early due to other operator activities
Talinga	2008	2009*	
Combabula	2011	2010	
Pine Hills	2013	2010	Yes
Reedy Creek	2012	2011	
Condabri South	2012	2010	Yes
Condabri Central	2013	2010	Yes
Orana	2013	2010	Yes
Orana North	2013	2012	Yes
Kainama	2015	2010	Yes
Ramyard	2014	2013	
Dalwogan	2014	2013	
Gilbert Gully	2016	2014	
Woleebee	2015	2014	
Carinya	2017	2014	

* Monitoring commenced in 2009

7.4.2 Local monitoring – locations and timing

Infrastructure (for example, retention ponds and brine ponds) and operational activities (such as vehicle refuelling) have the potential to contaminate the watertable aquifer through leakage and spills. Should aquifer injection be used as a management option for disposal of associated water, it too has the potential to change the groundwater chemistry of the receiving aquifer, as well as increasing the water level in the receiving aquifer over a large area (volume and aquifer dependent).

Monitoring of these situations should be in the immediate vicinity of the infrastructure and activities and actual locations must be identified when their designs are finalised. The identification of monitoring locations should take into account the local scale conceptual hydrogeology, particularly an understanding of anticipated groundwater flow directions, preferential pathways for groundwater movement and receptors of potential impacts (that is, essentially a risk-based approach). The

existence of local wellbore infrastructure, through which longer term background data can be incorporated, will be assessed.

Monitoring bores should be installed prior to, or simultaneously with, construction activities to ensure that background monitoring data is collected before potential impacts can occur.

7.5 Proposed groundwater monitoring strategy

7.5.1 Indicator parameter selection

Indicators can be used to measure the cause and effect relationship between human activities on the landscape and the environmental response to those activities. Suitable indicators include those:

- Commonly found in the environment
- Relatively easy and inexpensive to measure
- Sensitive to environmental change
- Specific to disturbance impacts.

Indicators can be grouped as condition and development indicators. Condition indicators relate to the physical, chemical and biological aspects of the groundwater system, while development indicators relate to anthropogenic activities. Below is a description of indicators to evaluate quality, quantity and surface-groundwater interactions as they relate back to the framework outcomes listed above in Section 7.3.

Water quantity indicators

Changes in quantity of groundwater (or availability of groundwater), flow volumes in aquifers and interaction between groundwater and surface water features are primarily determined based on groundwater surface elevations and related changes in these elevations.

Natural fluctuations in groundwater surface elevations occur in response to daily and seasonal cycles and variability in climatic conditions (that is, precipitation and evaporation). The duration of these fluctuations range from short-term (for example, shallow monitoring wells responding to individual precipitation events) to long-term (multi-year variations in climate and basin water balance).

Development-induced changes in groundwater surface elevations can be caused by removal of groundwater from an aquifer, changes in basin water balances (due to land cover changes including removal of wetlands, construction of lakes etc) and pressure effects due to injection of water into deeper aquifer intervals. More localised effects can occur as a result of leakage from ponds and dams.

The primary indicator for groundwater quantity is therefore defined as:

- *The temporal change to groundwater surface elevation in a defined aquifer interval at an established monitoring location.*

As a result, water levels at established locations will need to be monitored until the monitoring wells have reached a stabilized condition and/or sufficient background conditions have been established to compare and assess future trends. Characterisation of expected natural fluctuations in groundwater elevation in each specific aquifer is necessary to establish baseline conditions and variability prior to assessing for development influences (see Section 7.5.3 for more details). Water level fluctuations

based on seasonal effects of annual recharge events and changing climatic conditions is necessary to fully understand the natural variation in a given interval.

Using a regional-scale monitoring system, cumulative effects of groundwater withdrawal and injection can be monitored by assessing water level measurements. One way of assessing for cumulative effects is to measure the temporal percent of available head change in each well within the regional monitoring network. If available head changes by more than 20% within a season of monitoring, or the identification of a statistically significant trend is made, then the monitoring well is identified for follow-up investigation.

Secondary indicators for water quantity include:

- Groundwater interaction with surface hydrology (that is, discharge or recharge rates)
- Accuracy of modelled projections for groundwater surface elevation changes, baseflow changes and wetland groundwater interaction changes with respect to actual measured conditions.

These items are selected as secondary indicators because changes in the rate of groundwater transfer between surface water features will be preceded by changes in groundwater surface elevations within aquifer intervals adjacent to the zone being influenced, and eventually in near-surface aquifers if a connection exists.

Changes in groundwater surface elevations in some aquifer units are anticipated from development activity in the Australia Pacific LNG gas fields mainly due to groundwater withdrawal, but potentially also due to injection activities (if implemented) and potential leakage from surface storage facilities. A similar tolerance as that defined for the primary indicator is identified as the target for follow-up investigation.

Water quality indicators

To determine relevant regional water quality indicators, it is necessary to initially sample the groundwater for a wide range of parameters. Review of these results allows the identification of primary and secondary indicators. Based on the Phase 1 Field Program (Appendix B) the following potential primary indicators have been identified:

Key field-measured parameters for all groundwater monitoring include:

- Electrical conductivity
- pH
- Temperature
- Oxidation-reduction potential.

Additionally, the following parameters of interest are considered primary indicators of CSG assessment:

- Dissolved methane
- Total dissolved solids
- Chloride (Cl)
- Sodium (Na)
- Barium (Ba)

- Boron (B)
- Iron (Fe)
- Strontium (Sr)
- Phenols (total)

For monitoring associated with infrastructure, parameters will be selected on the basis of potential contaminant sources and will be defined as part of the specific environmental management plan associated with that activity. Examples include:

- Feed ponds
  - Field parameters (as noted above)
  - Total dissolved solids
  - Major ions (Ca, Mg, Na, K, HCO_3 + CO_3, SO_4, Cl)
- Brine ponds
  - Field parameters (as noted above)
  - Total dissolved solids
  - Major ions (Ca, Mg, Na, K, HCO_3 + CO_3, SO_4, Cl)
  - Trace elements (including As, Se, Hg, Pb)
- Fuel storage areas
  - Field parameters (as noted above)
  - Major ions (Ca, Mg, Na, K, HCO_3 + CO_3, SO_4, Cl)
  - Petroleum hydrocarbons (volatile and semi-volatile)

Primary indicators are defined as those used to flag situations where conditions fall outside of a well-established range of natural variability or baseline conditions. Secondary indicators are intended to facilitate any follow-up investigation required to better understand a change from baseline conditions. If needed, more sophisticated approaches may be used (such as stable or radiogenic isotopes or gas chromatography-mass spectrometry). It should be noted that both primary and secondary indicators should to be monitored until sufficient measurements have been collected to demonstrate stable conditions at the point of measurement and that background conditions have been sufficiently established to compare and assess for future trends. Typically, at least four samples (and more likely up to eight samples) are needed to establish baseline conditions at a given location and begin to track natural variability with which to assess trends outside of normal conditions. Following the establishment of baseline conditions, only primary parameters need be monitored unless significant differences are observed.

Development indicators

A number of indicators relating to development activities of the Australia Pacific LNG Project within the study area exist. For the purpose of this framework, the most relevant include:

- Extent of CSG fields and associated infrastructure and how they differ, in time and space, from the information associated with submitted EIS documents

- Number of licensed water users or withdrawals in a given area based on the aquifer and the volumes withdrawn or allocated (that is, aquifer-use intensity index)
- Number of licensed injection wells in a given area based on the aquifer priority and volumes injected (water-injection intensity index)
- Number of functional water bodies or wetlands affected by water withdrawal or surface disturbance activities (surface water impact index).

7.5.2 Sampling strategy

As the Australia Pacific LNG development is phased-in, the implementation of groundwater monitoring will be similarly phased-in but will precede development to ensure that baseline conditions and, at least, seasonal variability are identified. It is proposed that, where practical, monitoring will commence at least 12 months prior to production commencing at a particular gas field.

Water levels

Water level (quantity) measures are currently sourced from the DERM database and monitoring bores already established as part of the Australia Pacific LNG groundwater monitoring network, which includes some DERM wells. These established monitoring bores have been instrumented with Solinst Levelogger© pressure transducers with onboard dataloggers set to continuously record water levels at 12-hourly intervals.

Dedicated monitoring bores will be instrument with permanent automated water level/pressure monitoring devices, similar to the Leveloggers, or of alternative technology suitable for the monitoring requirements (for example, vibrating wire piezometers where large changes in pressure are anticipated).

The data from the loggers will be downloaded on a regular basis and uploaded into a central database. Manual water level measurements will be collected at the time of download to assure the quality of the electronic data.

Water quality

Existing monitoring results (for example, from the DERM database) are generally sporadic and, although useful in assessing long-term trends, are unlikely to be useful in determining seasonal variations. A possible scenario for water quality sampling is that it is initially undertaken quarterly or semi-annually to allow baseline conditions and seasonal variations to be determined. This would be more applicable to shallower intervals given the potential for such seasonal effects. Following the demonstration of stable conditions and the establishment of natural variation, water quality sampling for primary indicators can be reduced to annually or bi-annually until such time as an investigation is required. If this occurs, an increased frequency and schedule of analytes may be required to assist in event assessment and closure.

Water quality sampling will be undertaken using a method suitable for the analytes of concern and appropriate for the bore construction. Sampling methodologies will be in accordance with established protocols including the Water Quality Sampling Manual (Queensland EPA 1999), and will be updated with revisions to this document, new research and sampling technologies become available.

With respect to sampling for dissolved gases, a literature review will be undertaken to determine the appropriate sampling methods for the types of bores to be sampled.

Samples will be submitted to laboratories registered with the National Association of Testing Authority (NATA) for analysis.

Following quality assurance/quality control checks on the data, all results will be uploaded to a central database for assessment and reporting.

7.5.3 Data analysis and monitoring bore trigger development

Different methods exist for the assessment of groundwater monitoring data. One method is the use of statistical tests for the development of indicator parameter trigger levels. This method is currently being used by the Government of Alberta to address groundwater conditions in the Canadian Oil Sands and supplement regional monitoring efforts. It is recognised that alternative methods do exist; however, statistics honour natural data variability and facilitate tracking of quality and quantity conditions. This approach is therefore considered appropriate and is discussed further as an indicative method of data assessment. It is also recognised that the regulator may define targets, triggers and thresholds against which monitoring data is to be assessed. Australia Pacific LNG is committed to working with the regulator to define scientifically justified and practical limits.

To facilitate identification of a situation requiring follow-up actions, past approaches have used established generic guidelines to indicate the limit or control condition. These criteria tend to be very conservative and may not take into consideration natural conditions of the area. A more useful approach is to derive screening level values based on data from established baseline monitoring wells. These results are used in combination with other statistical techniques such as control charting and trend analysis to filter out spurious data excursions from real events.

It should be kept in mind that effects from a certain activity may not manifest themselves for some time (for example, long-term pumping and the resulting effects on basin water balance) and when detected may be very difficult to mitigate. A risk-based approach will be used to assess the potential for adverse effects from such activities and to derive criteria for action based on receptor proximity and sensitivity. Projections from modelling will be used to assess the future risk associated with certain activities, followed by monitoring for future model validation.

Preliminary targets and limits

Once enough data is collected (greater than eight readings) targets will be developed based on a statistical analysis which considers natural variability within the aquifer and well, and trend identification (for example, Mann Kendall test for trend and Sen's slope estimator). At this time, there is insufficient historical and spatial data in the region to generate such values. Therefore, a proposed approach is provided for guidance only:

Table 7.3 Criteria for application of preliminary trigger and threshold

Number of indicator measurements	Preliminary trigger value	Preliminary threshold value
4 or less	80th percentile	Published criterion (if available)
5 to 8	80th percentile	Published criterion (if available) or exceedance of 95th percentile
Greater than 8	See Section 7.5.3	See Section 7.5.3

Water quality thresholds need to be established through adoption of existing relevant guidelines (depending on aquifer use) and background data. Where established, water quality guidelines should

be compared against the median and the 90th percentile of background values. If both values are naturally exceeded, the 90th percentile can be identified as the preliminary threshold. These limits can be used until more data becomes available for the region, at which point the framework can be amended as per the adaptive management process. Site-specific water quality limits have previously been set using the percentile approach – for example, 80th percentile (Australia, ANZECC and ARMCANZ 2000); 95th percentile (New Zealand, ANZECC & ARMCANZ 2000).

The occurrence of some constituents of potential concern (for example, strontium identified during the Phase 1 monitoring program – see Appendix B) is not uncommon as many parameters are present naturally. However, it is important to identify pathways of concern as some groundwater may never reach a receptor, or constituents may be significantly attenuated in the subsurface prior to reaching an exposure point. For this reason, it is common to use well-established baseline values to generate targets rather than stewarding to a published guideline for the same constituent. For indicator parameters with no guidelines, the percentile approach described previously can be implemented.

As more groundwater quality data becomes available through the monitoring of the regional network, it will become possible to assess statistical trends for each indicator parameter at each well (see next section for statistical approach). Adverse trends in water quality can be identified and follow-up investigation can be initiated per the established approach outlined in Section 7.5.4. The intent of the investigative follow-up is to identify natural exceptions to established targets and thresholds and facilitate revision of the targets and thresholds as per the adaptive management approach.

Future targets and limits

As more data becomes available, statistical control charting can be utilised for each selected indicator parameter measured at a regional monitoring well. This method honours natural data variability and allows tracking of quality and quantity conditions at each designated location. The technique is commonly used to determine whether or not an observed value, within a given set of data, is significantly different from historical values (Gibbons 1994). An Upper Control Limit (UCL) is calculated for each parameter measured at a well where a large number of data points exist. Similarly, a Lower Control Limit (LCL) is calculated to determine the lower bounds on the temporal data set. A data point that exceeds either control limit is an indication that something unusual may be occurring with respect natural conditions. Such an excursion can result from a false detection; therefore, verification of the data point is required first and may be followed by a more in-depth review using more sophisticated techniques of analysis.

An example of the style of proposed data charting, and comparison to established control limits is provided in Figure 7.2. In this figure, the action level and initiation of a follow-up response is indicated at the point where a condition moves from the natural range of variability past an established target level or trigger value. The approach uses a green, yellow and red condition to establish the level of action to a particular situation. Thus, changing from a green condition to yellow condition can be defined as exceeding an established trigger level. Subsequently, if conditions move from yellow to red, more stringent controls and/or mitigation may be necessary. This can be further described as follows:

Green condition: Groundwater quality and/or quantity results are within the range of natural variability or established baseline conditions.

Yellow condition: Evaluation of data indicates a trigger level has been exceeded. As a result, implement the investigation phase of the groundwater management plan. Management activities can be invoked as appropriate and must clearly demonstrate trend reversal through their implementation.

Red condition: Exceeding a water quality or quantity threshold requires an increased level of groundwater management, risk assessment, remediation and/or mitigation to demonstrate trend reversal and an ultimate return to baseline conditions.

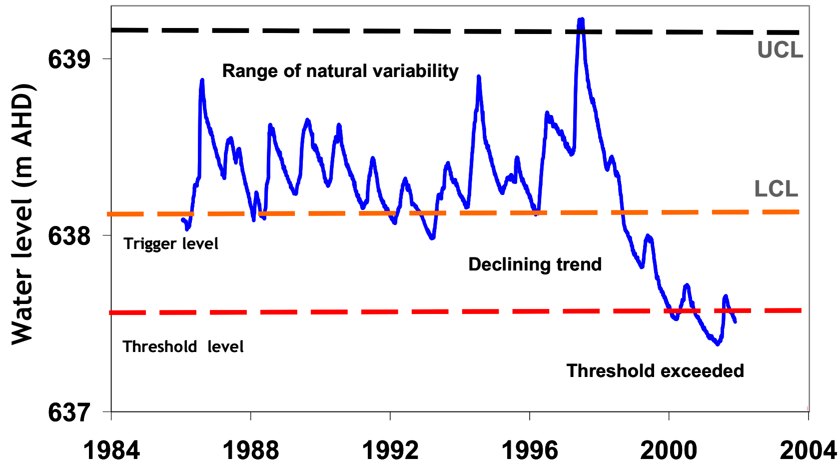


Figure 7.2 An example of statistical charting for follow-up response

As part of the approach to assessing indicator conditions, trend analysis can be used to assess direction and rate of parameter change. One example of this is the non-parametric Mann Kendall test for trend (Mann 1945, Kendall 1975) combined with a modified version of Sen's non parametric slope estimator (Sen 1968).

Trend analysis for selected indicator parameters can use all available data generated following selection and/or installation of regional monitoring wells. The Mann-Kendall and Sen's slope are evaluated only on data sets where at least four, and no more than 40, data points exist. To indicate potentially significant trends, results can be screened according to the following criteria:

- A probability of 95% or greater usually forms the first level of screening, based on the convention of a 95% confidence interval used in statistical reporting.
- An absolute slope threshold may then be used to screen out high probability trends with very low slopes. A normalised slope threshold of ±10% per year may subsequently be used to screen out small relative trends superimposed on high concentrations.

The overall goal of control charting and trend analysis is to detect situations that may be heading in a direction and at a rate that is unacceptable. Therefore, reversal of adverse trends in water quality or quantity indicators is a fundamental part of achieving the regional outcomes outlined in Section 7.1.

7.5.4 Reporting monitoring results

Monitoring results, both water quantity and water quality, should be verified and stored in an integrated database. Review of the data should be undertaken on an agreed-upon basis with DERM (for example, annually). At a minimum, these reviews should identify and provide comment on:

- Changes to the proposed monitoring network from the previous report (for example, new monitoring bores coming online)
- Most recent and historical monitoring results, trends, changes in trends in comparison with interim or adopted triggers and thresholds

- Differences between the actual development sequence and that included in the most recent version of the cumulative effects numerical model
- Comparisons between the monitoring results and the cumulative effects numerical model predictions
- Histories of complaints regarding water level drawdown or gas migration in private water bores
- The proposed response plan for investigation of indicator parameters outside the control limits.

The monitoring report will be submitted to the approving agency in accordance with the requirements of the PAG Act. Consideration will also be given to providing a non-technical summary for public distribution.

7.5.5 Investigation and response process

A network of regional monitoring wells will be established in the study area, which will include some existing baseline monitoring wells (for example, existing DERM wells), and new monitoring wells to be installed to form the regional network. Depending on sampling frequency and the amount of time for well conditions to stabilise, it may take more than a year to properly characterise baseline conditions in key regional aquifers, and much longer to establish the range of natural variability. It will also be necessary to establish baseline conditions in landholder bores against which potential impacts and claims to 'make good' can be assessed.

To help facilitate stabilization of well conditions (particularly quality) newly installed regional monitoring wells should be assessed more frequently at first to establish a database of values for future comparisons. During this time, monitoring data collected from existing and new regional wells can still be reviewed against preliminary targets and thresholds to roughly assess against regional outcomes. As sufficient data is collected, results from individual monitoring wells that indicate either:

- Deviation from established baseline conditions
- Levels exceeding statistical control limits *or*
- Identification of a significant trend

can then be assessed using an investigative approach.

For example, follow-up to the detection of an indicator parameter excursion, outside of established variability or established criterion, may initiate a phased investigative approach incorporating four basic stages of review. These include:

- Verification
- Initial evaluation
- In-depth evaluation (including risk assessment)
- Modification of activities, or management of the effect (e.g. 'make good')

An example flow diagram for follow-up activities during operation of the regional groundwater monitoring network is provided in Figure 7.3.

Prior to responding to a data excursion using the following investigative approach, it must be clearly demonstrated that the monitoring well(s) has stabilised sufficiently to indicate baseline conditions. Because it can take some time for conditions in a newly installed well to stabilise, it is recommended

that at least four measurements for each indicator parameter be collected prior to applying any follow-up response.

The initial step in the process is *verification* of the measurement. This process begins with a check on integrity of the measurement, including a review of the protocol used to collect the measurement and the integrity of the monitoring well itself.

If the original data point is found to be correct, then an investigation of the results is conducted and an *initial evaluation* phase is initiated to identify the origin or source of the indicator excursion. This phase of investigation is conducted in a phased manner so that all applicable information is accessed and utilised, including the influence of other groundwater users (e.g. increased pumping), changes in climatic conditions, changes in operations, etc. This includes identification of knowledge and/or data gaps and completion of additional characterization work to fill these gaps and bring the issue into proper context. The goal of the review process is to ensure that any potential effects linked to the indicator change are properly assessed in order to reduce or eliminate any associated consequences. This is achieved by accessing essential information for the decision-making process.

If the *evaluation* phase of the investigation identifies the issue as being a natural aberration of the system, then the result is documented and the area characterisation is updated. This may lead to the revision of a trigger or threshold, or identification of an area as a natural exception to the regional setting. If, however, the results indicate an anthropogenic influence, an assessment of risks is undertaken, and/or use of predictive modelling to assess potential future effects.

If the *initial evaluation* phase of the investigation indicates a positive result (stabilisation or reversal of unacceptable trend or low risk situation) then a more *in-depth evaluation* or characterisation of the area is updated along with associated trigger and threshold for the associated parameter, and regional monitoring is continued to ensure stabilisation and/or trend reversal. If the result is negative, then *modification* to the identified operation or operations may be required, followed by an *evaluation* phase including risk assessment, or mitigation measures implemented (for example, ‘make good’). If a positive result is anticipated, and trends are expected to stabilise or reverse, then the result is documented and a return to regular monitoring occurs. If not, then the continued operation of the identified activity or activities causing the effected may need to be reviewed in consultation with the regulator and other affected parties. Additionally, ‘make good’ obligations may need to be fulfilled pursuant to the requirements of the *Petroleum and Gas (Production and Safety) Act (2004)*.

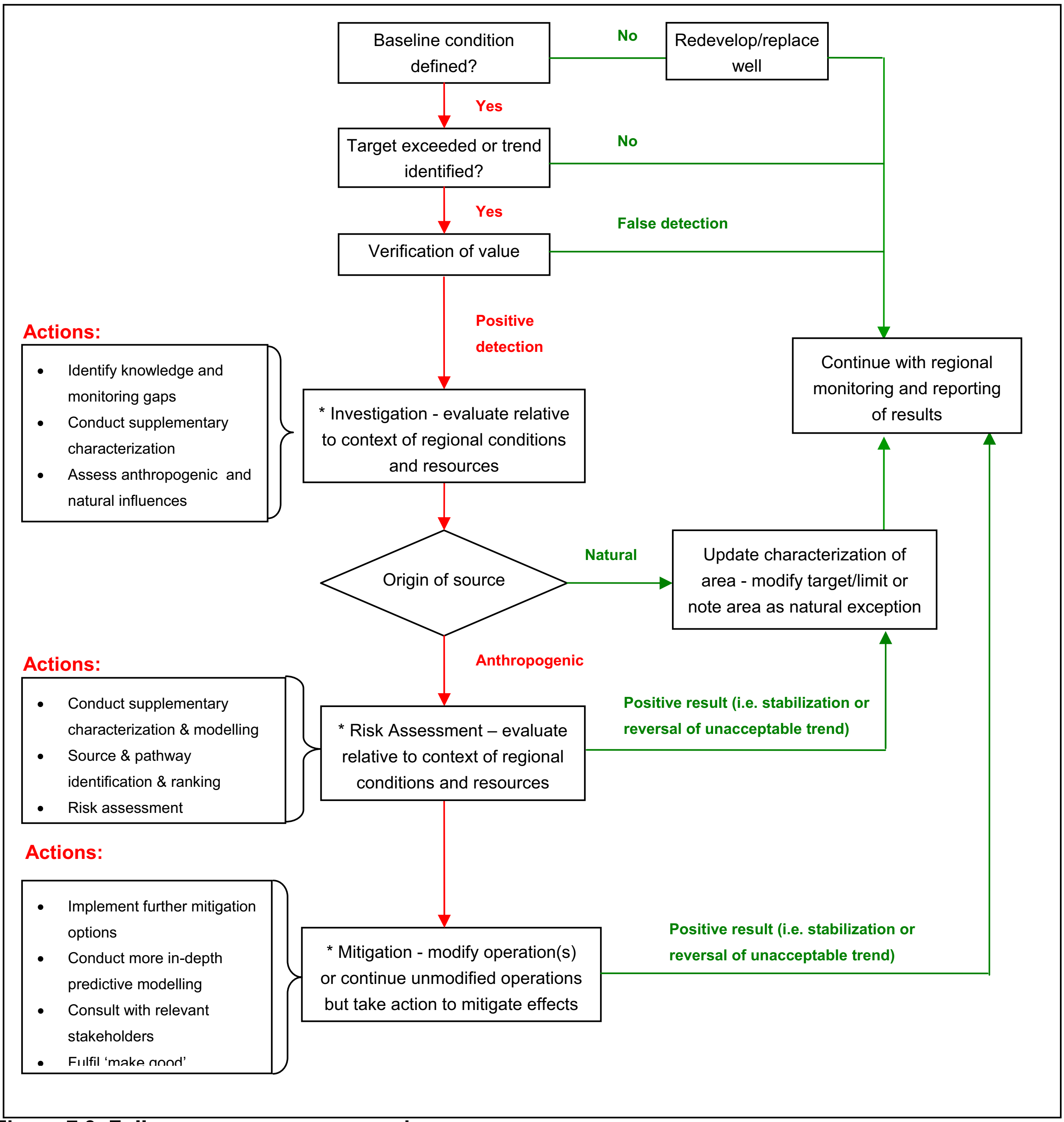


Figure 7.3 Follow-up response approach

7.6 Baseline monitoring – Phase 1 fieldwork program

The Phase 1 fieldwork of the groundwater monitoring program resulted in the following data being collected:

- 17 individual water level readings
- Laboratory analyses for 10 bores
- Installation of pressure transducers and dataloggers and ongoing 12-hourly water level readings in 10 bores
- Geophysical bore surveys.

Water quality conditions between aquifers were found to be variable, particularly in the Cainozoic Units where the electrical conductivity of the groundwater ranged from 3.2mS/cm to 18.9mS/cm. Strontium, boron and barium were identified at relatively high concentrations particularly in samples collected from the Cainozoic-aged aquifer.

Analysis of dissolved methane indicated the presence of methane in the Gubberamunda Sandstone at concentrations similar to those noted for the Walloon Coal Measures. The headworks and method of collection of the samples from the coal measures may have enhanced volatilisation of some the gas, hence the dissolved concentrations may be under-reported, as much of the gas will have been in the vapour phase. Monitoring of wellhead gas concentrations with a portable gas meter did not reveal the presence of gas emissions in any of the bores visited.

The potential for gas migration was observed an old petroleum exploration well as gas bubbles were noted to be rising in the water column. Based on gamma logging, the well was deemed to be open across the top of the Walloon Coal Measures, the Springbok Sandstone, the Westbourne Formation and a small interval of the Gubberamunda Sandstone.

The video camera inspections of many of the DERM wells indicated that some had dislocations in their pipe sections, and that the PVC used in their construction was becoming compromised. Consideration should be given the refurbishment or replacement of these monitoring bores if they are to be used for future monitoring.

As no existing monitoring wells were established in the Springbok or Hutton Sandstones during the Phase 1 program, considered key intervals for monitoring, existing CSG exploration and testing wells were investigated for potential retro-fitting into monitoring wells. Talinga 11 and Talinga 17 have been identified for retro-fit into Hutton and Springbok monitoring bores, respectively.

The work-over on Talinga 11 commenced in mid-October 2009. Talinga 11 was an early pilot well and was originally completed with perforations across the coal seams and the Hutton Sandstone. Formation fracturing had been carried out in the well to improve local permeability, and a bridge plug was installed beneath the lowermost perforated interval within the coal seams to inhibit inter-aquifer flow. During the work-over, it was found that the well stimulation program had damaged the well casing within the coal measures such that it was not possible to complete the retrofit.

Workover of Talinga 17 was completed in January 2007 to convert this CSG exploration well into a Springbok Sandstone monitoring well. This has been successfully achieved and instrumentation of the well to assess temporal water level changes is to occur sometime in 2010.

7.7 Monitoring potential for land subsidence

The potential for aquifer deformation and land subsidence should be addressed by way of baseline and ongoing regional groundwater level monitoring in areas at higher risk of CSG effects. If groundwater level monitoring detects significant drawdown in high risk areas, additional monitoring may be required. An early detection of potential land subsidence impacts may trigger mitigation measures, an example of which is the injection of water into affected aquifers to counteract the effects.

Groundwater level and quality monitoring may also assist in identifying any compromise to aquitard integrity through fracturing (and inter-aquifer flow); a possible consequence of geological deformation.

8. Mitigation and management

Most of the potential groundwater-related impacts associated with the Australia Pacific LNG coal seam gas extraction will be mitigated through appropriate design, construction and management practices. However, some residual risk remains, and measures are proposed to mitigate these risks should they eventuate.

8.1 Minimising drawdown effects through conservative production well construction

Drawdown effects in overlying and underlying aquifers are strongly controlled by the thickness and permeability of the intervening aquitards between the coal measures and the Springbok Sandstone and Hutton Sandstone. The Springbok Sandstone unconformably overlies the Walloon Coal Measures and in places, erosion of the upper Walloon Coal Measures has resulted in the Springbok being in direct connection with the coal seams. Thinner accumulations of aquitard material, or lack thereof, will lead to greater drawdown effects.

Some of the effects can be mitigated by effectively increasing the distance, and aquitard thickness, between the uppermost coal seam and the Springbok Sandstone. This can be achieved by sacrificing the uppermost coals (where practicable) by sealing them off from the productive part of the CSG well.

Australia Pacific LNG employs this design in the majority of production wells where a connection is identified. This control measure will continue to be employed (where practicable) where the aquitards are thin or non-existent.

8.2 Mitigating impacts to existing water bores

8.2.1 Trigger thresholds

Trigger levels are yet to be developed by the Chief Executive in accordance with the *Petroleum and Gas (Production and Safety) Act 2004* for the aquifers in the Surat Basin. Australia Pacific LNG is working with the Government of Queensland to establish appropriate trigger levels for groundwater drawdown in the Study area aquifers. The current Great Artesian Basin Resource Operations Plan (2007) indicates a drawdown influence of 5m for any new water licence in order to protect existing entitlements.

Under the requirements of the *Petroleum and Gas (Production and Safety) Act 2004,* the triggers must take into account the hydrogeological regime as arbitrarily designated values may not be relevant in assessing reductions to groundwater availability.

As there is little existing precedence with regards to a blanket rule for assessing impacts, it is proposed that Australia Pacific LNG continue to consult with Government of Queensland to develop appropriate triggers and thresholds based on available drawdown. The use of triggers and thresholds apply to changes of water level in a groundwater extraction bore only and are not applicable to monitoring bores where a trend analysis approach may be proposed.

Breach of the trigger level will initiate an investigation into the cause of the drawdown to gain a full understanding of the level of effect. This will be achieved through monitoring and assessment of the data in relation to natural variability of conditions and possible changes to extracted volumes and rates of extraction.

8.2.2 'Making good'

Should the regional investigation program (Section 7.5.5) indicate that declining water levels or changes to groundwater quality conditions are the result of Australia Pacific LNG activities rather than in response to natural variation or another groundwater extraction, and if an established trigger or threshold has been exceeded by Australia Pacific LNG's activities, Australia Pacific LNG will 'make good' the water supply to the impacted water bore in accordance with the make good requirement of the *Petroleum and Gas (Production and Safety) Act 2004*. The actions to make good may include, but are not limited to:

- Deepening the pump to increase the available drawdown
- Deepening the bore within the same aquifer if the current construction allows
- Installing a replacement bore at a location less affected by the CSG operations or into a different aquifer
- Injection of treated water (of similar quality to the native groundwater)
- Monetary compensation for the increased cost of pumping, or for the effects of impaired capacity
- Provision of an alternative water source of equitable quality to the impaired bore *or*
- Actions to make good should not be implemented with appropriate consultation and agreement with relevant stakeholders.

It is noted that with respect to these actions to 'make good' the water supply in an impacted bore a CSG industry-wide response will be required. In this regard, Australia Pacific LNG is committed to collaborating with the Government of Queensland, and other CSG operators in the region, to develop an approach to regional-scale groundwater monitoring program and cumulative effects groundwater modelling, along with an agreed process to assessing and apportioning the 'make good' responsibility. Consideration will need to be given to the applicable timing of the 'make good' requirement as the drawdown effects are projected to continue post CSG-production.

8.3 Mitigating risks associated with gas migration

Experiences in the USA suggest that a good understanding of natural and existing modes of gas seepage prior to the onset of CSG development is critical for the future management of potential issues. Although risks associated with gas migration are considered low, further investigation is warranted. This should commence with a risk assessment to better identify the risks associated with:

- Potential seepage areas
- Potential wellbore pathways
- Potential areas where gas could accumulate in overlying aquifers

Should the risk be considered medium or high, targeted field investigations may be warranted, which may include:

- Collection of additional samples for analysis from water wells that are licenced to extract from the Walloon Coal Measures in the Springbok Sandstone and Gubberamunda Sandstone in the high risk areas to identify the source of the gas
- Analysis of samples for dissolved methane and representative isotopes to determine biogenic or thermogenic provenance

- Further investigation of the potential for abandoned petroleum wellbores to act as conduits for gas migration through sampling and analysis, particularly on Australia Pacific LNG tenements.

Should the presence of gas seeps or conduits be identified, an assessment should be undertaken to determine the risk to human health and the natural environment. If a high risk situation is identified, mitigation measures will be implemented, which may include:

- Appropriate abandonment of wellbores acting as conduits
- Installation of hydraulic barriers (for example, injection or extraction wells)
- If these are water bores, ‘making good’ the water supply.

With regard to Australia Pacific LNG CSG production wells, wellhead integrity will be assessed on an ongoing basis as part of normal operations.

9. Future activities

9.1 Groundwater model revisions

Revisions to the numerical groundwater model will likely be conducted as a result of the monitoring process. Data obtained from the regional monitoring network will be compared to model projections as a *verification* stage.

Results from model projections derived by the refined model will then be assessed in the context of the current regional monitoring system. Consideration will be given to monitoring network refinements if significant gaps are noted.

9.2 Groundwater monitoring

Aquifer risk mapping has identified areas where receptors are at higher potential for drawdown effects from CSG field development activities. The landholders in these areas may be contacted and bore surveys may be undertaken to assess current conditions. Where possible, these surveys should identify existing well condition, water level, water quality and pump setup.

A significant volume of data has been utilised in this study, and it is anticipated that a much larger dataset will be accumulated as a result of future monitoring activities. This data should be stored in an integrated database which will facilitate the data review and model validation process. Information from the monitoring programs should be communicated to relevant stakeholders and public bodies to inform them, in a timely manner, of regional conditions of the groundwater resources.

10. Conclusions

The initial numerical groundwater flow model was developed to simulate associated water production from the coal seams according to two scenarios: the Australia Pacific LNG Project operating independently of other developments ('project case') and in conjunction with other operators ('cumulative case'). The magnitude of the projected groundwater level drawdown in the overlying and underlying aquifers was generally related to the thickness of the intervening lower permeability layers and the projected drawdown in the coal seams. Broadly, the extent of the groundwater level drawdown in aquifers of the Surat Basin underlying and overlying the Walloon Coal Measures is projected to expand in the 'cumulative case' (relative to the 'project case') due to the consideration of associated water production by all CSG operators.

It is cautioned that the numerical model projections presented in this document are preliminary. However, on the basis of the assumptions adopted, the model outcomes and the interpretation of potential impacts are expected to be very conservative. Potential effects and impacts associated with the projected 'cumulative case' groundwater level drawdown include:

- A low potential for adverse groundwater quality changes and groundwater induced salinity
- A medium risk of reduction of groundwater production rates in landholder bores, which should be managed by monitoring and mitigation according to the 'make good' requirement of the PAG Act. Such measures may reduce the residual risk to low
- A low risk of the reduction of baseflow to surface water systems and/or increases in stream losses
- A low risk of reductions to spring flows and negative effects of reduced water availability to groundwater dependent ecosystems
- A medium risk of gas migration away from the gas fields and through wellbore pathways. This risk should be managed through further investigation and potential monitoring, and mitigated through appropriate abandonment of affected bores to reduce the residual risk to low
- A low risk of differential land subsidence
- A low risk of Australia Pacific LNG production wells providing an artificial connection between aquifers thereby locally exacerbating drawdown effects in overlying aquifers
- A low risk of existing wellbores providing an artificial connection between aquifers thereby locally exacerbating drawdown effects in overlying and underlying aquifers.

Potential hydrogeological impacts and effects associated with associated water and waste stream management associated with gas production include:

- A low risk of uncontrolled discharge of water and/or wastewater from storage ponds through appropriate design and construction. The low residual risk should be managed through compliance monitoring and mitigation measures (if necessary)
- A low risk of potential impacts associated with the temporary discharge of high quality treated water to surface water courses (Phase 1)
- Risks associated with the potential injection water or brines should be further assessed following comprehensive feasibility testing, including field trials.

Potential hydrogeological impacts associated with the construction and operation of infrastructure proposed for the gas fields include:

- Low risk of a reduction of groundwater recharge due to the creation of low permeability surfaces
- Low risk associated with pipeline leakage due to appropriate testing and management controls
- Low risk of groundwater quality impacts from potential spills due to appropriate management controls
- Low risk of impacts to potential receptors associated with groundwater extraction for construction purposes. Potential impacts to landholder bores should be mitigated through 'making good' the water
- A low risk of Australia Pacific LNG production wells providing an artificial connection between aquifers due to appropriate design and construction which exceeds the requirements for water bores in Australia
- Low risk of groundwater quality impacts resulting from drilling activities due to the use of appropriate drilling fluids.

It has been recommended that risks associated with the project are managed through an adaptive management process whereby defined outcomes promote the continual acquisition of monitoring data which is then used to inform management decisions. This should be accompanied by future revisions and verification of the numerical groundwater flow model and ongoing assessment of risks.

An indicative monitoring program has been proposed. Indicative locations for groundwater monitoring were based on the projections of the numerical model and taking into account receptors of potential CSG effects. Water level, water quality and development indicators have been proposed for monitoring. It has been recommended that monitoring data be reviewed on an agreed-upon basis with DERM using a trend analysis and control charting approach to the assessment of the data. A baseline monitoring program has been implemented which focused on the Talinga development area. It is suggested that this programme be expanded into other CSG tenures at least 12 months in advance of production development. Community groups should be involved in the implementation of the groundwater monitoring program.

Potential impacts to landholder groundwater supplies should be mitigated through the 'make good' requirement of the PAG Act. Consultation with DERM regarding appropriate triggers thresholds relating to the available drawdown should continue. If an agreed-upon trigger level is exceeded, mitigation and/or 'make good' measures should be implemented. 'Make good' measures should only be implemented through consultation with relevant stakeholders.

Drawdown effects to overlying aquifers can be reduced by increasing the effective thickness of intervening aquitards. This practise should be continued in the construction of CSG production works where the upper coal seams are in direct connection with the Springbok Sandstone or where the intervening aquitard is thin.

A risk assessment to evaluate the potential for gas migration should be undertaken and the feasibility of injection of water and waste streams should be further investigated.

References

Age Consulting. 2005, Great Artesian Basin Water Resource Plan, River Baseflow from Aquifers of the GAB.

Airey, P.L., Calf, G.E., Campbell, B.L., Habermehl, M.A., Hartley, P.E. and Roman, D. 1979, Aspects of the isotope hydrology of the Great Artesian Basin, Australia. In: Isotope Hydrology 1978, 1, p. 205-219. Proceedings International Symposium on Isotope Hydrology – International Atomic Energy Agency and United Nations Educational, Scientific and Cultural Organisation, Neuherberg, Fed. Rep. Germany, 19-23 June 1978. International Atomic Energy Agency, Vienna, 1979.

Alberta Environment 2009, Potential for Gas Migration Due to Coalbed Methane Development. Alberta Environment, Authors: Armstrong, J., Mendoza, C. and Gorody, A. July 2009.

Alberta Environment 2006, Water Conservation and Allocation Guideline for Oilfield Injection. Alberta Environment.

ANZECC and ARMCANZ. 2000, The Australian and New Zealand Guidelines for Fresh and Marine Water Quality. National Water Quality Management Strategy.

Audibert, M. 1976, Progress Report on the Great Artesian Basin Hydrogeological Study 1972 – 1974. Bureau of Mineral Resources, Geology and Geophysics.

Barnett, B.G. and Muller, J. 2008, Upper Condamine Groundwater Model Calibration Report. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia.

Bureau of Rural Sciences and Queensland Department of Natural Resources and Mines (BRS & NRM). 2003, Groundwater Recharge in the Great Artesian Basin Intake Beds, Queensland Department of Natural Resources and Mines Technical Report.

BRBC 2008, Bow Basin Watershed Management Plan – Phase 1. Prepared by the Bow Basin Watershed Management Plan Steering Committee, Version 1.0, Bow River Basin Council. September 10, 2008.

Cadman, S.J., Pain, L. and Vuckovic, V. 1998, Bowen and Surat Basins, Clarence-Moreton Basin, Gunnedah Basin, and other minor onshore basins, Queensland, NSW and NT. Australian Petroleum Accumulations Report 11, Bureau of Resources Sciences, Canberra.

Calf, G.E. and Habermehl, M.A. 1984, Isotope hydrology and hydrochemistry of the Great Artesian Basin, Australia. In: Isotope Hydrology 1983, p. 397-413. Proceedings International Symposium on Isotope Hydrology in Water Resources Development, International Atomic Energy Agency and United Nations Educational, Scientific and Cultural Organisation, Vienna, Austria, 12-16 September 1983. International Atomic Energy Agency, Vienna, 1984.

Chafin, D.T. 1994, Sources and Migration Pathways of Natural Gas in Near Surface Ground Water Beneath the Animas River Valley, Colorado and New Mexico. U.S. Geological Survey Water-Resources Investigations Report 94-4006. Denver, Colorado, 65 pp.

Clifton, C. and Evans, R. 2001, A framework to assess the environmental water requirements of groundwater dependent ecosystems. In Third Annual Stream Management Conference (Eds: Rutherford, I, Sheldon, F., Brierley, G., and Kenyon, C.) Brisbane 29 August, 2001 149-155.

Cranfield, L.C., 1992. Maryborough, Queensland. 1:250 000 Sheet SG 56-6. First Edition, Queensland. Department of Resource Industries

CSIRO 2007. Climate Change in Australia – Technical Report 2007. ISBN 978192123947.

CSIRO 2008, Water availability in the Condamine-Balonne. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia. 169pp.

Department of the Environment, Water, Heritage and the Arts. 2001, The Community of Native Species Dependant on Natural Discharge of Groundwater from the Great Artesian Basin.

DEEPI 2009, Blueprint for Queensland's LNG Industry, LNG Industry Unit, Department of Employment, Economic Development and Innovation. Queensland Government. August, 2009.

DERM 2004 Great Artesian Basin stock and domestic groundwater estimates, Department of Environment and Resource Management (DERM) digital data.

DME 1997 The Surat and Bowen Basins in South-East Queensland, Queensland Minerals and Energy Review Series. P. Green (editor). Queensland Government Department of Minerals and Energy. CD Reprint 2009.

Edgar, T.V. and Case, J.C. 2000, Pumping Induced Settlement of Aquifers: Wyoming State Geological Survey Preliminary Hazards Report PHR 00-1, 9 p.

Environmental Protection Agency. 2005, Wetland Management Profile: Great Artesian Basin Spring Wetlands.

EPAV 2000, Groundwater Sampling Guidelines. State Government of Victoria Environment Protection Authority, Publication 669, April 2000.

Exon, N.F. 1967. Eddystone, Queensland, 1:250 000 geological series sheet SG55-7. First Edition. Bureau of Mineral Resources, Australia,

Exon, N.F., Burger, D., Jensen, A.R., Thomas, B.M., Reiser, R.F., 1971. Chinchilla, Queensland, 1:250 000 geological series map. Sheet SG/56-09, 1st edition., Bureau of Mineral Resources, Australia

Exon, N.F., Mond, A., Reiser, R.F., 1972. Dalby, Queensland, 1:250 000 geological series map. Sheet SG/56-13, 1st edition., Bureau of Mineral Resources, Australia

Exon, N.F. 1976, The Geology of the Surat Basin in Queensland. Bureau of Mineral Resources, Geology and Geophysics. Australian Government Publishing Service, Canberra.

Faifax R. J., R. Fensham, R. Wager, S. Brooks, A. Web and P. Unmack. 2007, Recovery of the red-finned blue-eye: an endangered fish from springs of the Great Artesian Basin. Wildlife Research 34: 156-166.

Fensham R. J., R.J. Fairfax and P.R. Sharpe. 2004, Spring wetlands in seasonally arid Queensland: floristics, environmental relations, classification and conservation values. Australian Journal of Botany 52: 583-595.

Fensham, R.J. 2010, Personal Communication, 18 February 2010. The Department of Biological Sciences, University of Queensland.

Fisher, J.B. 2001 Environmental Issues and Challenges in Coal Bed Methane Production, http://ipec.utulsa.edu/Conf2001/fisher_92.pdf

Folland, C. 2008, Interdecadal Pacific Oscillation Time Series. Met Office Hadley Centre for Climate Change, Exeter, UK. July 2008.

Forbes, V.R., Jensen, A.R., Mollan, R.G., Gregory, C.M., Exon, N.F., 1967. Taroom, Queensland. 1:250 000 geological series sheet SG55-8. First Edition., Bureau of Mineral Resources, Australia

Freeze, R.A. and J.A. Cherry. 1979, Groundwater. Prentice-Hall, Inc., Englewood Cliffs, NJ, 604 pp.

Great Artesian BasinCC 1998 Great Artesian Basin Resource Study. Great Artesian Basin Consultative Council, Ed. Cox, R. and Barron, A., November 1998.

Gibbons, R.D. (1994) Statistical Methods of Groundwater Monitoring, John Wiley & Sons, New York.

Golden Software 2007 Surfer Version 8.08 Surface Mapping System, Golden Software Inc., Golden Colorado, 31 October 2007.

Golder Associates Pty Ltd. 2008, Report on the Groundwater Impact Study for the Coal Seam Gas Operations Chinchilla, Surat Basin Queensland. Report prepared for Queensland Gas Company and Origin Energy.

Gray, A.R.G., 1972, Stratigraphic Drilling in the Surat and Bowen Basins, 1967-1970. Geological Survey of Queensland Report 71.

Great Artesian Basin Consultative Council. 1998, Great Artesian Basin Resource Study. R. Cox and A. Barron, eds.

Great Artesian Basin Consultative Council, September 2000, Great Artesian Basin Strategic Management Plan.

Habermehl, M.A. 1980, The Great Artesian Basin, Australia. BMR Journal of Australian Geology and Geophysics, 5, p.9-38.

Habermehl, M.A. 1982, Springs in the Great Artesian Basin, Australia – Their Origin and Nature. Australian Government Publishing Services

Habermehl, M.A. 2001, Chapter 11 – Hydrogeology and Environmental Geology of the Great Artesian Basin, Australia. In: Gostin, V.A. (editor), Gondwana to Greenhouse – Australian Environmental Geoscience. Geological Society Inc., Special Publication 21, p.127-143, 344-346.

Habermehl, M.A., 2001 - Wire-line logged waterbores in the Great Artesian Basin, Australia - Digital data of logs and waterbore data acquired by AGSO. Bureau of Rural Sciences, Canberra

Habermehl, M.A. 2002, Hydrogeology, Hydrochemistry and Isotope Hydrology of the Great Artesian Basin. Bureau of Rural Sciences, Water Science Program, Canberra, ACT.

Hatton, T. J. and Evans, R. 1998, Dependence of ecosystems on groundwater and its significance to Australia. LWRRDC Occasional Paper 12/98.

Hennig, A. 2005, A Summary of the Hydrogeology of the Southern Eromanga and Surat Basins of the Great Artesian Basin. CO2CRC Report No. RPT05-0024

Herczeg, A.L., Torgersen, T., Chivas, A.R. and Habermehl, M.A. 1991, Geochemistry of groundwaters from the Great Artesian Basin, Australia. Journal of Hydrology, 126, p.225-245.

Hillier, J. 2000, Response to Comments Made by Professor L Endersbee on the Great Artesian Basin of Australia. ATSE Focus No. 114, November / December 2000.

Holling CS, 1978. Adaptive environmental management and assessment. Wiley, Chichester.

Huxley W.J. 1982, Condamine River Groundwater Investigation. The Hydrogeology, Hydrology and Hydrochemistry of the Condamine River Valley Alluvium, vol. 1. Queensland Water Resources Commission.

Intergovernmental Panel on Climate Change (IPCC), 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Integovernmental Panel on Climate Change [Core writing team Pachauri, R.K. and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

Kendall MG, 1975. Rank Correlation Methods, Charles Griffin, London

Lane, W.B. 1979, Progress Report on Condamine Underground Investigation to December 1978. Volume 1. Queensland Water Resources Commission.

Love, AJ, Herczeg, AL, Sampson, L, Cresswell, RG, Fifield, LK 2000: Sources of chloride and implications for 36Cl dating of old groundwater, south-western Great Artesian basin, Australia. Water Resour. Res. 36(6), 1561-1574.

LWBC 2003. Minimum Construction Requirements for Water Bores in Australia Edition 2 Revised September 2003. Land and Water Biodiversity Committee, Queensland Department of Natural Resources, Mines and Energy, 2003.

Mann, HB 1945. Nonparametric tests against trend, Econometrica, 13, 245-259.

Milligan, E.N., Exon, N.F., Wilford, G.E., 1971. Roma, Queensland, 1:250 000 geological series map. Sheet SG/55-12, 1st edition., Bureau of Mineral Resources, Australia

Mond, A. , Olgers, F. , Flood, P.G. 1972. Goondiwindi, Queensland, 1:250 000 geological series map. Sheet SH/56-01, 1st edition. Bureau of Mineral Resources, Australia

National Health and Medical Research Council and Natural Resource Management Ministerial Council. 2004, Australian Drinking Water Guidelines. National Water Quality Management Strategy.

Oil Company of Australia (Moura) Limited. 2003, Summary of Potential Sandstones for Walloon Subgroup Production Water Reinjection in the Talinga Region Report. April 2003.

Parsons Brinkerhoff. 2004, Coal Seam Gas Water Management Study. Report prepared for the Department of Natural Resources, Mines and Energy.

Queensland Department of Natural Resources. 2005. Hydrogeological Framework Report for the Great Artesian Basin Water Resource Plan Area.

Queensland Department of Natural Resources and Water. 2006. The Great Artesian Basin. March 2006.

Queensland Department of Natural Resources. 2007, Great Artesian Basin Resource Operations Plan and Explanatory Notes. Prepared by the Water Management and Use Group.

Queensland Department of Natural Resources and Water. 2008, Moratorium Notice Water Regulation 2000 (Section 66) Condamine Catchment Underground Water Area.

Queensland Department of Natural Resources and Water. 2008, Condamine and Balonne Resource Operations Plan and Explanatory Notes.

Queensland Department of Environment and Resource Management. 2009, Fitzroy Basin Resource Operations Plan, January 2004. Amended July 2009 (Revision 2).

Queensland EPA 1999, Water Quality Sampling Manual, For use in testing for compliance with the Environmental Protection Act 1994. Queensland Government Environmental Protection Agency, Third Edition 1999.

Queensland Gas Company. 2007, Kenya Pond Groundwater Investigation Report.

Queensland NRW 2008 Moratorium Notice Water Resource (Condamine and Balonne) Plan 2004 Water Act 2000 (Section 26). Queensland Government Department of Natural Resources and Water.

Queensland Parliamentary Counsel. 2006, Water Resource (Great Artesian Basin) Plan 2006. Reprint No.1.

Queensland Parliamentary Counsel. 2006, Water Resource (Condamine and Balonne) Plan 2004. Reprint No.1B.

Queensland Parliamentary Counsel. 2008, Environmental Protection (Water) Amendment Policy (No.1) 2008. Subordinate Legislation 2008 No.433.

Queensland Parliamentary Counsel. 2008, Water Supply (Safety and Reliability) Act 2008. Act No. 34 of 2008.

Queensland Parliamentary Counsel. 2009, Environmental Protection (Water) Policy 1997. Reprint No.3C.

Queensland Parliamentary Counsel. 2009, Water Act 2000. Reprint No.6E.

Queensland Parliamentary Counsel. 2009, Petroleum and Gas (Production and Safety) Act 2004. Reprint No.4C.

Queensland Parliamentary Counsel. 2009, Environmental Protection Act 1994. Reprint No.8E.

Radke, B.M., Ferguson, J., Cresswell, R.G., Ransley, T.R. and Habermehl, M.A. 2000, Hydrochemistry and Implied Hydrodynamics of the Cadna-owie – Hooray Aquifer, Great Artesian Basin, Australia. Bureau of Rural Science, Canberra.

Robinson 2002. Construction and Operating Costs of Groundwater Pumps for Irrigation in the Riverine Plain. CSIRO Land and Water, Tech Report 20/02

RWC 1993. Groundwater Management Strategy. Victoria Rural Water Corporation, November 1993.

Sen, PK 1968. Estimates of the regression coefficient based on Kendall's tau. Journal of the American Statistical Association. 63:1379-1389

Senior, D., Senior, B., 1971. Saint George, Queensland, 1:250 000 geological series map. Sheet SH/55-04, 1st edition., Bureau of Mineral Resources, Australia

SENRM 2009. Confined Aquifer Condition and Extraction Limits in the Tintinara Coonalpyn Prescribed Wells Area (PWA). South East Natural Resources Management Board. Version 2, 2009.

Scott, S., Anderson, B., Crosdale, P., Dingwall, J. and Leblang, G. 2007. Coal petrology and coal seam gas contents of the Walloon Subgroup – Surat Basin, Queensland, Australia. International Journal of Coal Geology, 70 (2007), 209-222.

Scott, S., Anderson, B., Crosdale, P., Dingwall, J. and Leblang, G. 2004. Revised Geology and Coal Seam Gas Characteristics of the Walloon Sub-group. PESA Eastern Australasian Basins Symposium II, Adelaide.

Theis, C.V., 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. Transactions of the American Geophysical Union, Vol. 16, pp. 519 – 524.

Thomas, B.M., Reiser, R.F., 1971. Surat, Queensland, 1:250 000 geological series map. Sheet SG/55-16, 1st edition., Bureau of Mineral Resources, Australia

Viellenave, J.H., Fontana, J.V. and Gorody, A.W. 2002, Environmental Risk Assessment Methods Useful for Coalbed Methane Development: Cost-effective Ways to Manage Risk. IPEC Special Symposium: Environmental Issues in the Production of Coal Bed Methane. 9th Annual International Petroleum Environmental Conference, Albuquerque, 2002.

Whitaker, W.G., Murphy, P.R., Rollason, R.G., 1980. Mundubbera, Queensland, 1:250 000 geological series map. Sheet SG/56-5, 2nd edition., Bureau of Mineral Resources, Australia & Geological Survey of Qld

Woods, P.H., Walker, G.R. and Allison, G.B. 1990, Estimating groundwater discharge at the southern margin of the Great Artesian Basin near Lake Eyre, South Australia. In: Proceedings of the International Conference on Groundwater in Large Sedimentary Basins, Perth, 9-13 July 1990. Australian Water Resources Counsel Conference Series No. 20, p.298-309.

WorleyParsons. 2009a, Aquifer Injection of CSG Production Water – Phase 1 Prefeasibility Assessment.

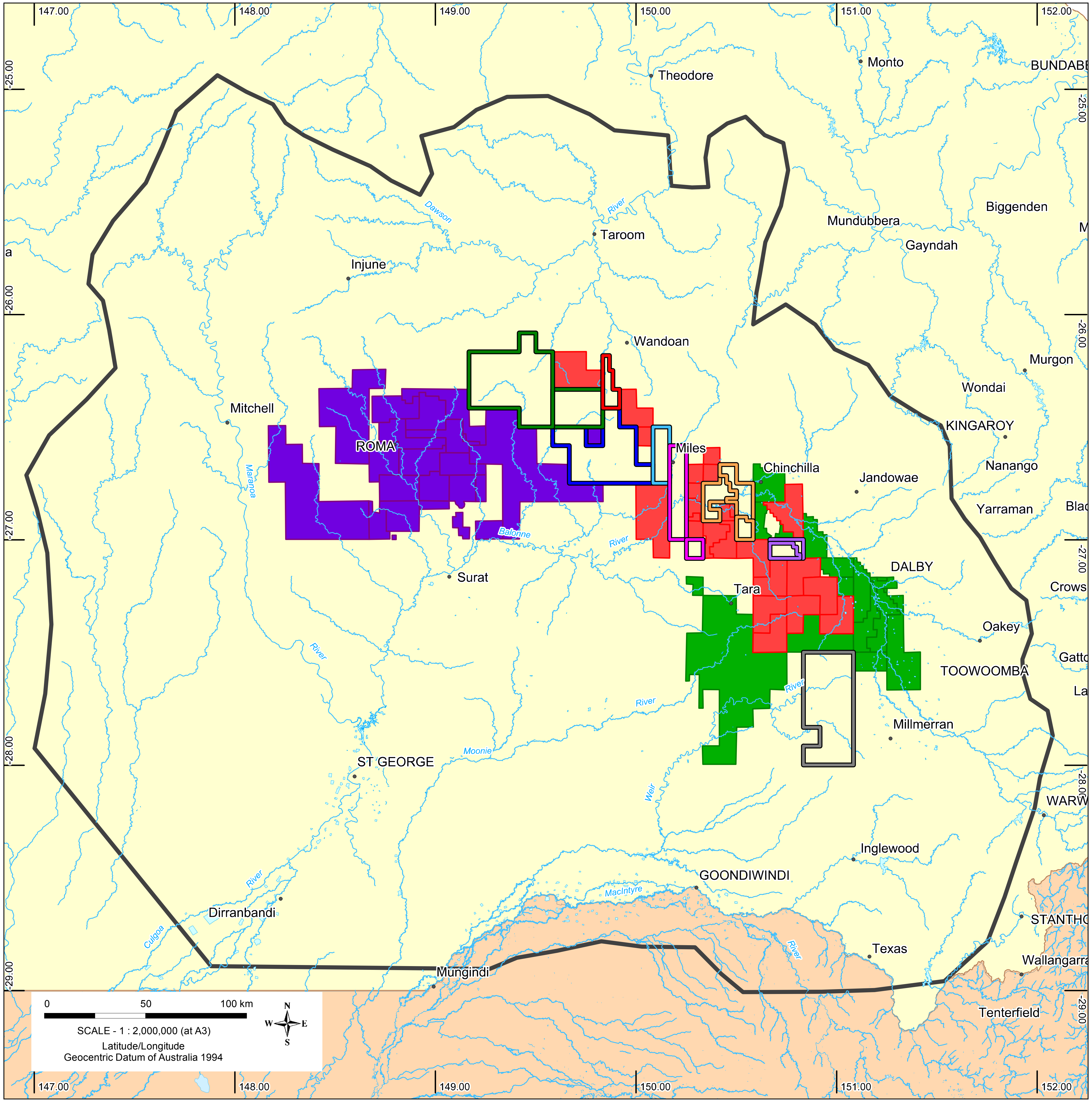
WorleyParsons. 2009b, Saline Water Management Study – Water Disposal Study.

Websites

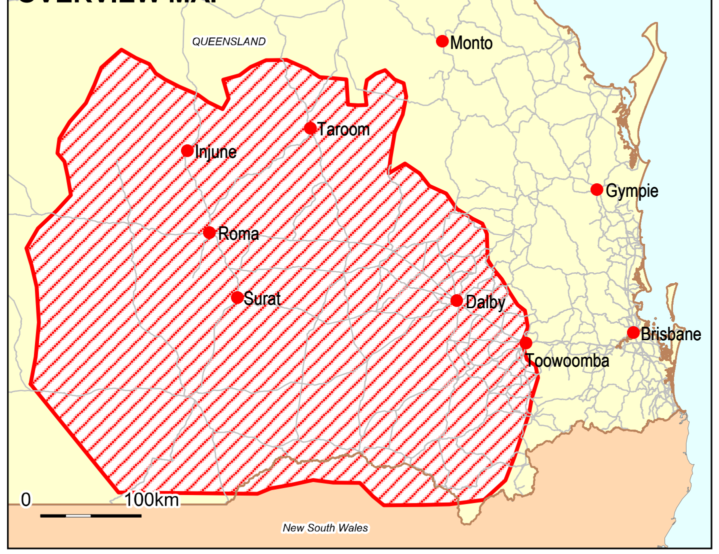
Australian Bureau of Meteorology (BOM). http://reg.bom.gov.au/cgi-bin/climate/change/trendmaps.cgi Accessed November 22, 2009

Climate Change in Australia. http://www.climatechangeinaustralia.gov.au/futureclimate.php, Accessed November 22, 2009

Appendix A Supporting GIS Maps



OVERVIEW MAP



LEGEND

- Major towns
- Major watercourses
- Model domain
- QGC leases
- Santos leases
- Arrow leases

Walloons Gas Fields Development Areas

- Talinga / Orana
- Dalwogan
- Kainama
- Gilbert Gully
- Combabula / Ramyard
- Woleebee
- Carinya
- Condabri

Rev	Date	Revision Description	ORIG	CHK	ENG	APPD
0	02/03/2010	Issued for use	GSB	KM	DG	RB

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AUSTRALIA PACIFIC LNG PROJECT

Map 1: CSG Operators in the Surat Basin

Project No: 301001-00448 | Figure: 00448-00-EN-DAL-0443 | Rev: 0

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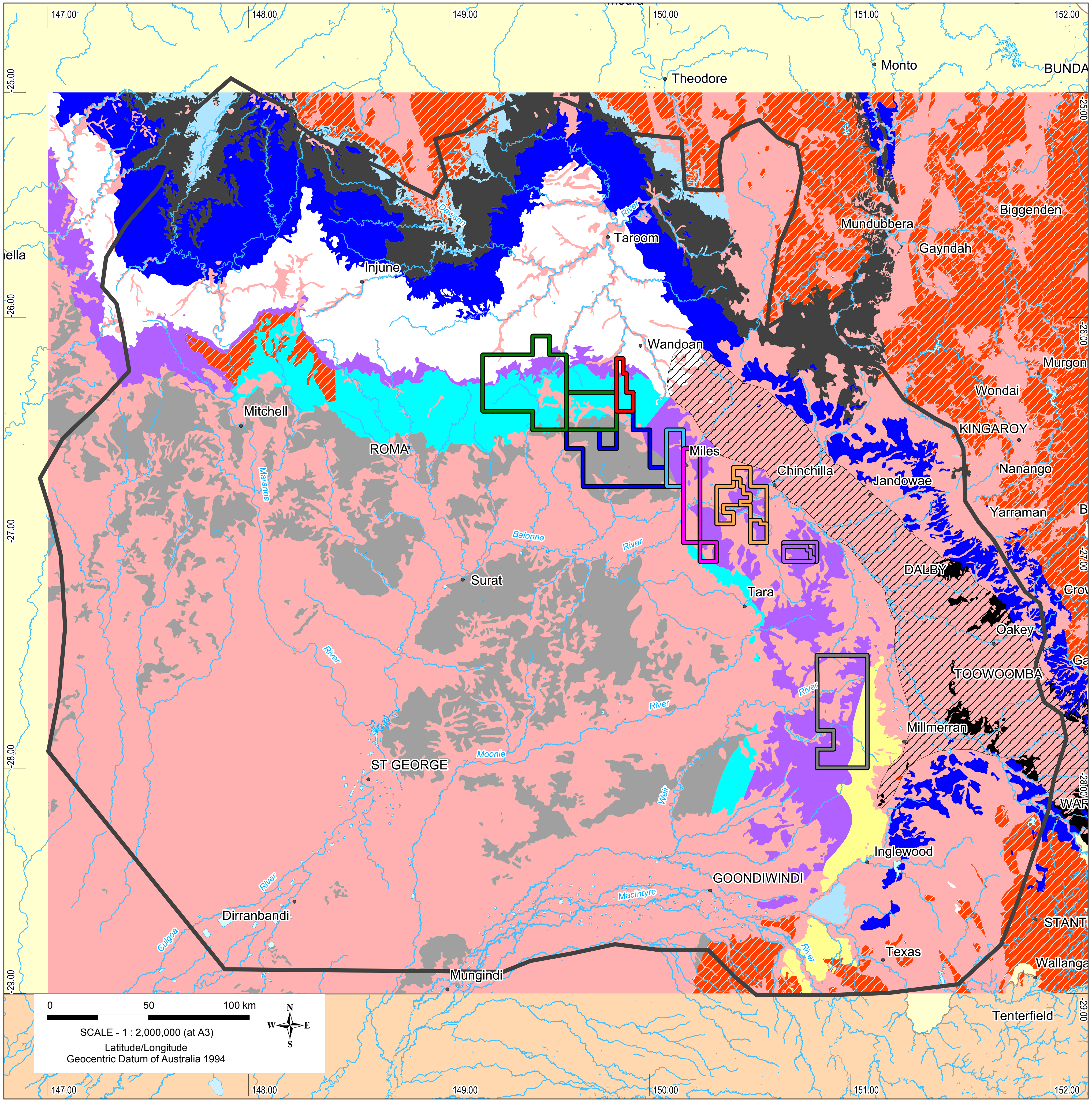

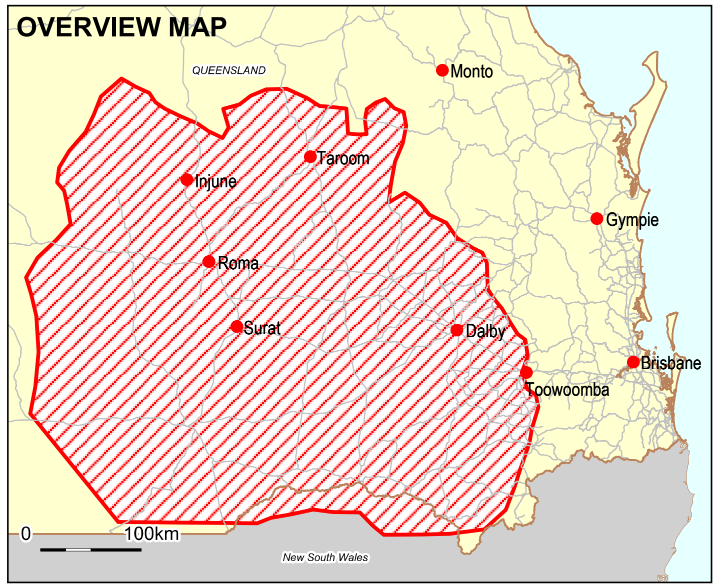

LEGEND

- Major towns
- Major watercourses
- Model Domain

Walloons Gas Fields Development Areas

- Talinga / Orana
- Dalwogan
- Kainama
- Gilbert Gully
- Combabula / Ramyard
- Woleebee
- Carinya
- Condabri

Hydrostratigraphic units

- Cainozoic units
- Rolling Downs group
- Bungil Mooga Orallo grouping
- Gubberamunda sandstone
- Hutton sandstone
- Evergreen formation
- Precipice sandstone
- Pre-Precipice formations
- Injune Creek Group:
  - Springbok sandstone
  - Walloon coal measures
  - Walloon coal measures sub-crop (after Exon, 1976)

Rev	Date	Revision Description	ORIG	CHK	ENG	APPD
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Map 2: Hydrostratigraphic unit outcrop

Project No: 301001-00448 | Figure: 00448-00-EN-DAL-0444 | Rev: 0

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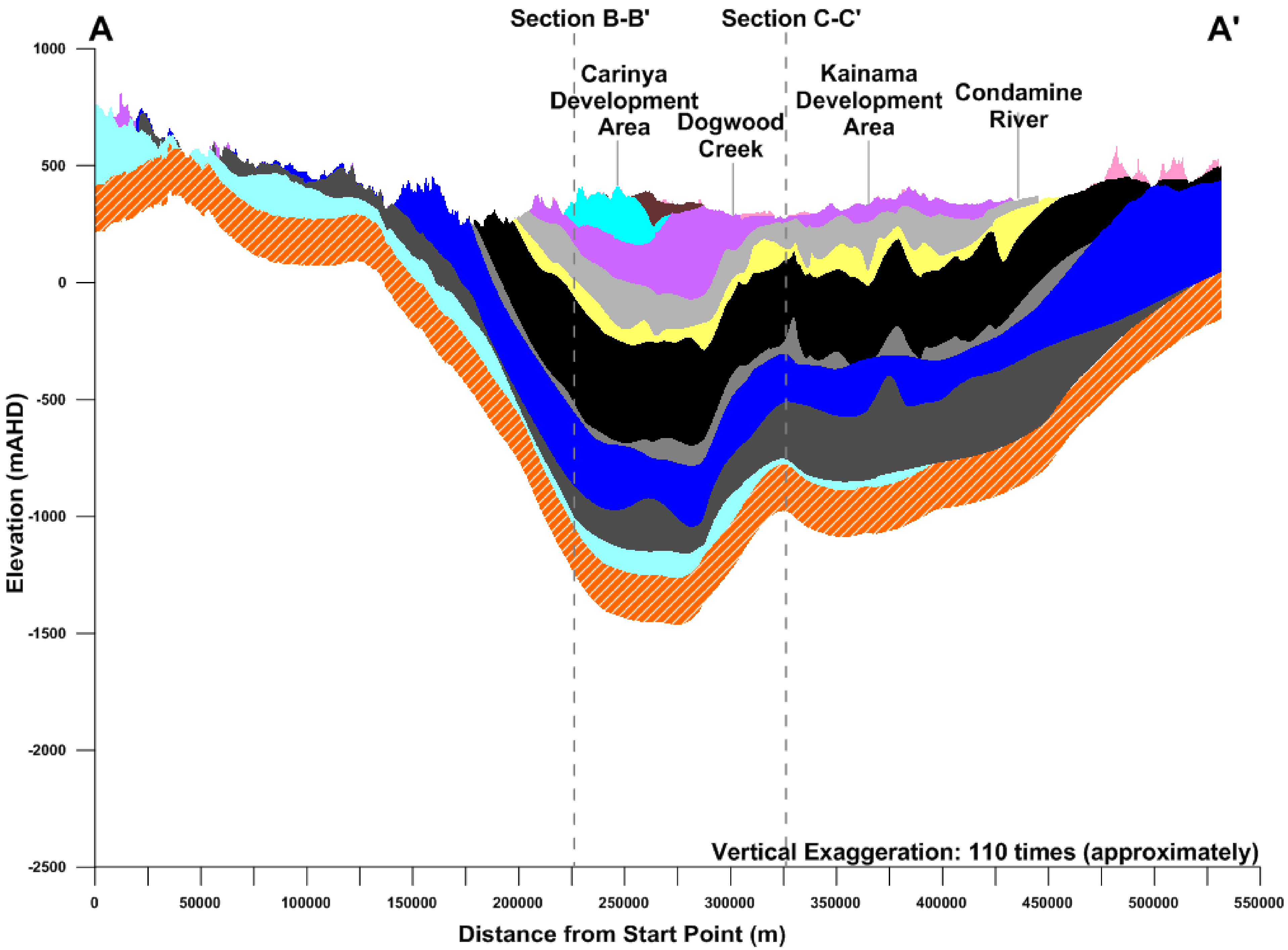

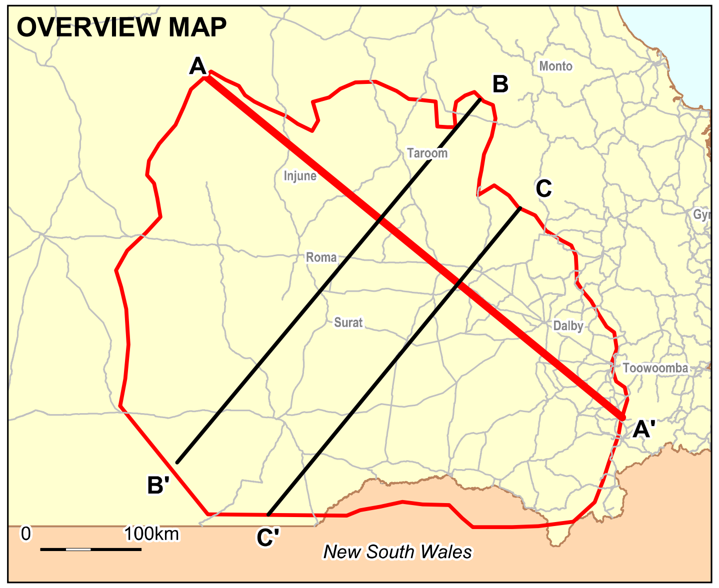

LEGEND

- Major towns
- Major roads
- Model domain

Hydrostratigraphic units

- Cainozoic units
- Rolling Downs group
- Bungil Mooga Orallo grouping
- Gubberamunda sandstone
- Westbourne formation
- Springbok sandstone
- Walloon coal measures
- Eurombah formation
- Hutton sandstone
- Evergreen formation
- Precipice sandstone
- Pre-Precipice formations

Rev	Date	Revision Description	ORIG	CHK	ENG	APPD
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Map 3: Hydrostratigraphic cross-section A-A'

Project No: 301001-00448	Figure: 00448-00-EN-DAL-0445	Rev: 0

Compiled by MELBOURNE GEOMATICS

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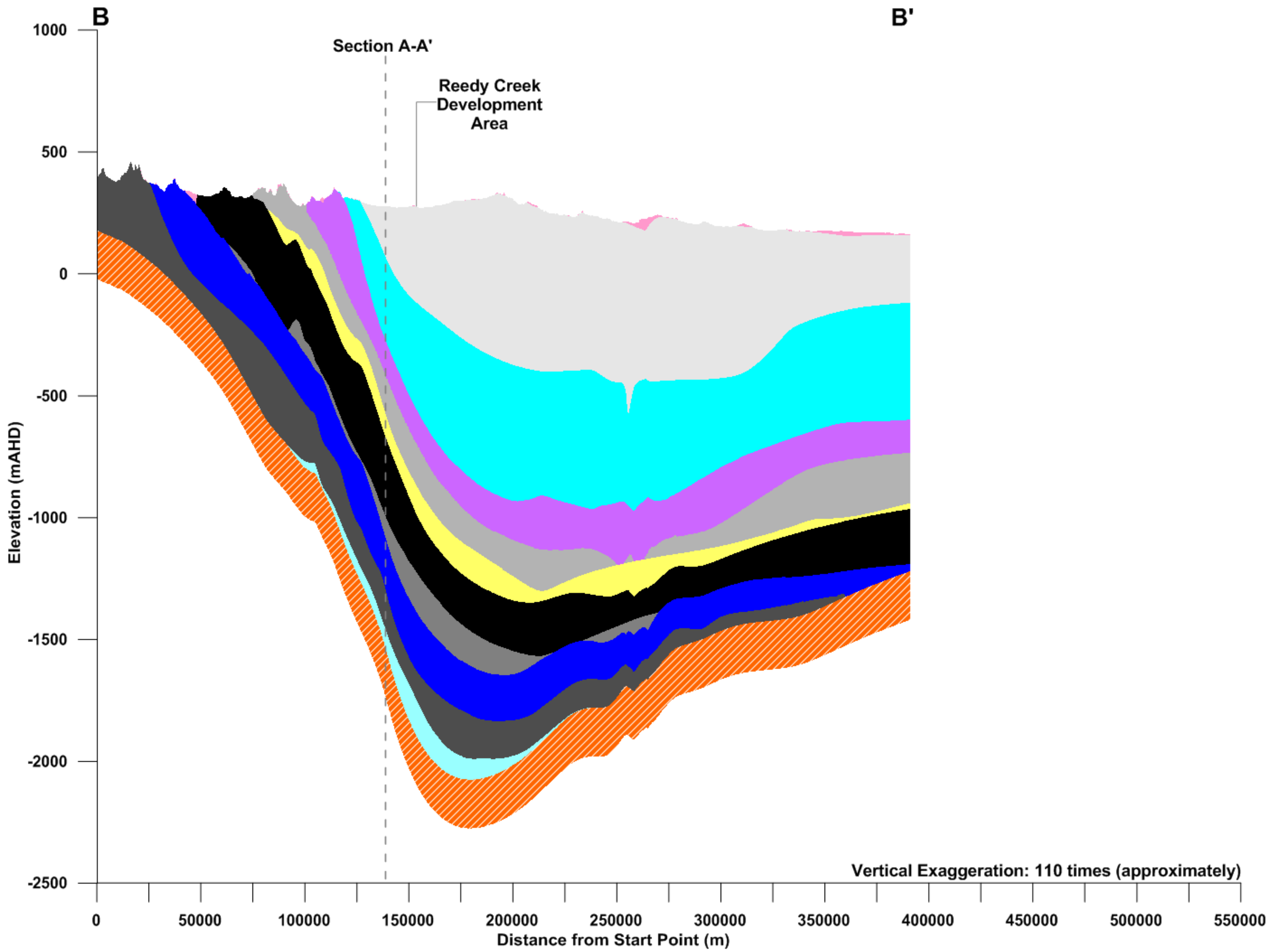

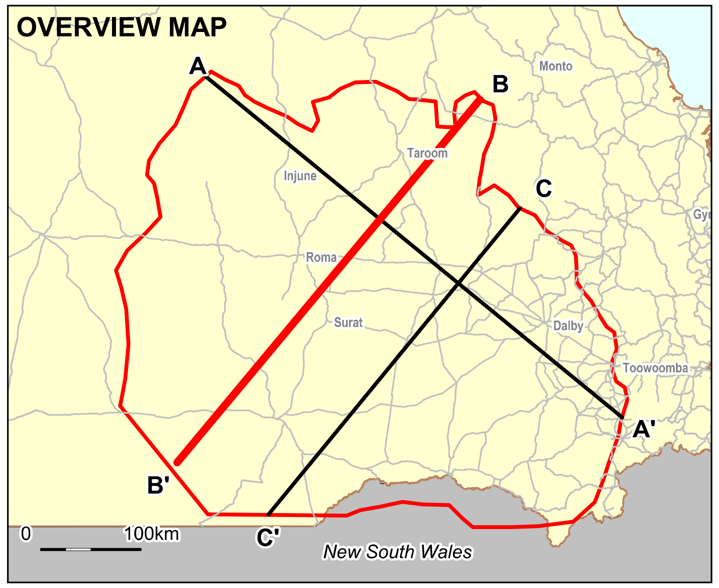

LEGEND

- Major towns
- Major roads
- Model domain

Hydrostratigraphic units

- Cainozoic units
- Rolling Downs group
- Bungil Mooga Orallo grouping
- Gubberamunda sandstone
- Westbourne formation
- Springbok sandstone
- Walloon coal measures
- Eurombah formation
- Hutton sandstone
- Evergreen formation
- Precipice sandstone
- Pre-Precipice formations

Rev	Date	Revision Description	ORIG	CHK	ENG	APPD
0	02/03/2010	Issued for use	GSB	KM	DG	RB

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Map 4: Hydrostratigraphic cross-section B-B'

Project No: 301001-00448	Figure: 00448-00-EN-DAL-0447	Rev: 0

Compiled by MELBOURNE GEOMATICS

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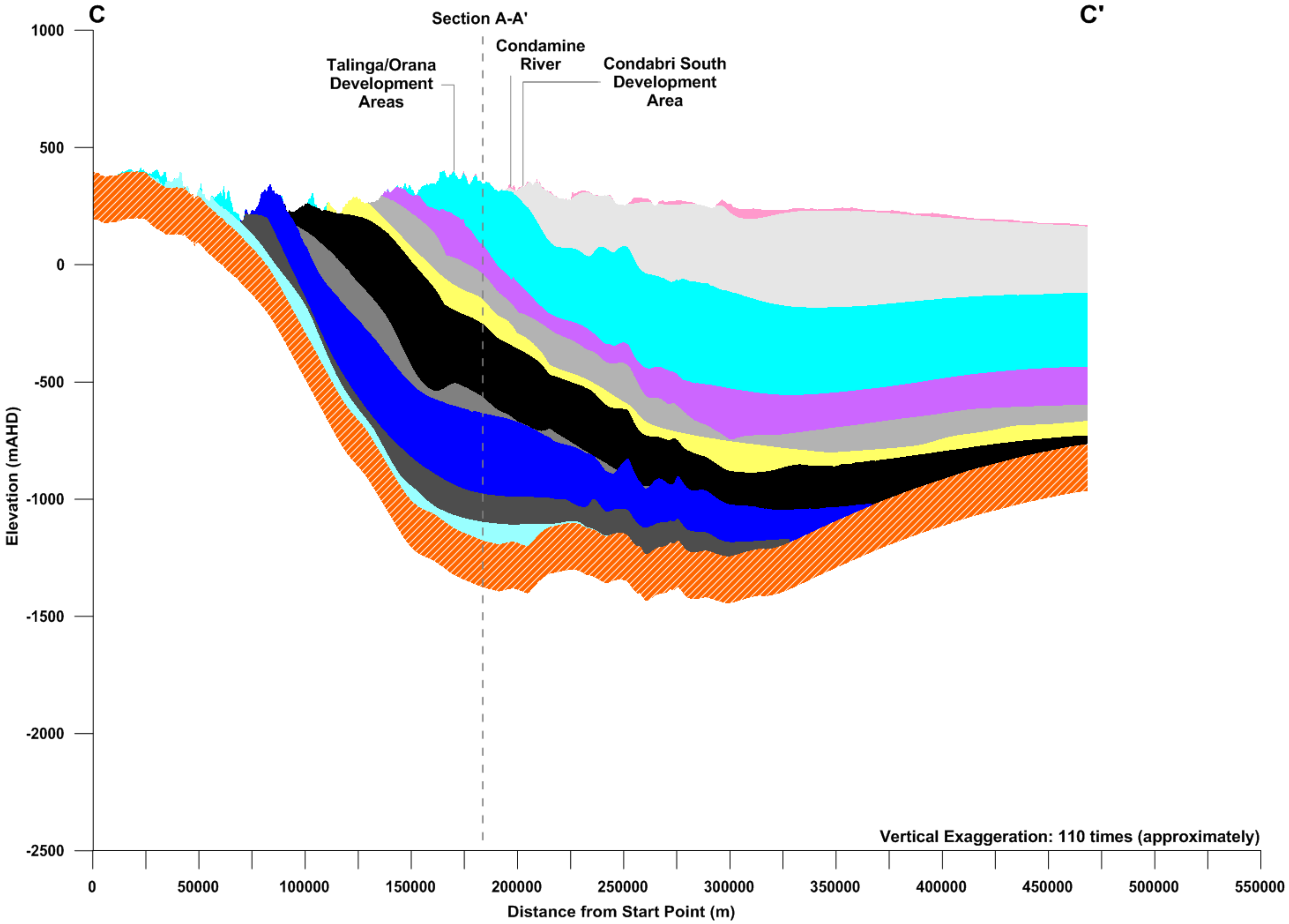

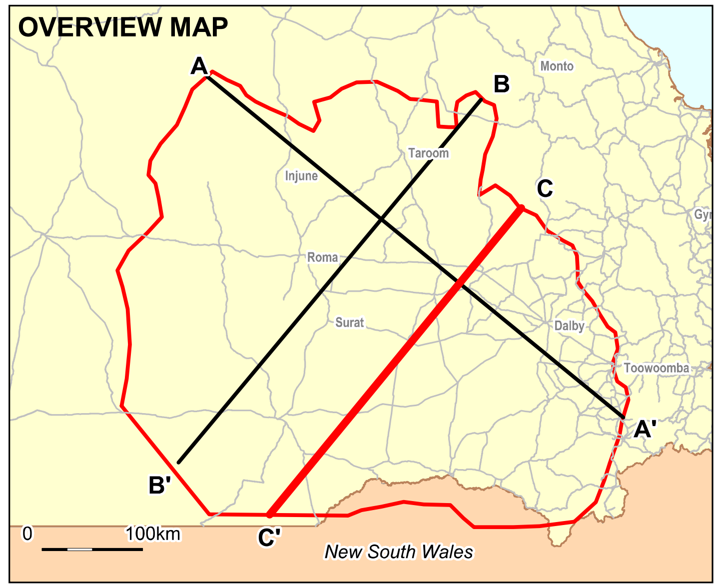

LEGEND

- Major towns
- Major roads
- Model domain

Hydrostratigraphic units

- Cainozoic units
- Rolling Downs group
- Bungil Mooga Orallo grouping
- Gubberamunda sandstone
- Westbourne formation
- Springbok sandstone
- Walloon coal measures
- Eurombah formation
- Hutton sandstone
- Evergreen formation
- Precipice sandstone
- Pre-Precipice formations

Rev	Date	Revision Description	ORIG	CHK	ENG	APPD
0	02/03/2010	Issued for use	GSB	KM	DG	RB

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Map 5: Hydrostratigraphic cross-section C-C'

Project No: 301001-00448 | Figure: 00448-00-EN-DAL-0453 | Rev: 0

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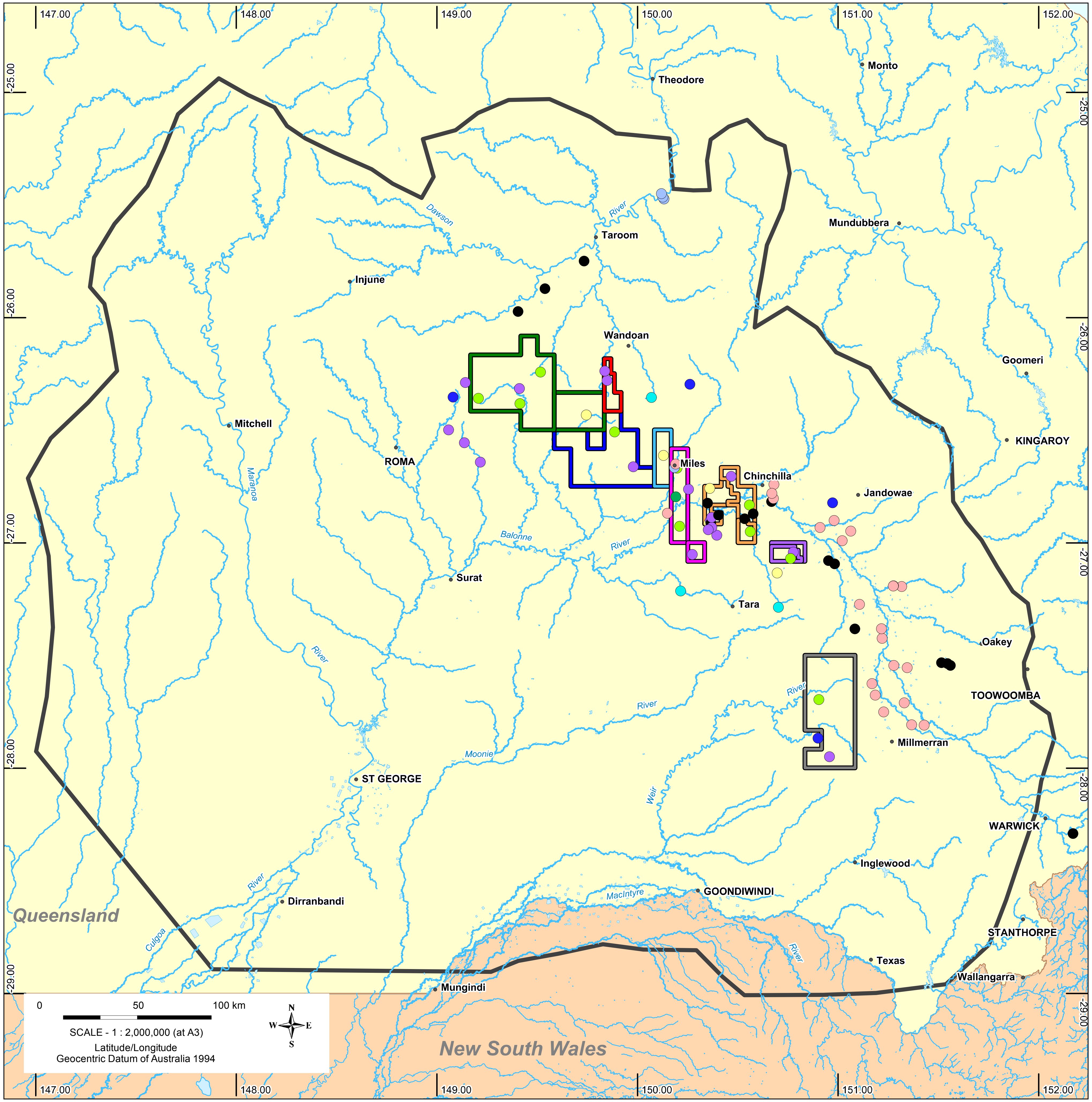

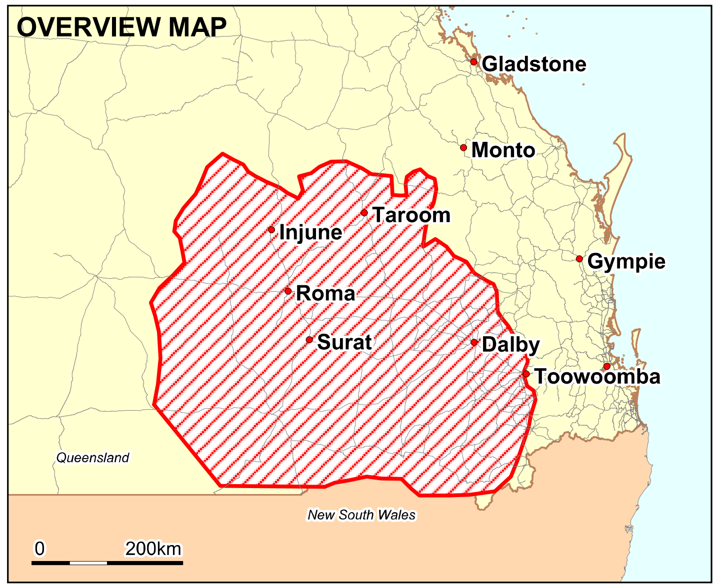

LEGEND

- Major towns
- Major watercourse
- Reservoir
- Model domain

Walloons gas fields development areas

- Talinga / Orana
- Dalwogan
- Kainama
- Gilbert Gully
- Combabula / Ramyard
- Woleebee
- Carinya
- Condabri

Proposed monitoring bores

- Cainozoic units
- Bungil Mooga Orallo grouping
- Gubberamunda sandstone
- Springbok sandstone
- Walloon coal measures
- Hutton sandstone
- Precipice sandstone
- Springbok and Hutton sandstones (nested)
- Gubberamunda, Springbok and Hutton sandstones (nested)

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Map 6: Locations of monitoring bores for water level trend assessment

Project No: 301001-00448 | Figure: 00448-00-EN-DAL-0446 | Rev: 0

Compiled by MELBOURNE GEOMATICS

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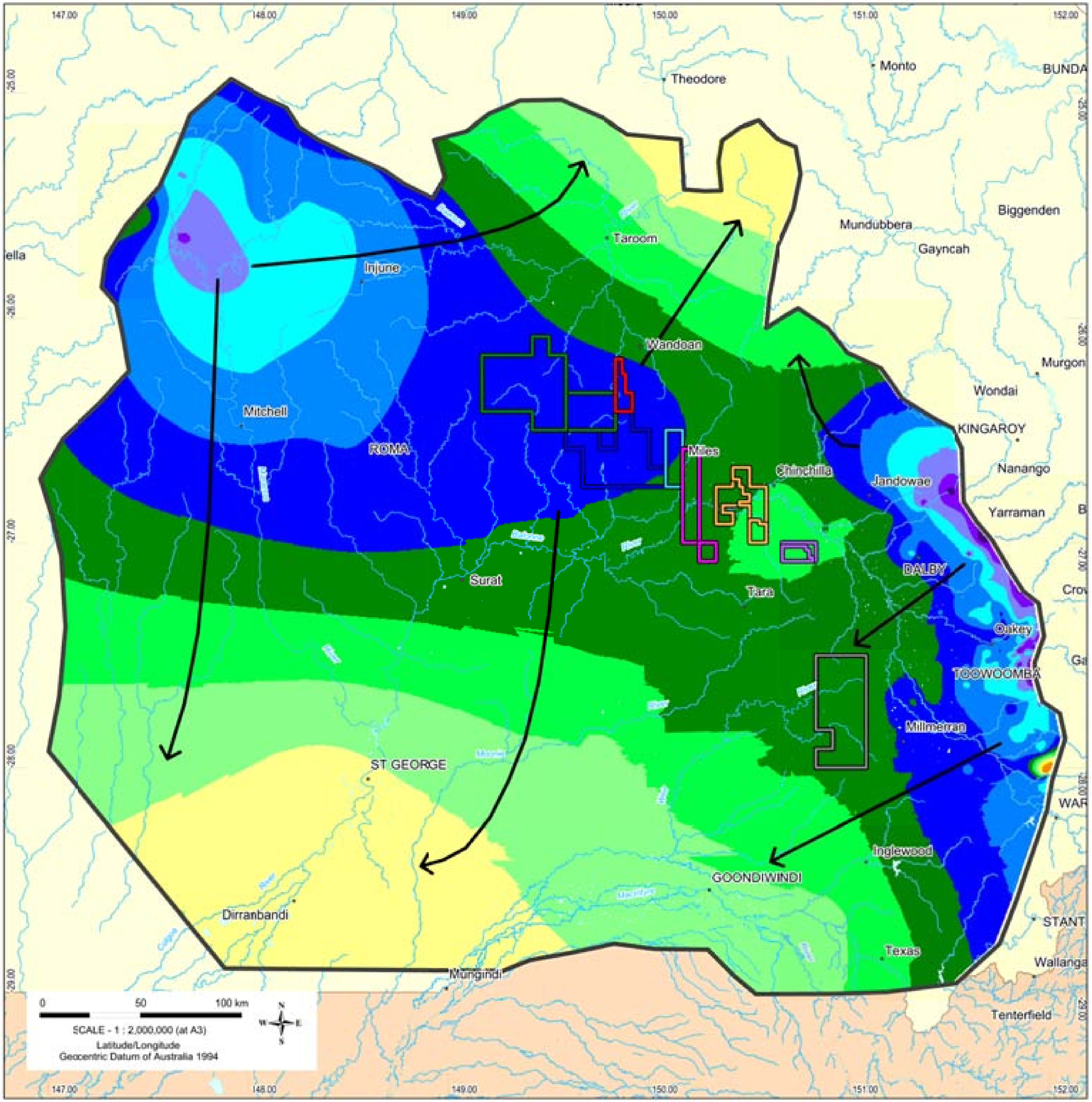

LEGEND

- Major towns
- Major watercourses
- Model domain

Walloons Gas Fields Development Areas

- Talinga / Orana
- Dalwogan
- Kainama
- Gilbert Gully
- Combabula / Ramyard
- Woleebee
- Carinya
- Condabri

Hydrostratigraphic units

- 50 - 100
- 100 - 150
- 150 - 200
- 200 - 250
- 250 - 300
- 300 - 350
- 350 - 400
- 400 - 450
- 450 - 500
- 500 - 550
- 550 - 600
- 600 - 650

Inferred groundwater flow direction

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Map 7: Cainozoic units reduced water level

Project No: 301001-00448 | Figure: 00448-00-EN-DAL-0455 | Rev: 0

Compiled by MELBOURNE GEOMATICS

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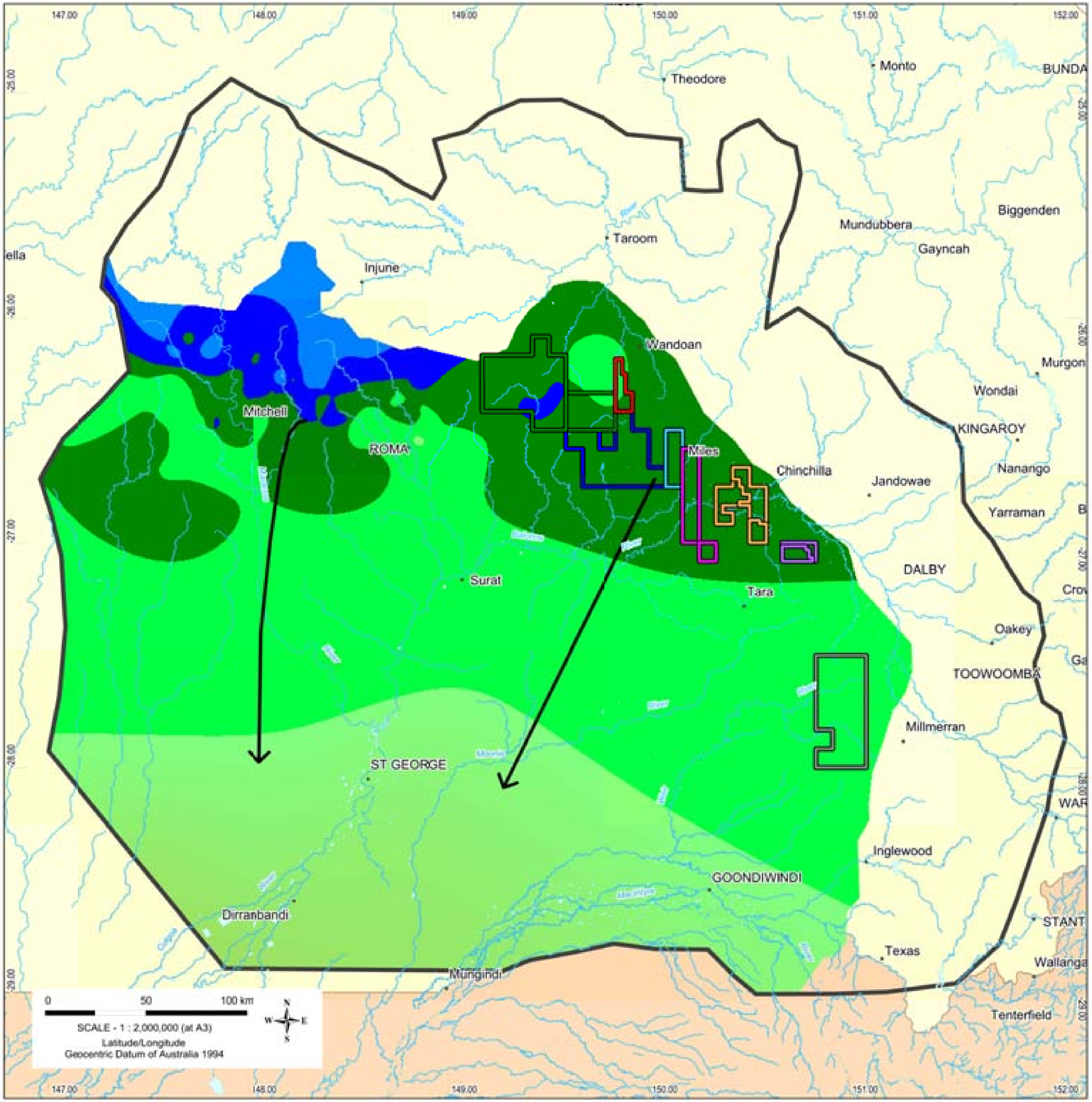

LEGEND

- Major towns
- Major watercourses
- Model domain

Walloons Gas Fields Development Areas

- Talinga / Orana
- Dalwogan
- Kainama
- Gilbert Gully
- Combabula / Ramyard
- Woleebee
- Carinya
- Condabri

Hydrostratigraphic units

- 50 -100
- 100 - 150
- 150 - 200
- 200 - 250
- 250 - 300
- 300 - 350
- 350 - 400
- 400 - 450
- 450 - 500
- 500 - 550
- 550 - 600
- 600 - 650
- Inferred groundwater flow direction

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Map 8: Gubberamunda Sandstone reduced water level

Project No: 301001-00448	Figure: 00448-00-EN-DAL-0456	Rev: 0

Compiled by MELBOURNE GEOMATICS

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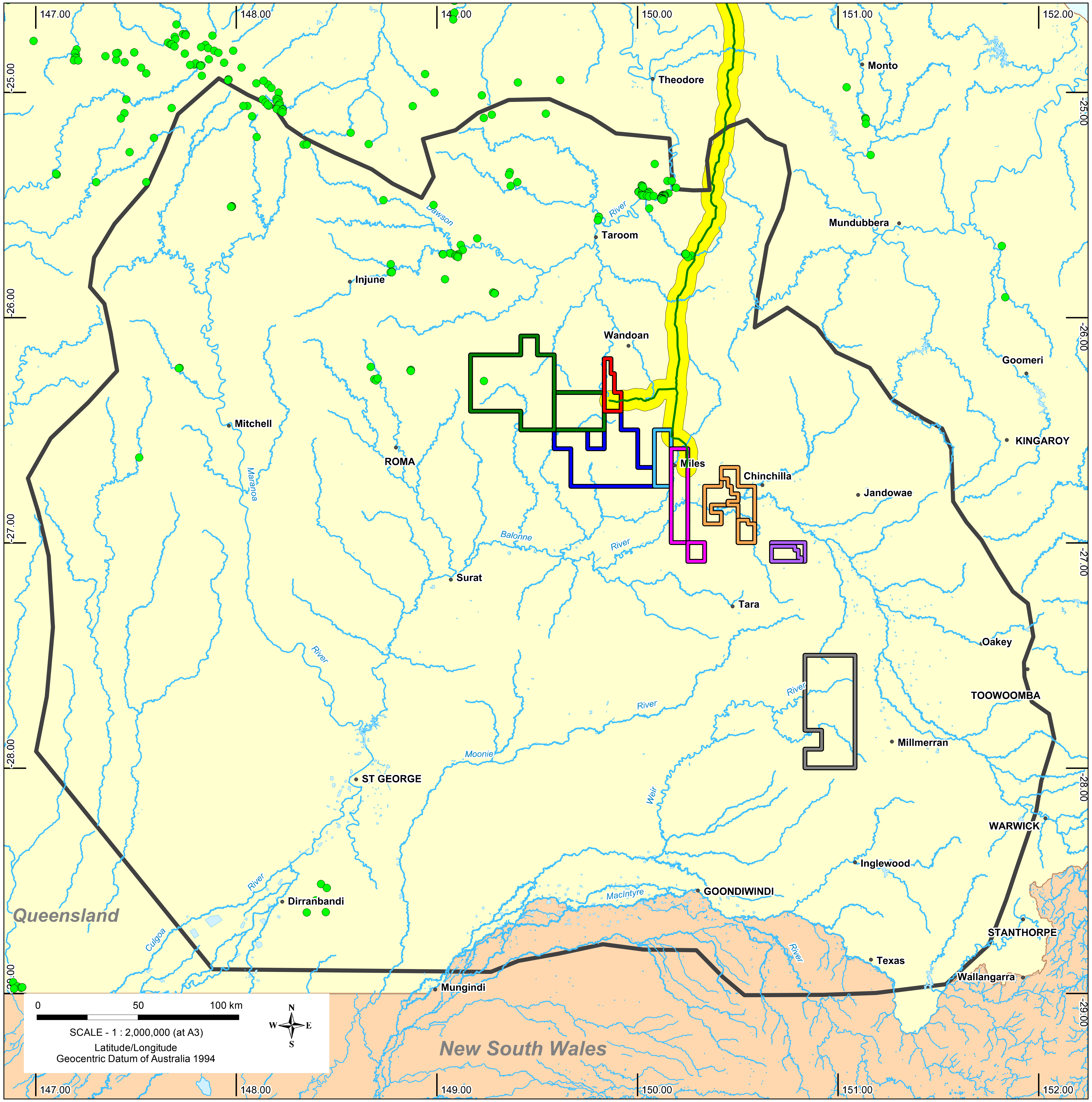

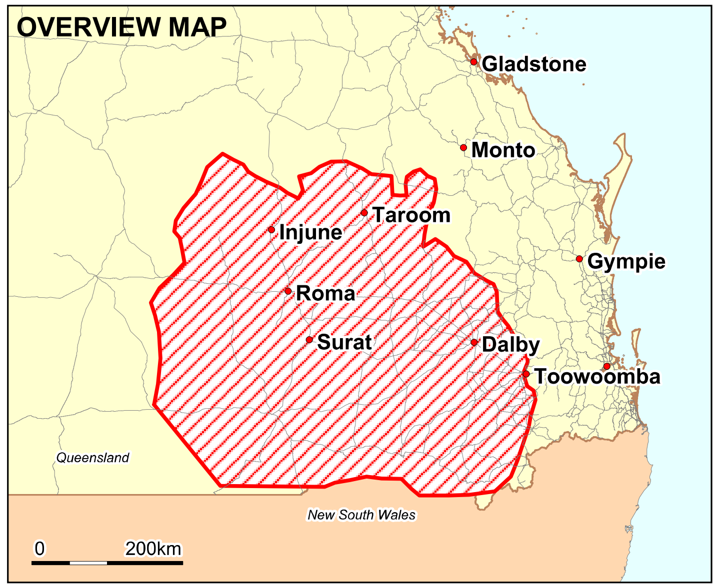

LEGEND

- Major towns
- Major watercourse
- Reservoir
- Gas pipeline route
- Gas pipeline route 5km buffer
- Model domain

Queensland Springs

- Mapped spring complexes

Walloons gas fields development areas

- Talinga / Orana
- Dalwogan
- Kainama
- Gilbert Gully
- Combabula / Ramyard
- Woleebee
- Carinya
- Condabri

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Map 9: Great Artesian Basin spring complexes in proximity to the study area (DERM wetland mapping database)

Project No: 301001-00448 | Figure: 00448-00-EN-DAL-0457 | Rev: 0

Compiled by MELBOURNE GEOMATICS

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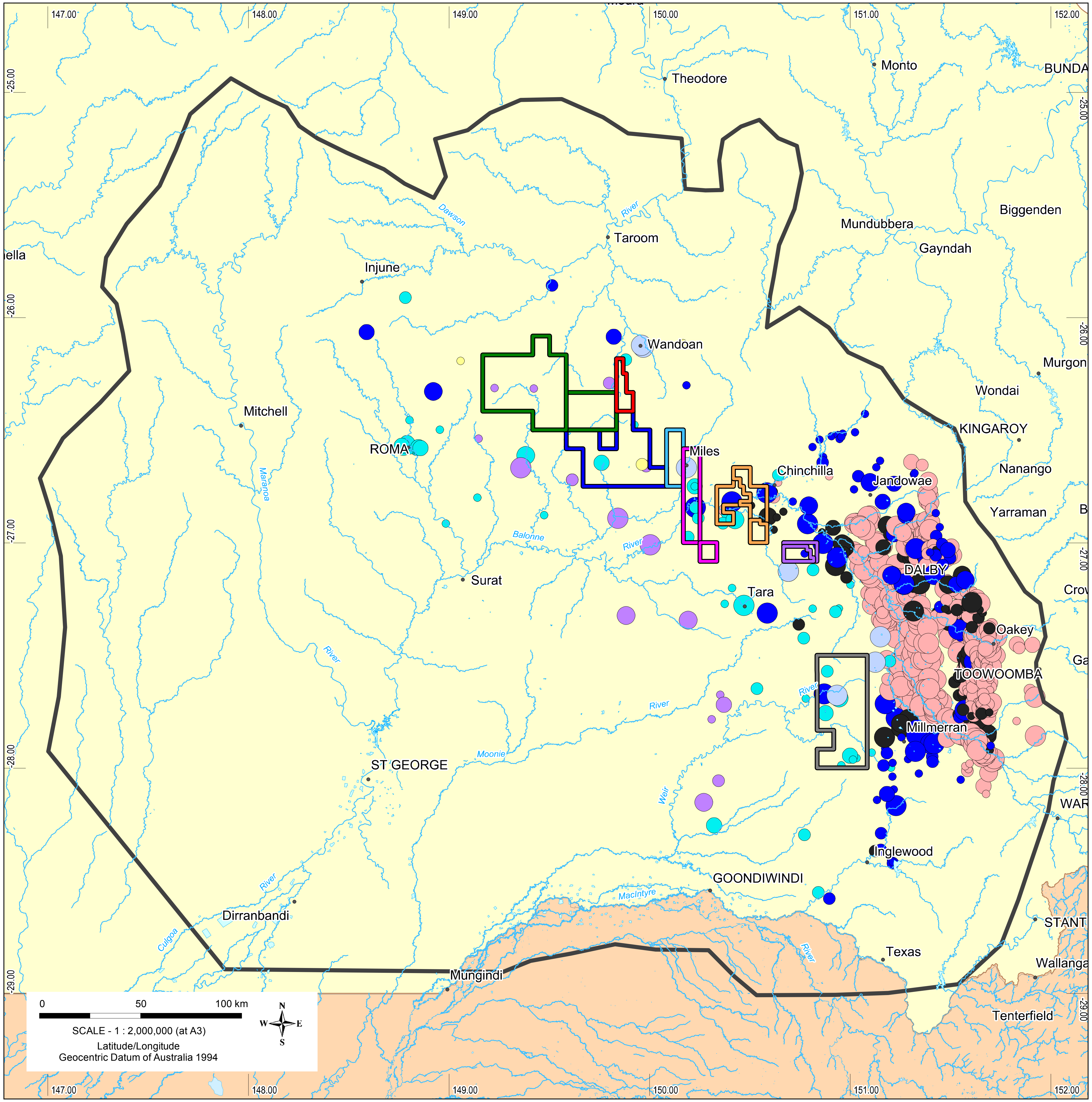
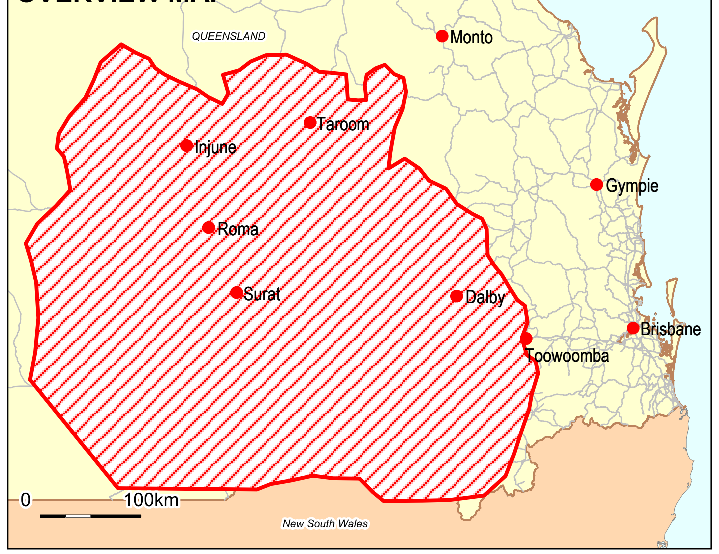


OVERVIEW MAP



LEGEND

- Major towns
- Major watercourses
- Model Domain

Walloons Gas Fields Development Areas

- Talinga / Orana
- Dalwogan
- Kainama
- Gilbert Gully
- Combabula / Ramyard
- Woleebee
- Carinya
- Condabri

Allocation by hydrostratigraphic unit

- Cainozoic units
- Bungil Mooga Orallo grouping
- Gubberamunda sandstone
- Springbok sandstone
- Walloon coal measures
- Hutton sandstone
- Precipice sandstone

Allocation in megalitres (ML)

- 200 to 2,300
- 80 to 200
- 50 to 80
- 20 to 50
- 0 to 20

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Map 10: Locations of licensed groundwater users

Project No: 301001-00448 | Figure: 00448-00-EN-DAL-0458 | Rev: 0

Compiled by MELBOURNE GEOMATICS

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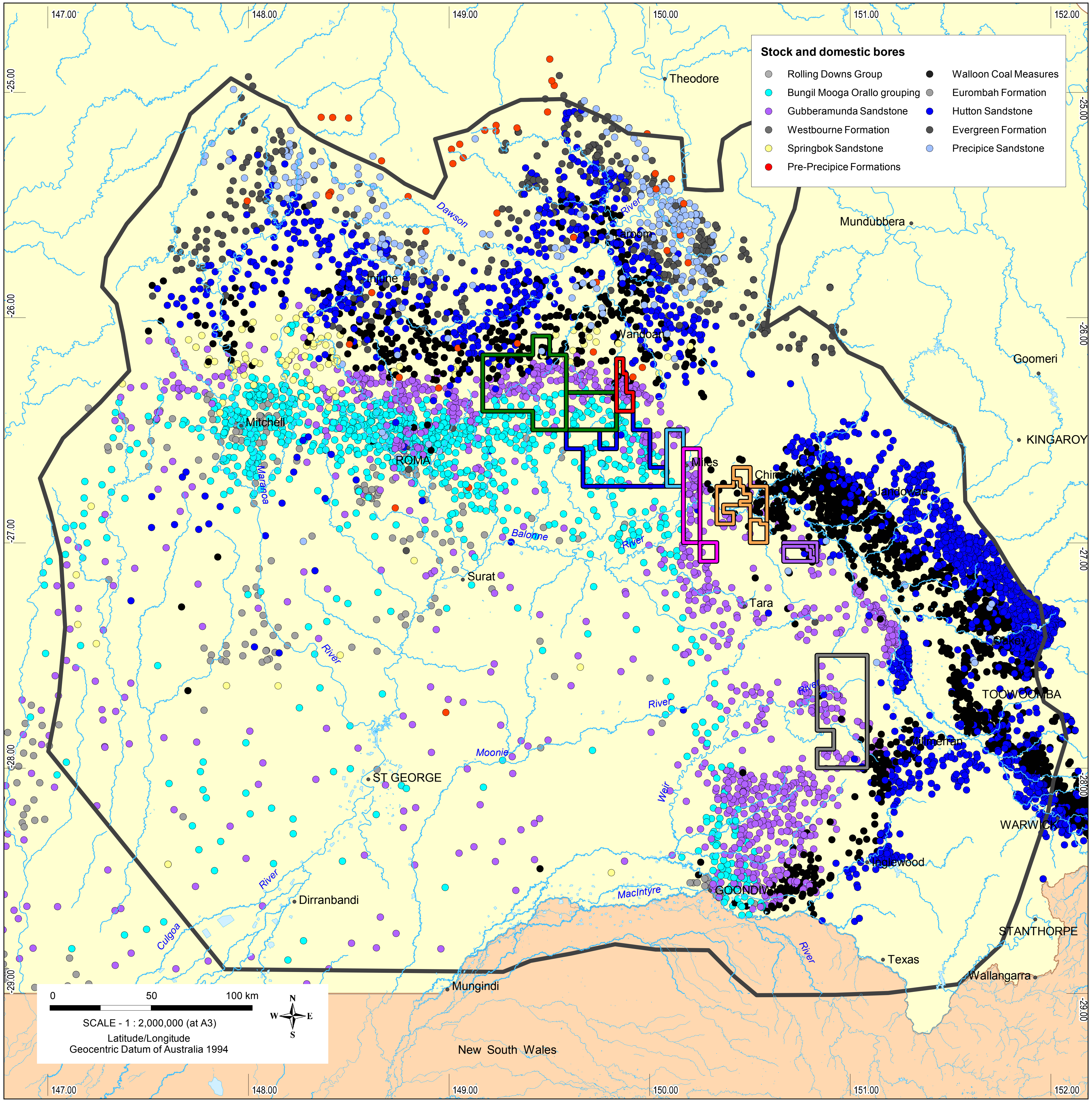

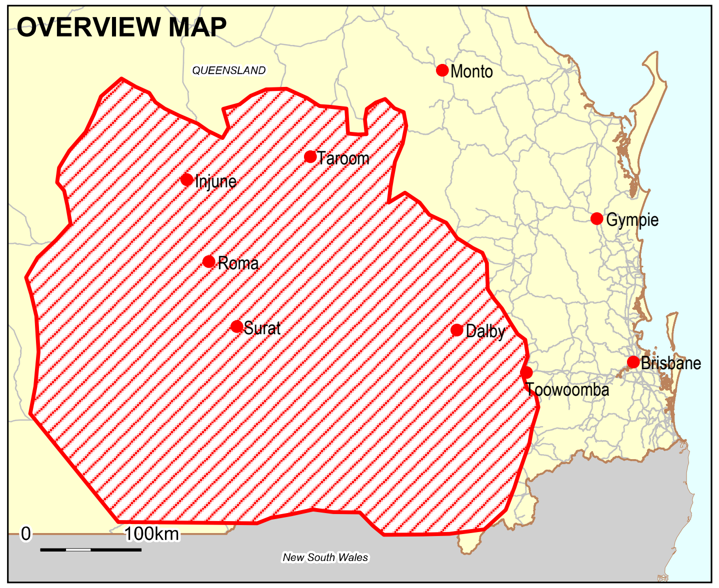

LEGEND

- Major towns
- Major watercourses
- Model Domain

Walloons Gas Fields Development Areas

- Talinga / Orana
- Dalwogan
- Kainama
- Gilbert Gully
- Combabula / Ramyard
- Woleebee
- Carinya
- Condabri

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Map 11: Location of stock and domestic bores

Project No: 301001-00448 | Figure: 00448-00-EN-DAL-0459 | Rev: 0

Compiled by MELBOURNE GEOMATICS

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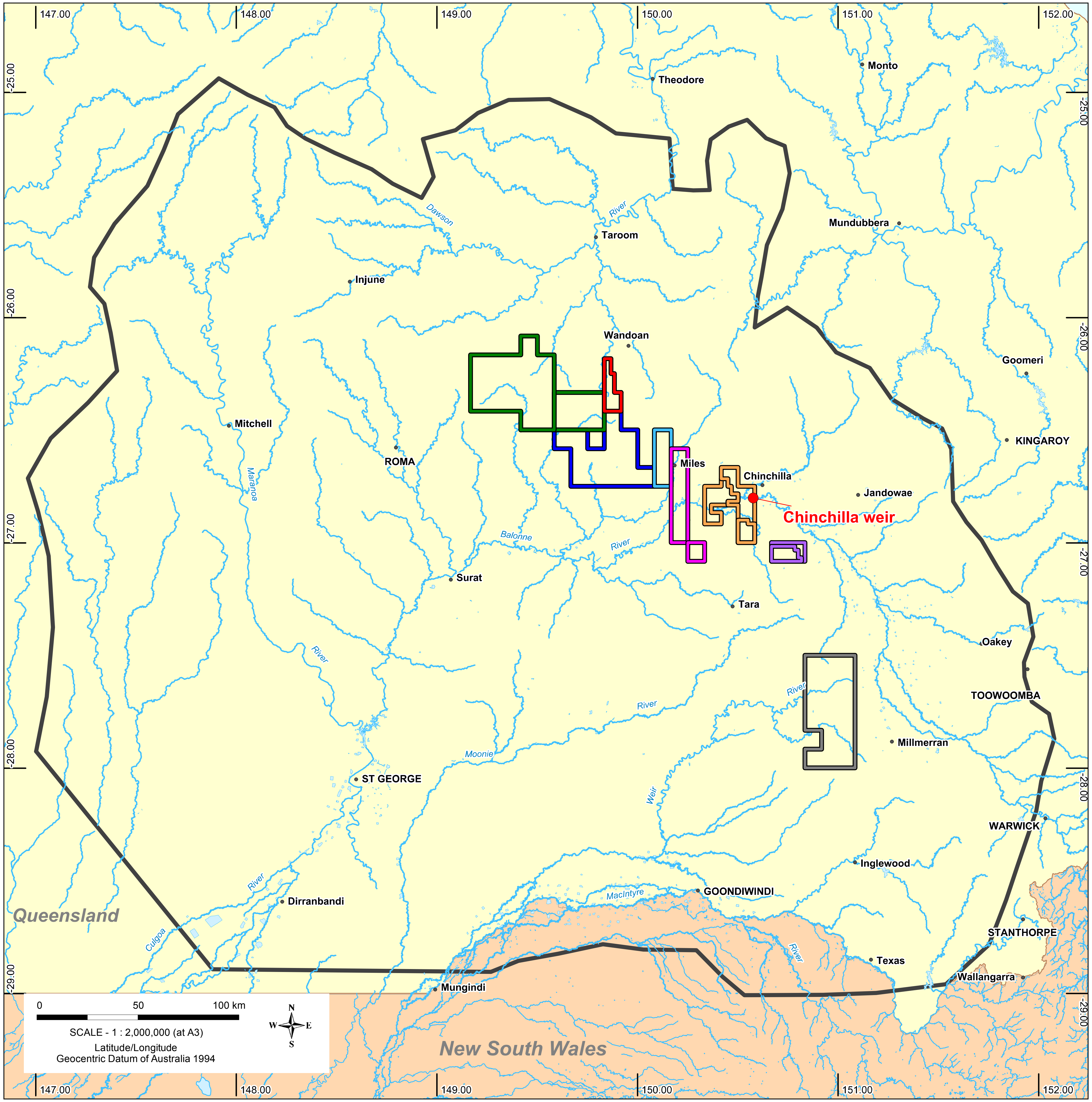

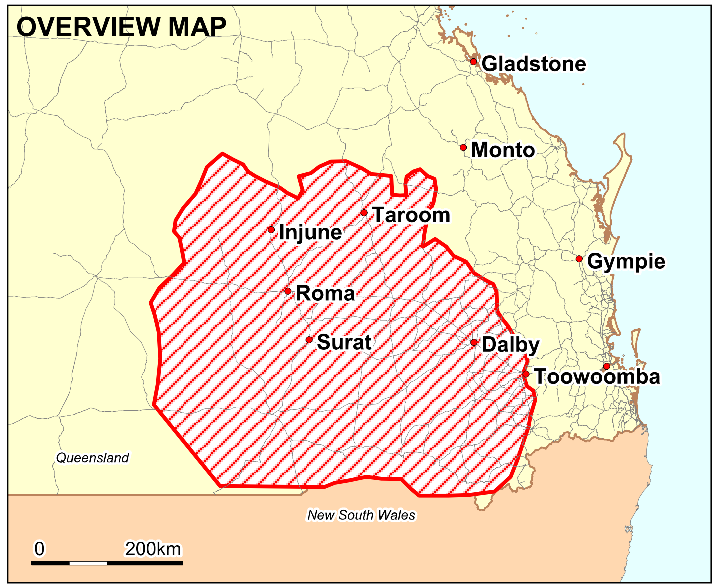

LEGEND

- Major towns
- Major watercourse
- Reservoir
- Model domain

Walloons gas fields development areas

- Talinga / Orana
- Dalwogan
- Kainama
- Gilbert Gully
- Combabula / Ramyard
- Woleebee
- Carinya
- Condabri

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Map 12: Numerical Groundwater Model Domain

Project No: 301001-00448 | Figure: 00448-00-EN-DAL-0460 | Rev: 0

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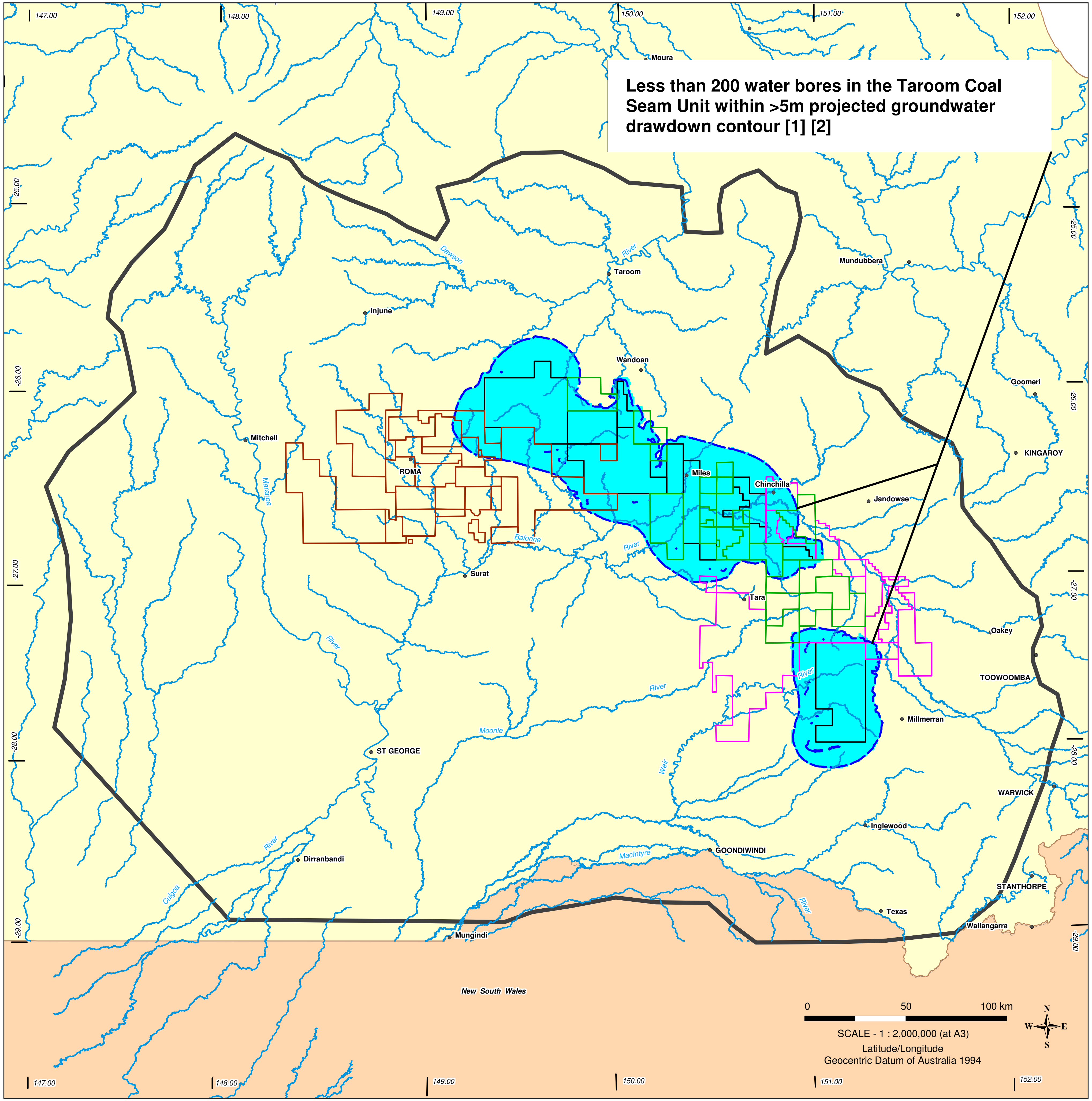

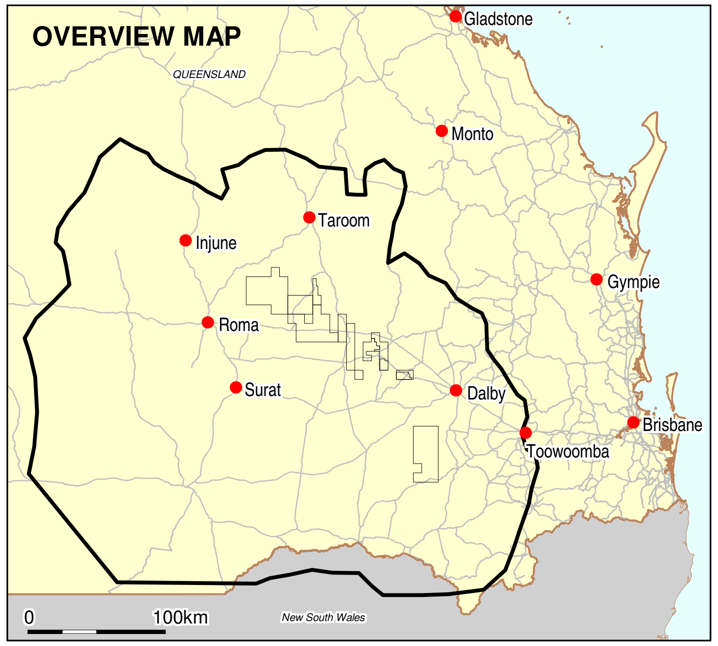

LEGEND

- Major towns
- Major watercourses
- Walloons gas fields development areas

Groundwater Level Drawdown

- Projected 5m groundwater drawdown contour at model year 2049 (best estimate project case scenario)
- Projected area of groundwater drawdown > 5m at model year 2049 (best estimate project case scenario)
- Santos leases
- Arrow leases
- QGC leases
- Model domain

[1] The water bores were derived from the DERM Groundwater Database and Great Artesian Basin Water Resource Stock and Domestic Register

[2] The Great Artesian Basin Resource Operation Plan (2007) adopts a 5m groundwater drawdown for evaluating the criteria for the protection of existing groundwater entitlements. The same criteria has been applied in the impact assessment to evaluate potential effects to existing registered groundwater bores.

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Map 13: Project case projected groundwater level drawdown in the Taroom Coal Seam unit at model year 2049 (best estimate)

Project No: 301001-00448	Figure: 00448-00-EN-DAL-0451	Rev: 0

Compiled by MELBOURNE GEOMATICS

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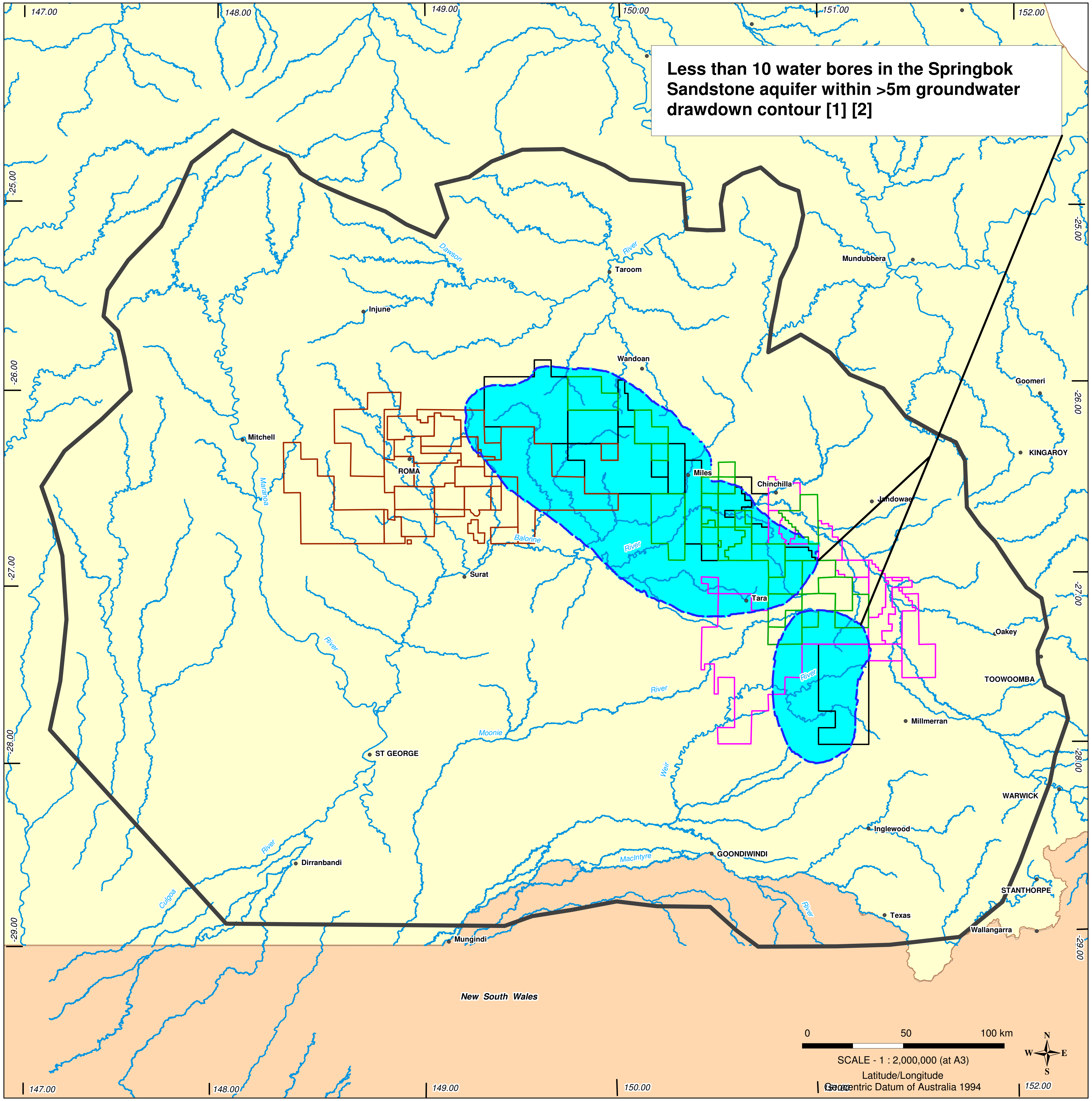

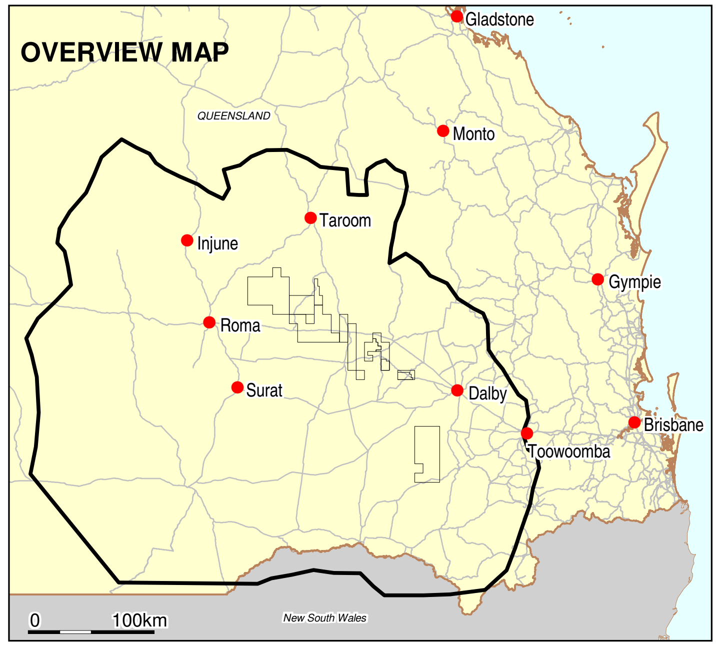

LEGEND

- Major towns
- Major watercourses
- Walloons gas fields development areas

Groundwater Level Drawdown

- Projected 5m groundwater drawdown contour at model year 2049 (best estimate project case scenario)
- Projected area of groundwater drawdown > 5m at model year 2049 (best estimate project case scenario)
- Santos leases
- Arrow leases
- QGC leases
- Model domain

[1] The water bores were derived from the DERM Groundwater Database and Great Artesian Basin Water Resource Stock and Domestic Register

[2] The Great Artesian Basin Resource Operation Plan (2007) adopts a 5m groundwater drawdown for evaluating the criteria for the protection of existing groundwater entitlements. The same criteria has been applied in the impact assessment to evaluate potential effects to existing registered groundwater bores.

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Map 14: Project case projected groundwater level drawdown in the Springbok Sandstone aquifer at model year 2049 (best estimate)

Project No: 301001-00448	Figure: 00448-00-EN-DAL-0450	Rev: 0

Compiled by MELBOURNE GEOMATICS

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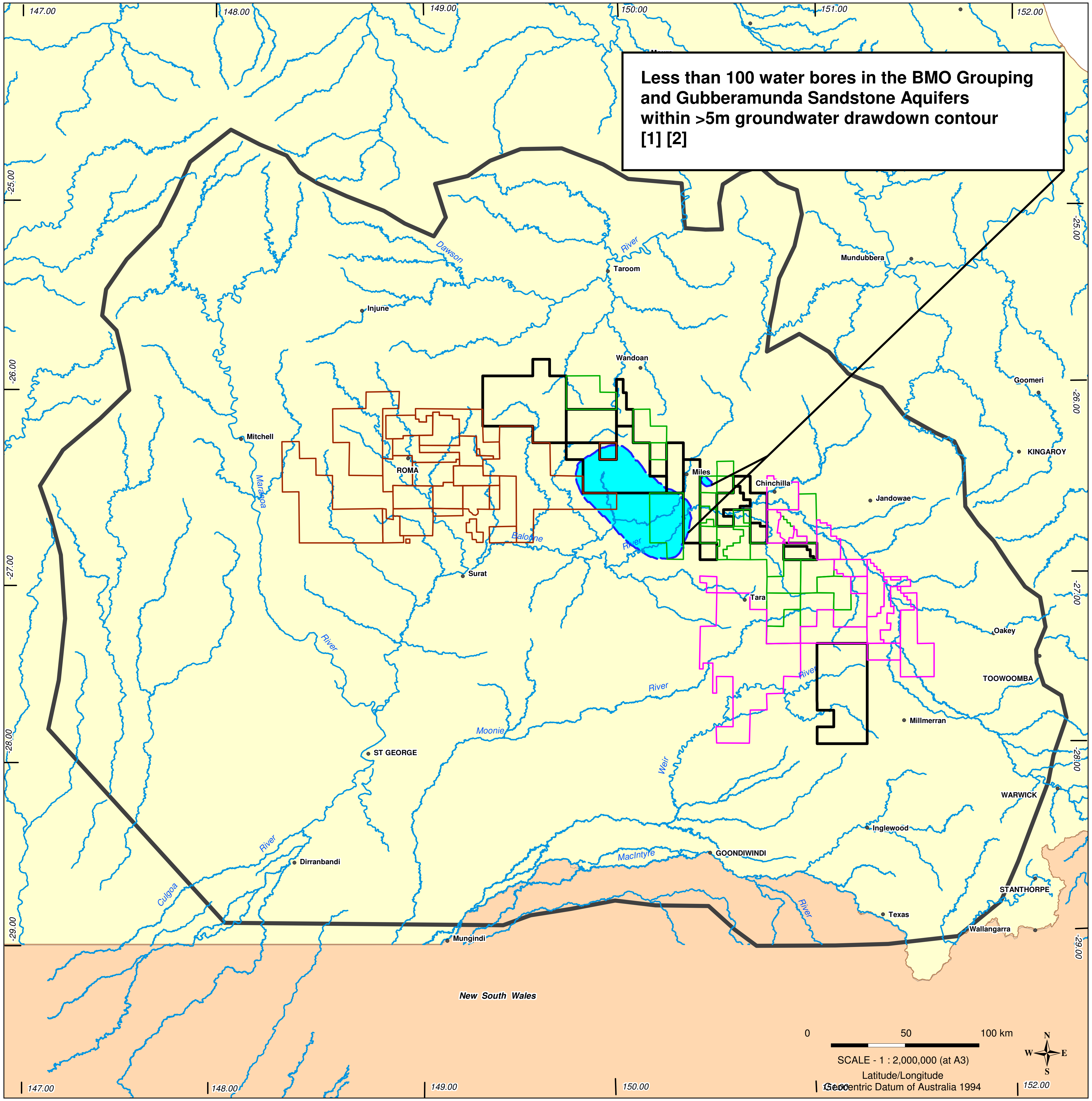

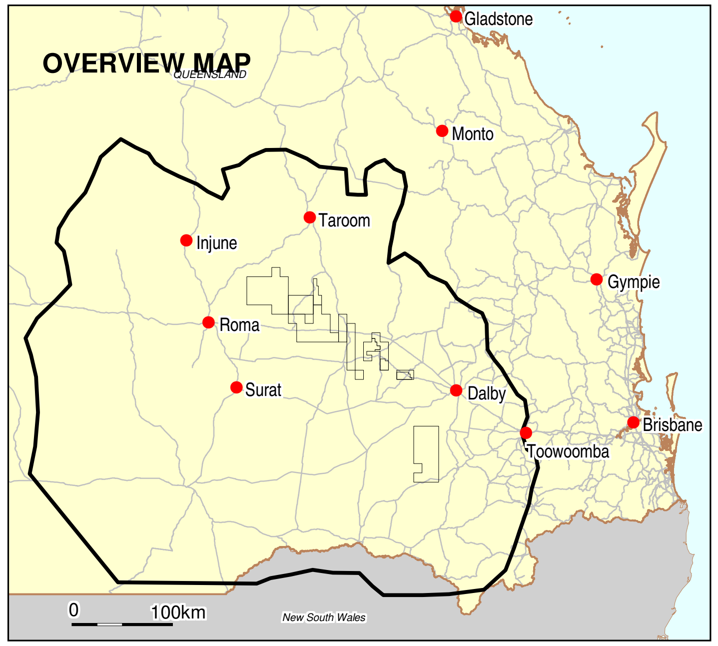

LEGEND

- Major towns
- Major watercourses
- Walloons gas fields development areas

Groundwater Level Drawdown

- Projected 5m groundwater drawdown contour at model year 2049 (best estimate project case scenario)
- Projected area of groundwater drawdown > 5m at model year 2049 (best estimate project case scenario)
- Santos leases
- Arrow leases
- QGC leases
- Model domain

[1] The water bores were derived from the DERM Groundwater Database and Great Artesian Basin Water Resource Stock and Domestic Register

[2] The Great Artesian Basin Resource Operation Plan (2007) adopts a 5m groundwater drawdown for evaluating the criteria for the protection of existing groundwater entitlements. The same criteria has been applied in the impact assessment to evaluate potential effects to existing registered groundwater bores.

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Map 15: Project case projected groundwater level drawdown in the BMO Grouping and Gubberamunda Sandstone aquifers at model year 2049 (best estimate)

Project No: 301001-00448 | Figure: 00448-00-EN-DAL-0449 | Rev: 0

Compiled by MELBOURNE GEOMATICS

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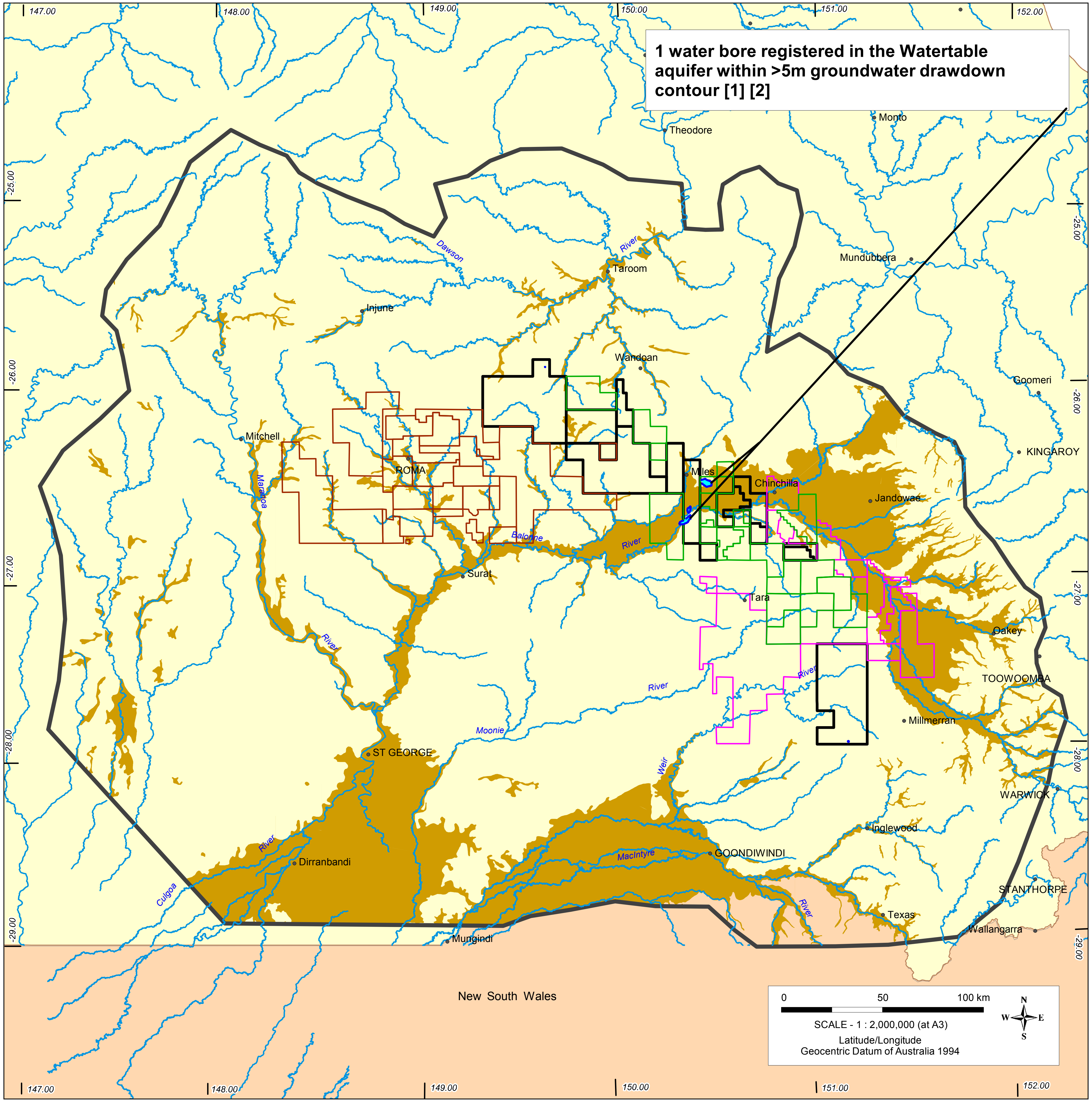

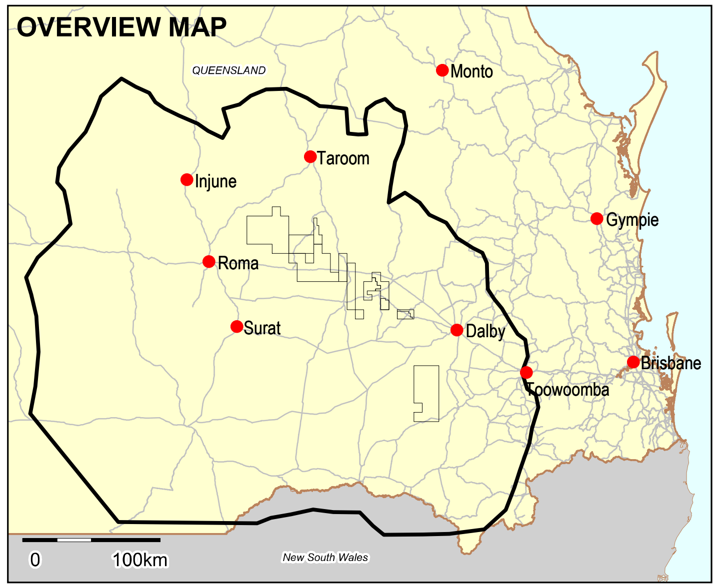

LEGEND

- Major towns
- Major watercourses
- Walloons gas fields development areas

Groundwater Level Drawdown

- Projected 5m groundwater drawdown contour at model year 2049 (best estimate project case scenario)
- Projected area of groundwater drawdown > 5m at model year 2049 (best estimate project case scenario)
- Santos leases
- Arrow leases
- Extent of Alluvium within the model domain
- Model domain
- QGC leases

[1] The water bores were derived from the DERM Groundwater Database and Great Artesian Basin Water Resource Stock and Domestic Register

[2] The Great Artesian Basin Resource Operation Plan (2007) adopts a 5m groundwater drawdown for evaluating the criteria for the protection of existing groundwater entitlements. The same criteria has been applied in the impact assessment to evaluate potential effects to existing registered groundwater bores.

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Map 16: Project case projected groundwater level drawdown in the Watertable interval at model year 2049

Project No: 301001-00448 | Figure: 00448-00-EN-DAL-0448 | Rev: 0

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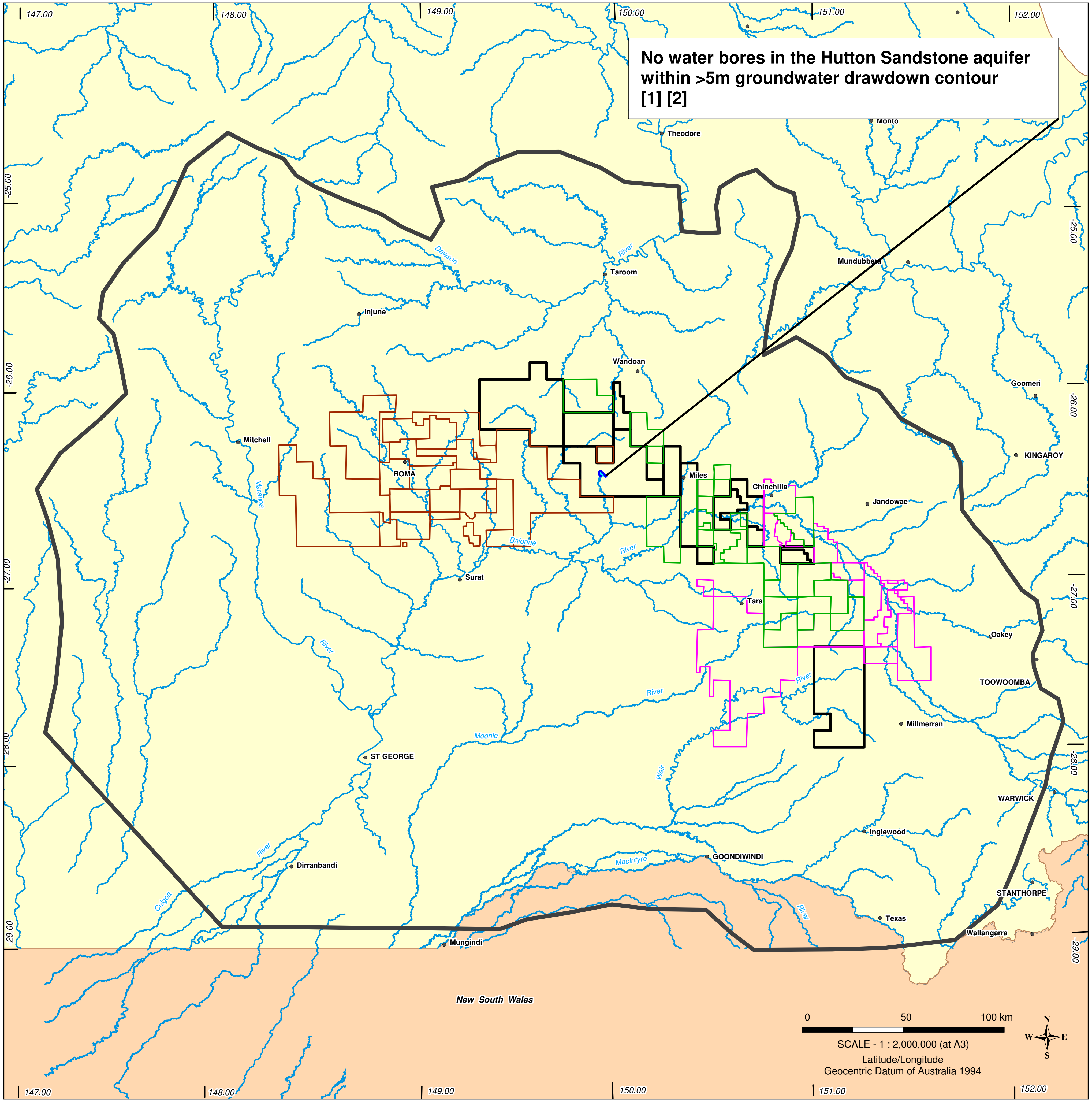

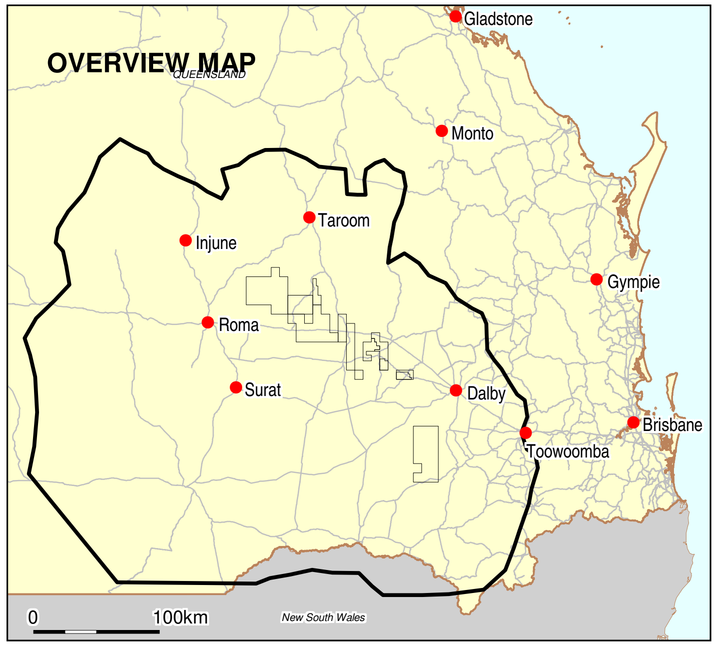

LEGEND

- Major towns
- Major watercourses
- Walloons gas fields development areas

Groundwater Level Drawdown

- Projected 5m groundwater drawdown contour at model year 2049 (best estimate project case scenario)
- Projected area of groundwater drawdown > 5m at model year 2049 (best estimate project case scenario)
- Santos leases
- Arrow leases
- QGC leases
- Model domain

[1] The water bores were derived from the DERM Groundwater Database and Great Artesian Basin Water Resource Stock and Domestic Register

[2] The Great Artesian Basin Resource Operation Plan (2007) adopts a 5m groundwater drawdown for evaluating the criteria for the protection of existing groundwater entitlements. The same criteria has been applied in the impact assessment to evaluate potential effects to existing registered groundwater bores.

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Map 17: Project case projected groundwater level drawdown in the Hutton Sandstone aquifer at model year 2049 (best estimate)

Project No: 301001-00448 | Figure: 00448-00-EN-DAL-0452 | Rev: 0

Compiled by MELBOURNE GEOMATICS

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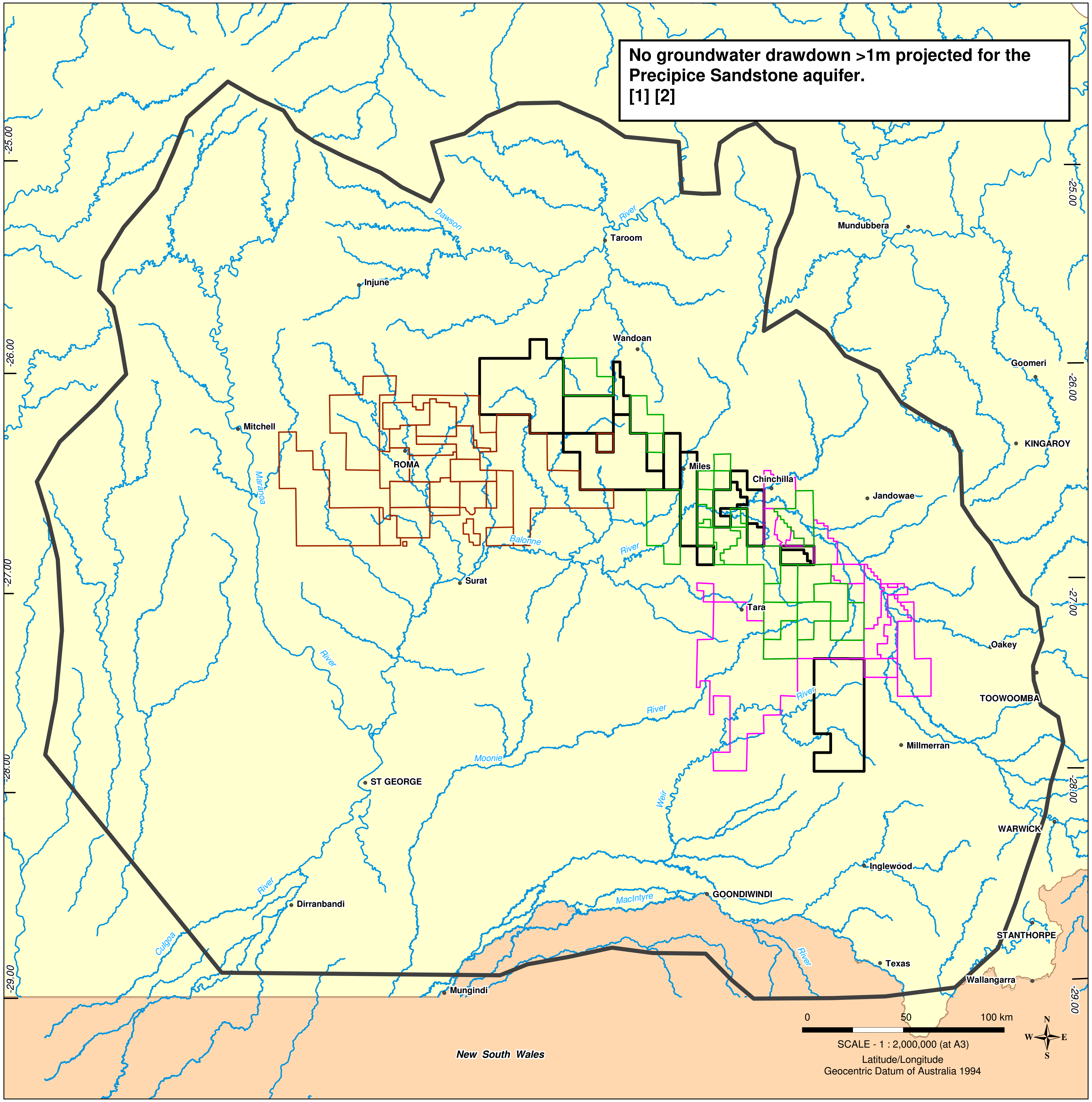

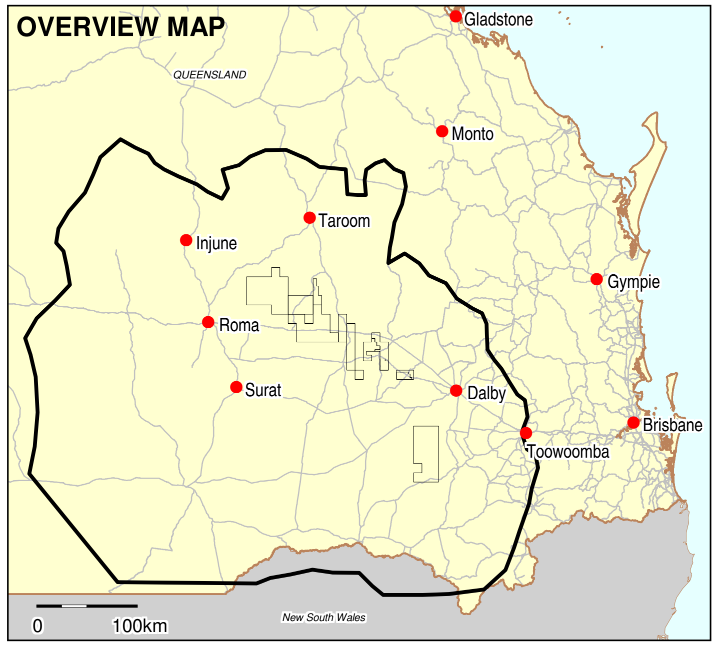

LEGEND

- Major towns
- Major watercourses
- Walloons gas fields development areas

Groundwater Level Drawdown

- Santos leases
- QGC leases
- Arrow leases
- Model domain

[1] The water bores were derived from the DERM Groundwater Database and Great Artesian Basin Water Resource Stock and Domestic Register

[2] The Great Artesian Basin Resource Operation Plan (2007) adopts a 5m groundwater drawdown for evaluating the criteria for the protection of existing groundwater entitlements. The same criteria has been applied in the impact assessment to evaluate potential effects to existing registered groundwater bores.

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Map 18: Project case projected groundwater level drawdown in the Precipice Sandstone aquifer at model year 2049 (best estimate)

Project No: 301001-00448 | Figure: 00448-00-EN-DAL-0454 | Rev: 0

Compiled by MELBOURNE GEOMATICS

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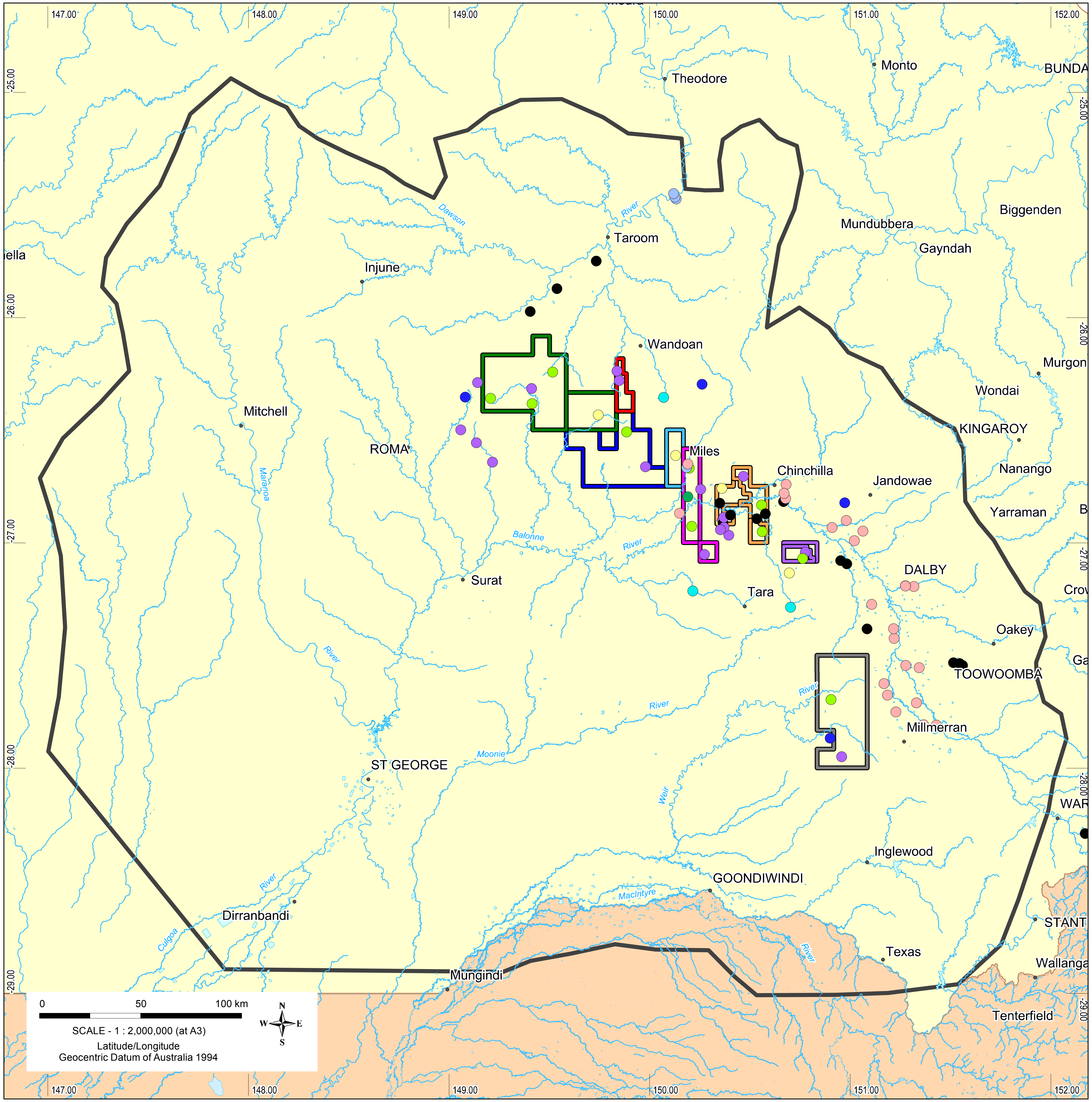

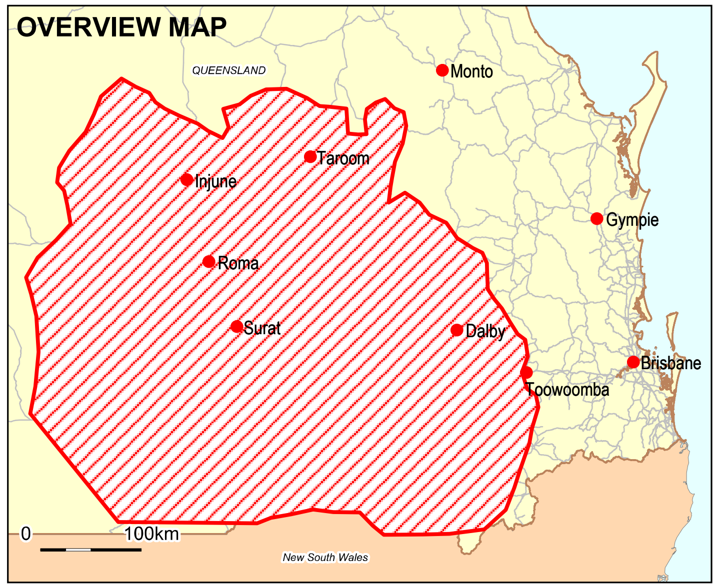

LEGEND

- Major towns
- Major watercourses
- Model Domain

Walloons Gas Fields Development Areas

- Talinga / Orana
- Dalwogan
- Kainama
- Gilbert Gully
- Combabula / Ramyard
- Woleebee
- Carinya
- Condabri

Proposed monitoring bores

- Cainozoic units
- Bungil Mooga Orallo grouping
- Gubberamunda sandstone
- Springbok sandstone
- Walloon coal measures
- Hutton sandstone
- Precipice sandstone
- Springbok and Hutton sandstones (nested)
- Gubberamunda, Springbok and Hutton sandstones (nested)

Rev	Date	Revision Description	ORIG	CHK	ENG	APPD
0	03/03/2010	Issued for use	GSB	KM	DG	RB

WorleyParsons resources & energy

AUSTRALIA PACIFIC LNG

AUSTRALIA PACIFIC LNG PTY LIMITED

AUSTRALIA PACIFIC LNG PROJECT

Map 19: Indicative monitoring network

Project No: 301001-00448 | Figure: 00448-00-EN-DAL-0461 | Rev: 0

Compiled by MELBOURNE GEOMATICS

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Appendix C Baseline field program

APLNG Groundwater Monitoring Program

Phase 1 Fieldwork Program Summary Report

07-Jul-09

WorleyParsons Document Number - Alternate Document Number

WORLEYPARSONS FORMAL REPORT TEMPLATE

REV	DESCRIPTION	ORIG	REVIEW	WORLEY-PARSONS APPROVAL	DATE	CLIENT APPROVAL	DATE
A	Issued for internal review	Ryan Morris	J Fennell	N/A	15-Jul-09	N/A	

Executive Summary

The phase 1 fieldwork of the groundwater monitoring program resulted in the following data being collected:

- 17 individual water level readings
- Laboratory analyses for 10 bores
- Ongoing 12 hourly water level readings in 10 bores

Water quality conditions between aquifers were variable, however water quality within each aquifer was variable, particularly in the Cainozoic where the range in electrical conductivity ranged from 3.2 mS/cm to 18.9 mS/cm. Strontium, boron and barium were reported in relatively high concentrations, particularly in samples from the Cainozoic aquifer.

Analysis of dissolved methane indicated the presence of methane in the Gubberamunda Sandstone at concentrations of a similar magnitude to those from the Walloon Coal Measures. The headworks and method of collection of the samples from the Coal Measures may have allowed volatilisation of some the gas, hence the dissolved concentrations may be under-reported, however much of the gas will have been in the vapour phase. Monitoring of wellhead gas concentrations with a portable gas meter did not reveal the presence of fugitive gas emission in any of the bores visited.

The potential for gas migration was observed as gas bubbles were observed in bore number 23457, which, based on the gamma logging is open across the top of the Walloon Coal Measures, the Springbok Sandstone, the Westbourne Formation and a small interval of the Gubberamunda Sandstone.

The CCTV inspections of many of the DERM wells indicated that some of these wells had already failed through dislocation of joins, and that the PVC used in their construction was degrading. Consideration should be given the refurbishment or replacement of these monitoring bores.

As no existing monitoring wells were established in the Springbok or Hutton Sandstones, considered key intervals for monitoring, existing CSG exploration and testing wells were investigated for potential retro-fitting into monitoring wells. Talinga 11 and Talinga 17 were identified for retro-fit into Hutton and Springbok monitoring bores respectively.

Contents

1. INTRODUCTION

WorleyParsons undertook Phase 1 of the fieldwork for the implementation of the APLNG Groundwater Monitoring Program from 10 June to 22,June 2009. The target area for the Phase 1 program was the Talinga-Orana development area, with the expectation that establishment of a monitoring network for the greater project area (GPA) would be undertaken in separate phases.

In brief, the scope of the fieldwork included the following (where possible and appropriate):

- Locating of nominated wellbores and obtaining of co-ordinates;
- Measurement of standing water levels in well bores accessed;
- Completion of well bore surveys (CCTV and natural gamma readings) to confirm or determine construction details and assess adjacent lithology;
- Collection of water samples for field measurements only, or field measurements and laboratory analysis; and
- Instrumentation of appropriate well bores with automated water level monitoring devices.

This document reports the works completed and the results of the field program. A concise summary is provided in **Table 1** at the end of the document.

2. METHODOLOGY

Phase 1 of the fieldwork for the implementation of the APLNG Groundwater Monitoring Program was conducted by Mr. Ryan Morris and Mr. Sean Frazer, both of WorleyParsons. The methodology followed is described in the following sections, and a summary of the works completed is tabulated as **Table 1.**

2.1 Health, Safety and Environment Management

2.1.1 Health and Safety

Prior to commencement of the field program, field personnel completed the Origin Energy (OE) online induction and a WorleyParsons project-specific fieldwork induction. Following these inductions, a risk review of the fieldwork program was completed to identify any potential hazards prior to execution. The result were used to generate project specific safe work procedures for groundwater sampling and geophysical logging, and a project specific Job Hazard Analysis (JHA), which identified specific risks and provided mitigation measures to reduce these risk. Field personnel were briefed on the JHA and signed their agreement to its requirements.

“Toolbox” meetings were held each morning prior to accessing any sites in order to discuss the coming day’s activities and the previous day’s health, safety and environment issues. When arriving at each site, a “Step Back” was completed to identify location-specific risks. If previously unidentified hazards were identified, a JHA was generated to assess the risk and develop mitigation measures. Specific JHAs were developed in the field for the following:

- Working underneath windmills; and
- Working over and adjacent to a water filled sump.

An site induction for the Talinga development area was also completed by field personnel prior to accessing any OE-owned sites, particularly the Rockwood and Turinga properties.

2.1.2 Environment

Upon mobilisation to the project area on June 11, 2009, a weed inspection and washdown was completed at the Chinchilla stockyards by Weed Hygiene Inspection Services. A second washdown was completed on June 19, 2009. The vehicle floor pans, tyres and obvious mud was brushed from the vehicle at each site visited prior to departure, and at the motel accommodation at the end of each day.

2.2 Landholder and Bore Owner Permission

Department of Environment and Resource Management (DERM) bores required an access agreement between the department and OE to be executed prior to accessing any DERM bores. In advance of the actual agreements, DERM provided email permission and a key for the bore locks. All agreements were subsequently received by OE during the field program.

Additionally, OE obtained permission from CS Energy to access the Lagoon Gully Monitoring Bore and the Klines Road Regional Monitoring Bore.

Landowner approval to access private bores was confirmed by OE land access officers (Damian Morris and Judy Green) prior to accessing any private property.

2.3 Bore Location Confirmation

A Garmin© etrex handheld global position system (GPS) device was used to navigate to the various bores using co-ordinates from the Queensland groundwater bore database or other databases. Where bores were found to be located at locations other than the given co-ordinates, new location data was obtained and recorded using the GPS device.

2.4 Wellhead Gas Concentration Measurement

The potential for explosive gases to accumulate in some of the bores to be accessed was identified during the HSE risk assessment. To mitigate the risk of explosion and asphyxiation, wellhead concentrations of methane (as a percentage of the lower explosive limit - LEL), oxygen, hydrogen sulphide and carbon monoxide were measured using a Rae® Systems QRAE gas monitoring device. The QRAE was calibrated by the equipment hire company prior to shipping and use in the field.

A 1 m length of 5mm diameter low density polyethylene (LDPE) tubing was attached to the inlet filter on the QRAE device. This tube was then fed into the wellhead prior to opening the cover to ensure gas concentrations did not pose a risk. If the methane concentration was below 10% LEL, the well was opened. Gas monitoring continued for the duration of works on the well by leaving the tubing in the well, and having the alarm set to 5% LEL.

2.5 Waterlevel and Bore Depth Measurements

Waterlevels were measured in each well (if possible) prior to conducting any other tasks. Measurements were made using a 150 m long Solinst© 101 water level measuring tape (electronic) and were taken in relation to the top of casing (TOC). It was not possible to measure waterlevels in many of the water supply bores with windmills or pumps due to sealed wellheads and the presence of the pumps, pipework and cabling.

The waterlevel tape was also used to measure bore depths that were less than 150 m. Where bore depth exceeded 150 m the gamma logging equipment was used.

2.6 Downhole Surveys

Downhole surveys (CCTV camera and natural gamma tool) were utilised to determine (or confirm) well construction, particularly depth of steel casing, screened (perforated) intervals, and general well condition. The natural gamma tool also provided information to qualitatively assess lithology and the type of interval being monitored by the associated well.

Geophysical surveys were undertaken using a portable Auslog W450-1 winch with 12V DC motor drive, Auslog A31 natural gamma sonde and a DLS 4 datalogger. The equipment was controlled with Wellvision Version 1.0.6 data acquisition software. An A200 Mighty CAM borehole video system (CCTV camera) was used to view the internal casing condition and to identify screened intervals. The equipment was powered using the vehicle battery.

The CCTV camera was run into the bore immediately following waterlevel measurement and prior to any disturbance to the water column and stirring up sediment, which would affect the visibility. The CCTV camera was run into the bore at a slow enough speed that allowed the casing to be viewed.

Gamma logs were recorded with the tools being run into and out of the bores. Data acquisition was at 10 cm intervals and the logging speed was maintained between 8 and 10 meters per minute. The tension on the cable was continually observed to indentify when the sonde had reached the bottom of the bore, particularly in those bore greater than 150m deep. When the cable became slack, the sonde was winched up and down until a consistent tension was maintained. The depth of the sonde was then recorded as the bore depth.

2.7 Water Sampling and Analysis

Groundwater samples were collected using either:

- A QED© low-flow bladder pump powered by compressed air;
- A Solinst© stainless-steel point-source bailer; or
- Existing permanently installed pumps.

The method used to sample each bore is provided in Tables XX and XX, and further details of the different methods are provided below.

Field water quality parameters (electrical conductivity (EC), pH and temperature) were measured with a Hanna Instruments HI98130 handheld meter. This device was calibrated on a daily basis with a two-point pH (pH 7 and pH 10) calibration and a one-point EC calibration (12,880 µS/cm). Dedicated containers were used for each calibration solution, and the solution was disposed of following calibration.

Groundwater samples for laboratory analysis were collected when field parameters had stabilised for at least three successive readings within the criteria defined in **Table 2-1**.

Table 2-1 Field Parameter Stabilisation Criteria for Water Sample Collection (Holmes, et al., 2001)

Parameter	Variability
pH	± 0.1 units
Electrical conductivity (<100 µS/cm)	± 5 %
Electrical conductivity (>100 µS/cm)	± 3 %
Temperature	± 0.2 ° C

Samples were collected into laboratory-supplied bottles containing appropriate preservatives where required. Samples for dissolved metals and trace elements were filtered in the field using separate Waterra© 0.45 micron inline disposable filter for each bore. Containers for semi-volatile organic compounds (SVOCs, such as phenols and polycyclic aromatic hydrocarbons) and stable isotopes of oxygen and hydrogen were filled to achieve zero headspace.

The samples were immediately placed on ice in a cooler, and shipped to the laboratory by same-day courier, generally on the day following collection. Analytical requests and Chain-of-Custody documentation accompanied the samples to the laboratory.

The primary laboratory used for sample analyses was LabMark Environmental Laboratories (LabMark) located in Brisbane. LabMark is accredited by the National Association of Testing Authorities (NATA) for the analyses performed. Samples for isotope analysis were submitted to the University of Queensland. All water samples were analysed for a combination of the following parameters:

- pH;
- Total dissolved solids (TDS);
- Dissolved organic carbon (DOC);
- Metals and trace elements (dissolved and total);
- Major cations and anions;
- Phenolic compounds;
- Polycyclic aromatic hydrocarbons (PAHs);
- Dissolved sulphide;
- Dissolved nitrogen species;
- Dissolved methane; and
- Stable isotopes (^{18}O and ^{2}H).

2.7.1 Low-flow sampling

Low flow sampling was only used in the 50 mm diameter wells as the method is unsuitable for larger bores. This sampling technique was selected as the primary method for DERM wells to minimise the volumes of purge water, and hence any concerns related to the disposal of potentially saline purge water.

The QED pump was lowered to middle of the screened interval. LDPE tubing and bladders were utilised; however, these were not replaced between wells. Pumping commenced at approximately 100 millilitres per minute (mL/min) and the waterlevel in the bore was continuously monitored for several minutes. If the waterlevel did not draw down, the pumping rate was gradually increased up to a maximum of approximately 600 mL/min, with continued waterlevel monitoring.

Field parameters were continuously assessed throughout purging using the field probes and a flow-through cell. Measurements were recorded at approximately 5 minute intervals, representing approximately 2.5 litres of purged water. Samples were collected after a minimum of 30 minutes of pumping, and only when water quality parameters had stabilised within the ranges specified in **Table 2-1**.

Once field parameters had stabilised, samples were collected directly from the discharge hose extending from the pump into laboratory-supplied bottles. Turbulence of flow into the bottles was minimised by reducing the pumping rate. When sampling for dissolved metals and trace elements, an inline filter was fitted directly into the discharge line. Samples for stable isotope analysis were collected by placing the discharge tube at the base of the bottle and filling until at least one bottle volume had overflowed.

2.7.2 Bailer

Due to an equipment malfunction, two wells required collection of samples using a bailer. These two well were 42230004 and 42231259. A Solinst© stainless-steel point-source bailer was used to collect these samples as well as all other samples from bores greater than 50 mm in diameter that did not have pumps installed.

It was not feasible to bail a sufficient volume of water from the larger diameter bores to ensure that the sample was representative of the aquifer, hence a "grab" sample was collected from either the screened interval or a maximum depth of 150 mTOC. The field water quality parameters were also measured and recorded.

For DERM wells 42230004 and 42231259, twenty five litres and forty litres, respectively, was purged, with field parameters measured every five litres to ensure parameter stabilisation. Samples were poured directly from the bailer into the laboratory-supplied bottles. For the stable isotope samples, the lid was closed between bailer loads. Samples for dissolved metal and trace element analysis were filtered by pouring the sample into a new, unpreserved plastic bottle, cutting a hole in the lid of the bottle and forcing an inline filter into the hole. The bottle was then squeezed to force the water through the filter into another laboratory-supplied bottle with preservative.

2.7.3 Existing Pumps

When an existing pump was used to collect a sample from a bore, the pump was run for at least five minutes prior to the sample being collected. It was ensured that the sample was collected from as close to the wellhead as possible and prior to flowing into a treatment system or collection tank.

The sample obtained from Talinga 15, a pumping CSG well, was collected directly from a port on the headworks. Field parameters were measured and recorded as well.

A sample was also collected from the Talinga 2 CSG well, which did not have a pump installed. A valve on the headworks was opened and water and gas were allowed to discharge for five minutes prior to sample collection. Water was collected in a clean bucket, and was then sub-sampled into laboratory-supplied bottles. The sample for dissolved metals and trace elements was filtered using the same method as the bailed samples.

2.8 Analytical Data Validation

Analytical data validation is the process of assessing whether data are in compliance with method requirements and project specifications. The primary objectives of this process are to ensure that data of acceptable quality are reported, and to identify if the data can be used to fulfil the overall project objectives.

The data validation guidelines adopted are based upon guidance documents published by the United States Environmental Protection Agency (USEPA). The process involves the checking of analytical procedure compliance and an assessment of the accuracy and precision of the analytical data from a range of quality control measurements, generated from both the sampling and analytical programs. Specific procedures that were implmeneted, checked and assessed for this investigation include:

- Collection and laboratory analysis of a field blind duplicate sample;
- Preservation and storage of samples on ice following collection and during transport to the laboratory;

- Review of sample holding times;
- Use of appropriate analytical procedures;
- Ensuring proper limits of reporting;
- Review of frequency of conducting quality control measurements;
- Review of laboratory blank results;
- Review of laboratory surrogate spike results; and
- Noting of the occurrence of apparently unusual or anomalous results, e.g. laboratory results that appear to be inconsistent with field observations and measurements.

2.9 Installation of Permanent Waterlevel Monitoring Devices

Dedicated Solinst Levelogger Gold pressure transducers were installed in selected bores by hanging the logger on a direct read optical cable attached to the bore headworks. The dataloggers were set to record waterlevels at twelve hour intervals.

3. Results

Table 1, at the end of this document, summarises the results of the fieldwork program. Specific aspects of the results are also discussed in further detail.

3.1 Bore Access and Locations

Wellbores visited included DERM groundwater monitoring bores, Origin Energy CSG wells and private water bores. The locations are shown on **Figure 1**. Several bores originally proposed were not visited because either access permission was not granted or the bores could not be located. This information is summarised in **Table 1**.

Of the bores that could not be located, and following communication with DERM, it was found that the co-ordinates for 42230190 were incorrect in the State's groundwater bore database (the actual bore location was in excess of 100 km from the expected location). Also, it was determined that bore 42231258 had been destroyed by Wilkie Creek Coal Mine operations. Some of the other DERM wells were found several hundred meters from their database locations. Bore 42231257 could not be located, although the database co-ordinates are expected to be within the error range of other bores (i.e. up to 500 m).

The co-ordinates of the Lagoon Gully monitoring bore were visited and the production bores were located; however, the monitoring bore could not be found. Permission was granted by CS Energy to access the Klines Road Regional Monitoring bore; however, it was located on Private Land and access was not obtained from the landholder during the field program.

Landholder permission was granted to access Orana 5; however, at the time the gate at the entrance to the property was locked.

Landholder access was not obtained for bores 87404, 42230214A (DERM-owned well on Sunwater land), and 42230211 (landholder could not be contacted).

Up-to-date co-ordinates, ownership and bore use are provided in **Table 1**.

3.2 Wellhead Gas Concentrations

Methane, hydrogen sulphide and carbon monoxide were not detected at any of the wellheads or bores prior to opening, or in the well during works at any of the bores visited during the field program. Oxygen concentrations were generally 20.9 %; however, in some bores the concentration within the casing, after the wellhead was opened, was measured as low as approximately 17%.

A few gas bubbles were observed in bore 23457, which is open across several units (see Section 3.4). However, gas concentrations in the wellhead were below instrument detection limits.

3.3 Waterlevels

Water levels were measured in 17 bores. Headworks on some bores precluded the ability to take level measurements; therefore, not all wells were assessed. Results are summarized in **Table 1**.

Although water levels were measured in Kainama 4 and Talinga 121 (existing CSG wells), they are not believed to be representative of the Walloon Coal Measures as levels were in close proximity to

surface. It is suspected that the casings may have not yet been perforated. The water level in bore 23457 is also suspect as it transects multiple units. DERM bore 42230202 was found to be effectively dry as the waterlevel was in the base of the well and below the bottom of the screened interval.

3.4 Bore Construction and Condition

The downhole surveys were utilised to determine or confirm well construction, particularly casing depths in old petroleum wells, screened (perforated) intervals, and general well condition. The natural gamma tool also provided information to assess the type of sediment being monitored by the well. Table 1 indicates the surveys completed as part of this program. Bore construction details are provided in the borelogs in Appendix 1 - . These logs are composites of data collected during the field campaign and data from the Origin Energy and DERM database.

The CSG wells and many of the private bores were not surveyed in this way because the bore headworks did not allow access inside the casing.

Use of the CCTV identified several DERM wells in compromised condition. Bore 42230208 was found to be severely out of plumb and with several dislocated casing joins and bulges in the casing. The well was compromised to the extent that the gamma sonde and sampling equipment could not pass 12.2 mTOC. A casing dislocation was observed in bore 42230202 at approximately 9.2 mTOC, and the CCTV camera could not pass a dislocation in at 3.5 mTOC in bore 42230203. In most DERM wells, the PVC casing was observed to be disintegrating.

The Old Woolshed Bore at Rockwood (9469) was found to have collapsed at 33.2 mTOC.

The gamma logging equipment proved very useful in determining the depth and construction details of the former petroleum investigation wells 23457, 23335 and 23642. Total depths and the depth of the casing shoe in each of these bores is summarised in **Table 3-1**.

Table 3-1 Construction Details of Former Petroleum Exploration Bores

Bore ID	Owner	Total Drilled Depth (m)	Current Depth (mbgl)	Casing Shoe Depth (mbgl)	Formation Monitored
23457	QGC	1134.2	420	109	Gubberamunda, Westbourne, Springbok, Walloon
23335	Private (Dougall)	1293.9	240	118	Gubberamunda
23642	Private (Dougall)	855.6	215	97	Gubberamunda

3.5 Water Quality Sampling

Full or partial field parameters were measured in 19 bores and samples from 11 (including one blind duplicate) were submitted for laboratory analysis. Sample collection methods and field chemistry are summarised in **Table 1**, while these together with laboratory chemistry results are summarised in **Table 2**. *Australian Drinking Water Quality Guidelines* (NHMRC, 2004) and ANZECC (2000) for primary industries have been provided for reference. Those concentrations which exceed guideline values have been highlighted for ease of reference. Full laboratory reports are provided in Appendix 2 -

From the results obtained, it was evident that water quality conditions between aquifers are variable. Also water quality within each aquifer is variable, particularly in the Cainozoic where the range in EC extends from 3.2 mS/cm to 18.9 mS/cm. Bailed grab samples were collected from the Gubberamunda bores (23335 and 23642) where extremely low field EC (electrical conductivity) values were measured (0.2 and 0.13 mS/cm respectively). This was taken as an indication of possible contamination by surface water entering into the bores.

Of particular note were the measureable dissolved methane concentrations in the Gubberamunda aquifer and the Precipice Formation at the same order of magnitude as the Walloon Coal Measures. The method of collection for samples from the Walloon Coal Measures (sub-sampling from an open bucket) would have allowed volatilisation of some of the methane and other associated gases, hence it is suspected that the results obtained may be under representing methane concentrations from that aquifer. The sample from the Miles Town Bore (Precipice Formation) was visibly degassing during collection.

Although the origin of the methane in the Gubberamunda aquifer is currently unknown, there are a number of potential sources of this dissolved gas:

- naturally-occurring methane (i.e., methanogenic conditions);
- cross-formational migration of methane from deeper intervals through intervening aquitards or via wellbores that may transit multiple aquifer intervals; or
- generation by bacteria that may reside in the well.

Strontium, boron and barium were reported in relatively high concentrations, particularly in samples from the Cainozoic aquifer.

Wirh the exception of bore 42230004, samples from the Cainozoic and Walloon Formations exceeded the guideline value for TDS for effects on poultry (2,000 mg/L), and the TDS of the Cainozoic samples was such that loss of beef, horse and pig production may occur (ANZECC, 2000). All other results were less than the adopted guideline values for livestock (ANZECC, 2000)

One or more samples exceeded the ANZECC (2000) guideline values for irrigation water for the following analytes:

- Dissolved and total boron;
- Dissolved and total manganese;
- Total chromium;
- Total cobalt;
- Total iron;
- Total chloride; and
- Total fluoride.

Additionally, one or more samples exceeded the Australian Drinking Water Guideline values (NHMRC, 2004) for the following analytes:

- Dissolved barium;
- Dissolved and total nickel;

- Dissolved and total selenium; and
- Total lead.

Samples for stable oxygen and hydrogen isotopes were collected from bores 42230004 (Cainozoic sediments – 31.4 m), Turinga House bore and Rockwood PB (Gubberamunda interval – approx. 100 m) and Talinga 2 CSG well (Walloons Coal Measures – 573 m). Results ranged from -5.8 to -7.6‰, respectively for $\delta^{18}O$ values, and -35 to -49‰, respectively, for $\delta^{2}H$ values.

3.6 Laboratory Analysis Data Validation

Laboratory quality assurance/quality control (QA/QC) results are provided with the reports in Appendix 2 - . Results are summarised below:

- **Laboratory analysis of the field blind duplicate sample** – The relative precision of the duplicate results was assessed by the magnitude of the relative percentage difference (RPD), calculated as:

  $$RPD(\%) = \frac{D_1 - D_2}{(D_1 + D_2)/2} * 100$$

  where D_1 and D_2 represent the two samples being compared. An acceptable range for field duplicates is generally <30-50%. A field duplicate (DUP1) of 42230209A was collected. The RPDs of the duplicate analyses were generally within the acceptable range, with the exception of dissolved organic carbon (RPD = 63%) and nitrate (RPD = 67 %). The large discrepancy in these results is believed to be a result of the low associated concentrations. Discussions with laboratories indicate that where detected concentrations are less than five times the method detection limit, higher RPDs (up to 200%) are common and are considered acceptable.
- **Preservation and storage of samples upon collection and during transport to the laboratory** – samples were correctly preserved, had zero headspace and were place on ice following collection and during transport to the laboratory.
- **Sample holding times** – required holding times were only exceeded for dissolved sulphide and pH for some samples. Field measured pH values were nonetheless collected and are considered more representative.
- **Use of appropriate analytical procedures** – all analytical techniques used were NATA approved.
- **Required limits of reporting** – limits of reporting were all less than the associated guideline values being assessed.
- **Laboratory blank results –** laboratory blank results all returned non-detectable concentrations.
- **Surrogate spike results –** surrogate spike results all fell within the required range of 80-120%.

Based on the above findings, it is considered that the QA/QC program was in accord with recommended good practice with some minor non-compliances with data quality objectives. Overall the program is considered adequate considering the scope and nature of the program undertaken. The data are considered sufficiently reliable for the purpose for which they have been obtained and used.

3.7 Permanent Waterlevel Monitoring

Solinst Levelogger© pressure transducers with on-board data loggers were installed in 10 bores across the Talinga/Orana development area. Instrumentation was installed in the following intervals

- Cainozoic - 6 bores (42230004; 42230203, 42230208; 42230209A ; 42230629; and 42231259); and
- Gubberamunda – 2 bores (10925; 30168; 23335 and 23642).

A Solinst Barologger© barometric pressure logger was also installed in 42230208. This device facilitates correction of measured waterlevels with atmospheric pressure fluctuations. Further details of the type of Levelogger and depth of installation are provided in **Table 1** and the locations of instrumented bores are show on **Figure 2**.

Although Leveloggers were installed in 10925, 30168, 23335 and 23642, these bores did not have lockable covers, hence a potential exists for the loggers to be moved or damaged. 23335 and 23642 are also surrounded by old drilling cellars making access to the wellhead difficult and potentially unsafe.

4. Conclusions

The Phase 1 fieldwork of the groundwater monitoring program resulted in the following data being collected:

- 17 individual water level readings;
- Laboratory analyses for 10 bores; and
- Ongoing waterlevel readings in 10 bores (at 12-hr intervals).

Permanent level monitoring devices were installed in 23335 and 23642 monitoring the Gubberamunda aquifer. At present, the cabling is not sufficiently secure or safe for long-term monitoring. As well, there is considerable cellar area around the wells which poses some HSE risks.

Analysis of dissolved methane indicated the presence of methane in the Gubberamunda Sandstone at concentrations of a similar magnitude to those from the Walloon Coal Measures. The headworks and method of collection of the samples from the Coal Measures may have allowed volatilisation of some the gas, hence the concentrations may be under-reported. The potential for gas migration was observed as gas bubbles were observed in bore number 23457.

The CCTV inspections of many of the DERM wells indicated that some of these wells had already failed through dislocation of joins, and that the PVC used in their construction was degrading. It is suspected that the DERM wells will not survive the life of the APLNG project.

No bores were identified that monitor the Springbok Sandstone or the Hutton Sandstone. .

No monitoring has been established in the BMO Aquifer, however pressure effects will be observed in the Gubberamunda Sandstone prior to them being transmitted to the BMO. It is not considered necessary to implement monitoring of the BMO Aquifer, unless impacts to the Gubberamunda Sandstone are observed.

Since demobilisation from the field, WorleyParsons has been informed by DERM that monitoring bore 42231257 is still in existence. According to the Queensland groundwater bore database, this bore accesses the Cainozoic aquifer near the Kainama development area where the Walloons Coal Measures sub-crop.

The existing Leveloggers are currently recording water levels at 12 hour intervals.

5. References

ANZECC (2000) Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000), Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand.

Holmes R.R., Jr., Terrio P.J., Harris M.A. and Mills P.J., 2001. Introduction to field methods for hydrologic and environmental studies. U.S. Geological Survey Open-File Report 01-50.

NHMRC (2004) Australian Drinking Water Guidelines 6, National Water Quality Management Strategy, Health and Medical Research Council and Natural Resource Management Ministerial Council.

Figures

Figure 1 Bores Visited During the Phase 1 Field Program

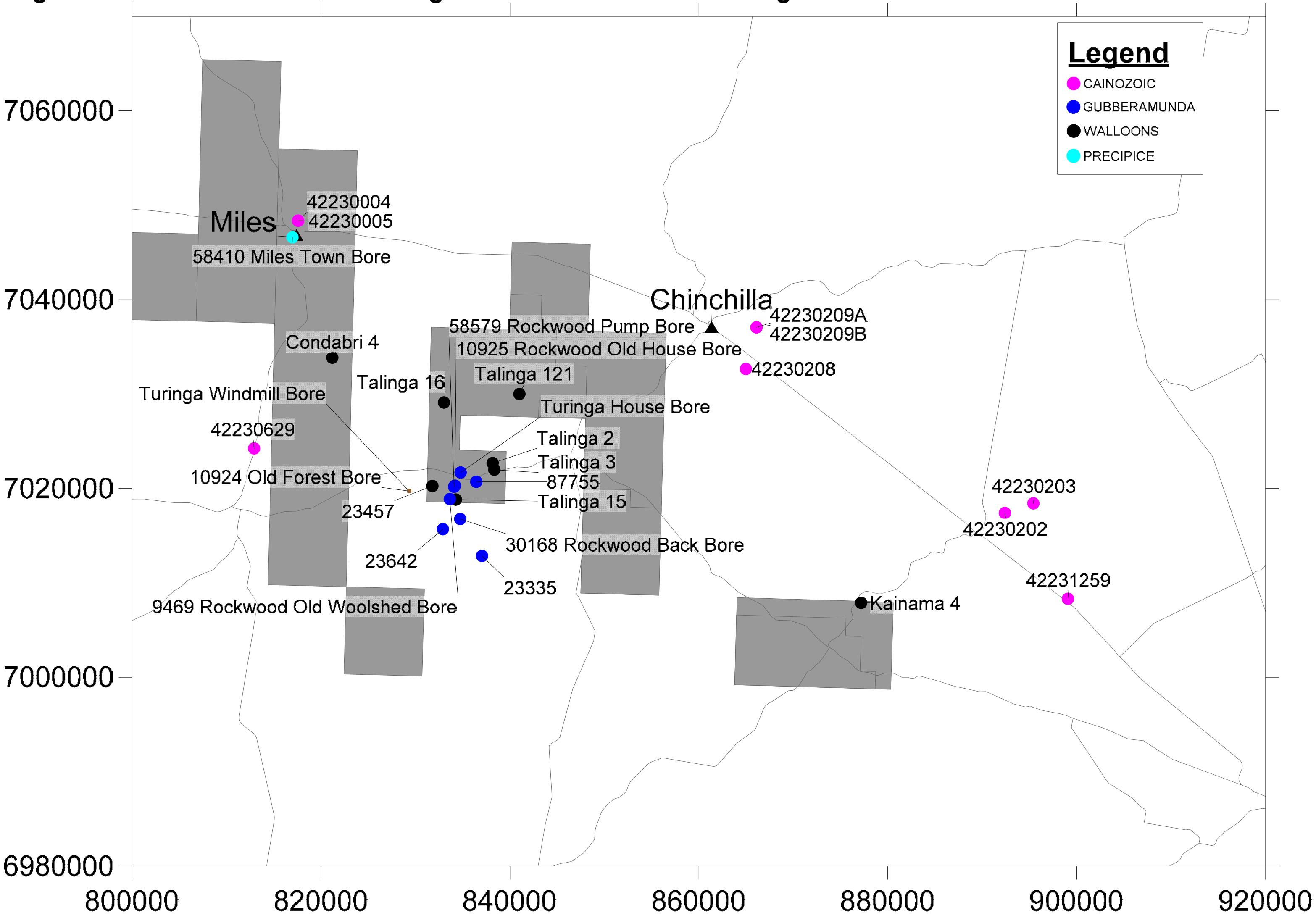


Figure 2 Bores Instrumented with Permanent Waterlevel Monitoring Devices

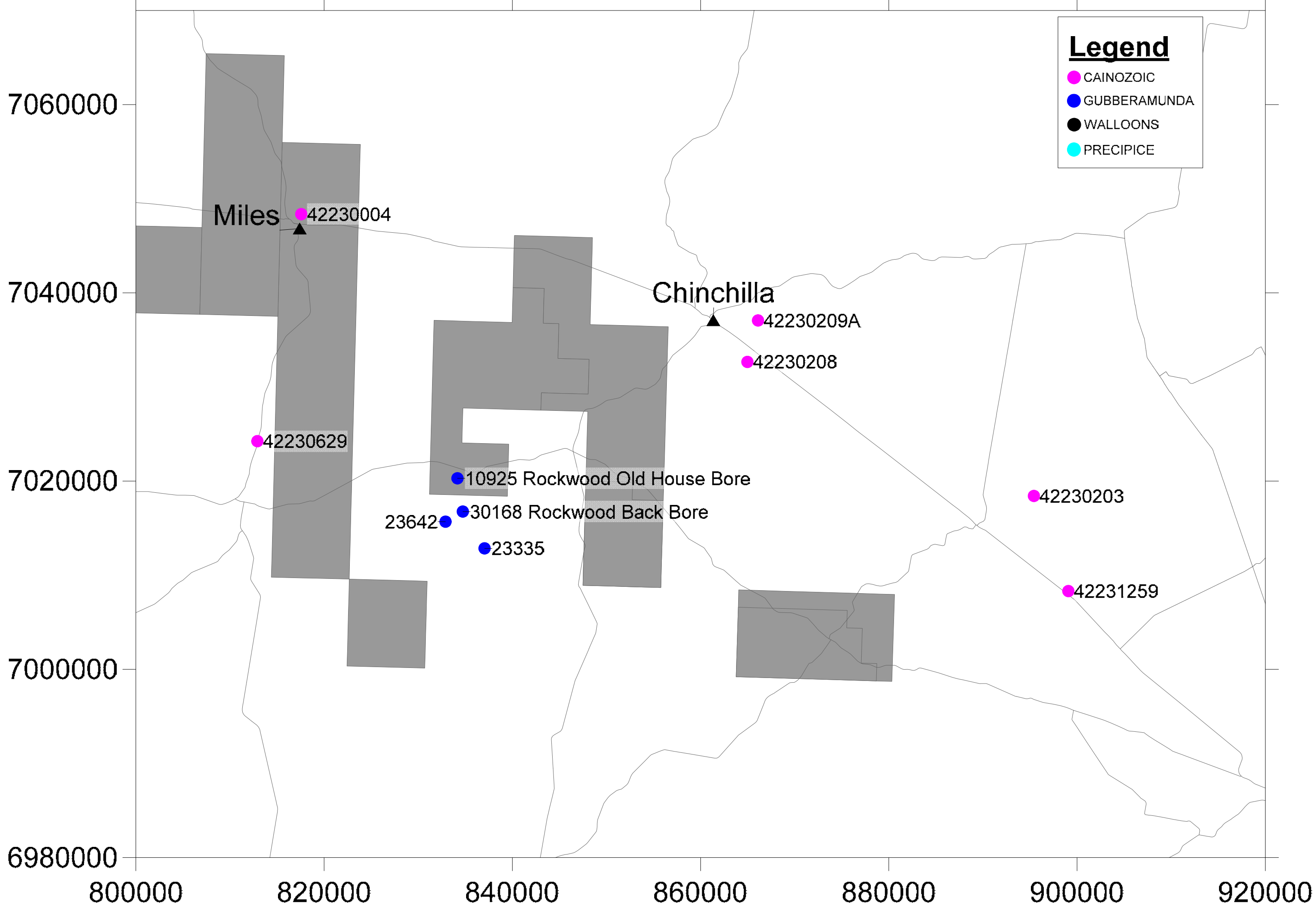
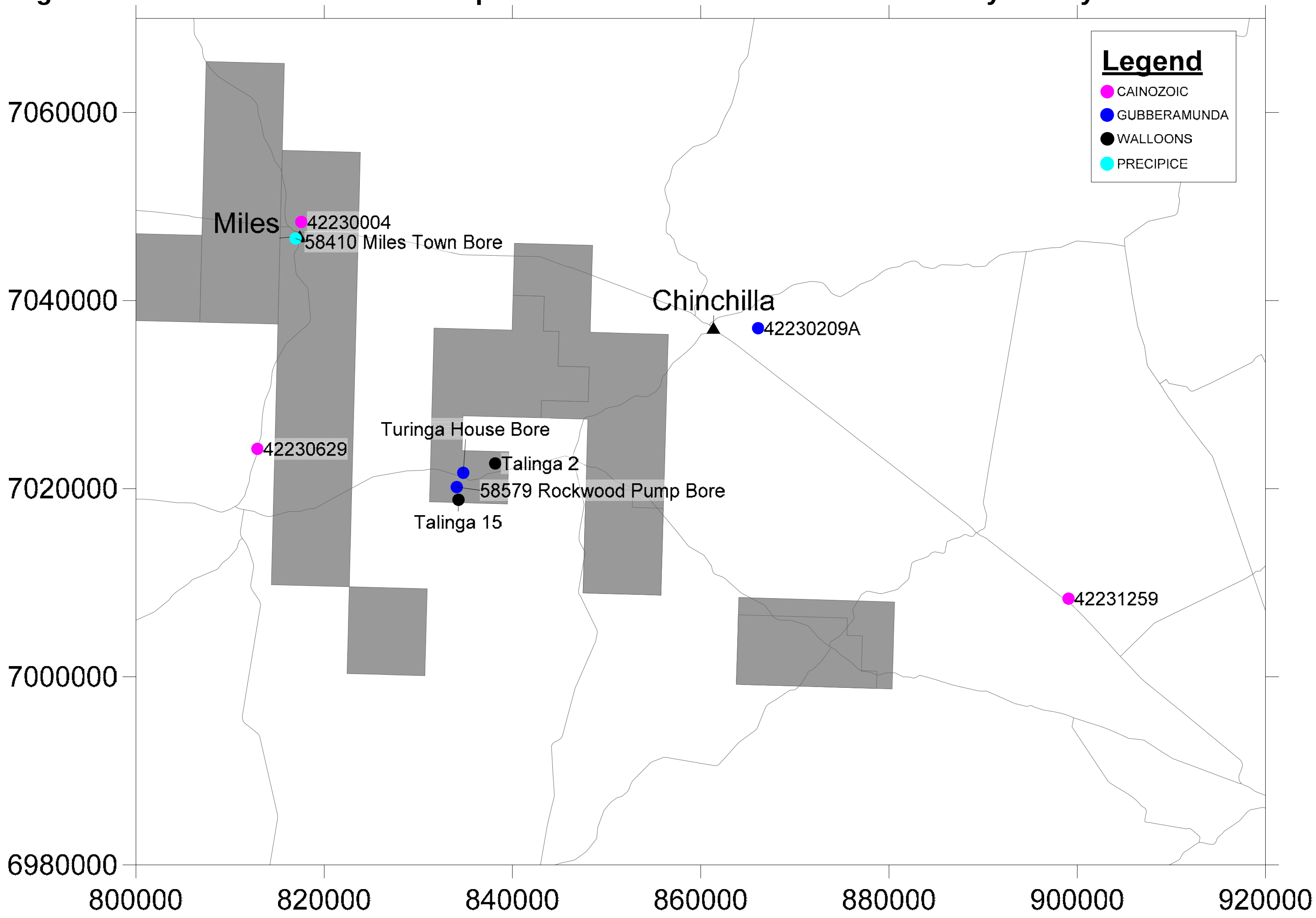


Figure 3 Bores from which Samples were Submitted for Laboratory Analysis



Tables

Appendix 1 - Borelogs

Appendix 2 - Laboratory Reports

Table 2 Summary of Phase 1 Groundwater Monitoring Program Laboratory Results

Bore ID	Units	Drinking Water[1]	Irrigation[2]	Livestock[2]	EQL	42230209A	42230209B	42230629	42230004	42231259	58579 (Rockwood PB)	87755	Turinga House Bore	Talinga 15	Talinga 2	58410 (Miles Town Bore)	DUP1 (42230209A)	RPD
Date Collected						14/06/2009	14/06/2009	15/06/2009	21/06/2009	21/06/2009	16/06/2009	17/06/2009	17/06/2009	16/06/2009	17/06/2009	18/06/2009	14/06/2009	
Latitude						-26.74223581	-26.74223581	-26.86851	-26.64981291	-26.99243382	-26.90024	-26.89485	-26.8864	-26.912381	-26.8766167	-26.666	-26.74223581	
Longitude						150.6799288	150.6799288	150.14921	150.1872157	151.0160259	150.36314	150.38665	150.36966	150.36535	150.4035	150.18441	150.6799288	
Elevation (mAHD)						308.58	308.58	287	295.85	323.98	296	296	300	311.53	292.78	301	308.58	
Screen Interval (Total Depth) (mbgl)						35.6-36.2	21.45-21.9	(27.65)	31.66	(27.75)	99	54-59	-	-	-	1187-1245	35.6-36.2	
Hydrostratigraphic Unit						Cainzoic	Cainozoic	Cainozoic	Cainozoic	Cainozoic	Gubberamunda	Gubberamunda	Gubberamunda	Walloons	Walloons	Precipice	Cainozoic	
Aquifer lithology						Sand and Clay	Fine Sand and clay	Sandy Clay	Sand and Gravel	Gravel	Sandstone	White sandy gravel	?	Coal	Coal	Sand (light)	Sand and clay	
Screen Construction Materials						PVC	PVC	PVC	PVC	PVC	Steel	PVC	PVC	Steel	Steel	Steel	PVC	
Field Results																		
Sample Collection Method						Low-flow	Low-flow	Low-flow	Bailed	Bailed	Existing Pump	Existing Pump	Existing Pump	Grab	Grab	Existing Pump	Low-flow	
SWL	mTOC	-	-	-	-	16.64	16.57	19.28	13.99	15.51	NA	NA	NA	NA	NA	NA	16.64	
EC	mS/cm	-	-	-	-	13.9	13.9	12.4	3.2	9.3	1	1.4	1.4	4.6	3.9	3.1	13.9	
pH	pH Units	-	<6	-	-	7.2	7.2	6.6	6.7	7.3	8.5	8.6	8.5	8	8.6	7.9	7.2	
Temperature	℃	-	-	-	-	23.7	25.2	19.2	20.9	22.3	25.2	15.5	22.9	36.9	27	32.6	23.7	
Laboratory Results																		
pH	pH Units	-	<6	-	0.1	7.5	7.6	6.9	6.9	7.1	8.8	8.3	8.6	8.5	8.9	8.4	7.6	1
Total Dissolved Solids	mg/L	-	-	2000	5	8500	8500	9000	1990	5400	840	810	830	2900	2400	1900	8400	1
Ion Balance (% Difference)	%	-	-	-	-	9.7	3.2	<1	5	3.8	3.2	3.2	3.2	7.3	2.3	5.6	15	43
Dissolved Gas																		0
Methane conc. of water @ 25℃	µg/L	-	-	-	-	4	3	78	2	<1	3200	590	2000	3000	3600	2400	4	0
Organic Analytes																		0
Sum of PAHs	µg/L	-	-	-	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	0
Total Reported Phenolics	µg/L	-	-	-	10	<2	<2	<10	20	20	<10	<10	<10	<10	<10	<10	<2	0
Dissolved Organic Carbon (mg/L)	µg/L	-	-	-	1	1.2	3	2	7	2	1.6	2	1.8	2.9	3.8	1.9	2.3	63
Dissolved Metals																		0
Arsenic	µg/L	7	100	500	1	6.2	6.6	6.8	*<20	*<20	<5	<5	<5	<5	<5	<5	5.9	5
Barium	µg/L	700	-	-	5	75	70	100	30	95	40	59	46	770	570	130	76	1
Beryllium	µg/L	-	100	-	1	<5	<5	<5	<1	<1	<5	<5	<5	<5	<5	<5	<5	0
Boron	µg/L	4000	500	5000	10	860	880	170	160	210	250	210	210	1200	770	1300	870	1
Cadmium	µg/L	2	10	100	0.1	<5	<5	<5	<0.1	<0.1	<5	<5	<5	<5	<5	<5	<5	0
Chromium	µg/L	-	100	1000	1	22	22	13	*<5	29	25	<5	<5	90	<5	<5	21	5
Cobalt	µg/L	-	50	1000	1	<5	<5	<5	42	5	<5	<5	<5	<5	<5	<5	<5	0
Copper	µg/L	2000	200	400	1	<5	7.1	<5	*<10	*<10	<5	<5	<5	<5	<5	<5	<5	0
Lead	µg/L	10	2000	100	1	<5	<5	<5	1	<1	<5	<5	<5	<5	<5	<5	<5	0
Manganese	µg/L	500	200	-	1	52	15	380	293	53	<5	<5	<5	<5	<5	<5	54	4
Molybdenum	µg/L	50	10	150	1	<5	<5	<5	2	<1	<5	<5	<5	<5	<5	<5	<5	0
Nickel	µg/L	20	200	1000	1	7.4	8	19	37	8	<5	<5	<5	<5	<5	<5	7.4	0
Selenium	µg/L	10	20	20	5	29	31	56	*<10	*<20	<5	<5	<5	9.8	6.9	<5	29	0
Silver	µg/L	100	-	-	0.1	<5	<5	8.9	<0.1	<0.1	<5	<5	<5	<5	<5	<5	<5	0
Strontium	µg/L	-	-	-	1	7800	7800	9500	294	10700	130	120	110	880	890	190	7700	1
Tin	µg/L	-	-	-	5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	0
Zinc	µg/L	-	2000	20000	5	39	36	31	167	45	18	5.5	<5	<5	7.8	<5	43	10
Mercury	µg/L	1	2	2	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0
Major Cations (Dissolved)																		0
Calcium	µg/L	-	-	1000000		178000	180000	396000	8300	266000	1620	2230	1660	2080	2760	1020	178000	0
Iron	µg/L	-	200	-	100	109	<100	12500	6550	710	<100	<100	<100	<100	<100	<100	125	14
Magnesium	µg/L	-	-	-	100	336000	305000	350000	42200	282000	329	821	465	764	835	167	365000	8
Potassium	µg/L	-	-	-	1000	3580	3180	12000	8000	6500	1190	1010	<1000	4620	3200	3840	3810	6
Sodium	µg/L	-	-	-	100	3170000	2920000	1960000	602000	1230000	332000	334000	331000	1320000	1030000	776000	3430000	8
Total Metals																		0
Arsenic	µg/L	7	100	500	5	-	-	5.5	*<20	*<20	<5	<5	<5	<5	<5	<5	-	0
Barium	µg/L	700	-	-	5	-	-	110	36	124	41	51	49	930	600	300	-	0
Beryllium	µg/L	-	100	-	1	-	-	<5	<1	<1	<5	<5	<5	<5	<5	<5	-	0
Boron	µg/L	4000	500	5000	10	-	-	160	160	230	190	240	220	940	870	1300	-	0
Cadmium	µg/L	2	10	100	0.5	-	-	<5	<0.5	<0.5	<5	<5	<5	<5	<5	<5	-	0
Chromium	µg/L	-	100	1000	5	-	-	<5	119	64	<5	11	6.9	<5	43	<5	-	0
Cobalt	µg/L	-	50	1000	5	-	-	<5	93	18	<5	<5	<5	<5	<5	<5	-	0
Copper	µg/L	2000	200	400	5	-	-	5.6	50	23	<5	<5	<5	<5	10	<5	-	0
Lead	µg/L	10	2000	100	5	-	-	<5	35	9	<5	<5	<5	<5	12	<5	-	0
Manganese	µg/L	500	200	-	5	-	-	390	377	260	<5	<5	<5	<5	15	<5	-	0
Molybdenum	µg/L	50	10	150	5	-	-	<5	<5	<5	<5	<5	<5	<5	<5	<5	-	0
Nickel	µg/L	20	200	1000	5	-	-	22	34	17	<5	<5	<5	<5	<5	<5	-	0
Selenium	µg/L	10	20	20	5	-	-	54	*<10	*<20	<5	<5	<5	8.6	7.6	<5	-	0
Silver	µg/L	100	-	-	0.5	-	-	9.3	<0.5	<0.5	<5	<5	<5	<5	<5	<5	-	0
Strontium	µg/L	-	-	-	10	-	-	9400	570	11100	140	140	110	1100	920	440	-	0
Tin	µg/L	-	-	-	5	-	-	<5	<5	<5	<5	<5	<5	<5	<5	<5	-	0
Zinc	µg/L	-	2000	20000	5	-	-	52	498	68	16	12	6	6.4	17	<5	-	0
Mercury	µg/L	1	2	2	0.1	-	-	<0.1	<0.1	0.6	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	-	0
Major Cations (Total)																		0
Calcium	µg/L	-	-	1000000	0.1	-	-	396000	13100	289000	1670	2250	1690	2400	3030	2280	-	0
Iron	µg/L	-	200	-	0.05	-	-	13400	11600	10200	<100	<100	<100	142	1120	<100	-	0
Magnesium	µg/L	-	-	-	0.1	-	-	350000	42500	307000	340	1070	467	800	861	267	-	0
Potassium	µg/L	-	-	-	0.1	-	-	12000	9300	10300	1330	1130	1060	4880	3330	4310	-	0
Sodium	µg/L	-	-	-	0.1	-	-	1960000	699000	1400000	338000	338000	338000	1360000	1070000	819000	-	0
Major Anions (Total)																		0
Chloride	mg/L	-	175	-	1	4100	4500	4000	532	3240	90	86	82	280	270	96	4200	2
Fluoride	mg/L	-	1	2	0.1	0.5	0.4	<0.5	0.1	<0.1	<0.5	<0.5	<0.5	3.4	3	8.8	0.5	0
Sulphate	mg/L	-	-	1000	2	390	390	440	663	323	<0.5	9.4	<0.5	<0.5	<0.5	<0.5	390	0
Bicarbonate as CaCO3	mg/L	-	-	-	5	791	787	283	282	471	591	656	639	2010	1610	1670	788	0
Carbonate as CaCO3	mg/L	-	-	-	5	<10	<10	<10	<5	<5	68	11	51	60	183	31	<10	0
Hydroxide as CaCO3	mg/L	-	-	-	5	<10	<10	<10	<5	<5	<10	<10	<10	<10	<10	<10	<10	0
Total Alkalinity as CaCO3	mg/L	-	-	-	5	791	787	283	282	471	660	667	690	2070	1790	1700	788	0
Nutrients																		0
Ammonia as N	mg/L	-	-	-	0.01	<0.02	<0.02	-	0.15	0.05	-	-	-	-	-	-	<0.02	0
Nitrate as N	mg/L	-	-	400	0.01	<0.01	0.01	-	-	-	-	-	-	-	-	-	0.02	67
Nitrite as N	mg/L	-	-	-	0.01	<0.01	<0.01	-	-	-	-	-	-	-	-	-	<0.01	0
Sulphur	µg/L	-	-	-		130000	130000	-	-	-	-	-	-	-	-	-	130000	0
Sulphide (Dissolved)	mg/L	-	-	-	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0

EQL - Estimated Quantification Limit, * increased due to matrix interference
NHMRC (2004) Australian Drinking Water Guidelines 6
ANZECC (2000) Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000) - Lowest available concentration. Generally the long-term trigger value (LTV) for heavy metals and metalloids (Irrigation) or poulty (livestock)

Table 2 Summary of Phase 1 Groundwater Monitoring Program Laboratory Results

Bore ID	Units	Drinking Water[1]	Irrigation[2]	Livestock[2]	EQL	42230209A	42230209B	42230629	42230004	42231259	58579 (Rockwood PB)	87755	Turinga House Bore	Talinga 15	Talinga 2	58410 (Miles Town Bore)	DUP1 (42230209A)	RPD
Date Collected						14/06/2009	14/06/2009	15/06/2009	21/06/2009	21/06/2009	16/06/2009	17/06/2009	17/06/2009	16/06/2009	17/06/2009	18/06/2009	14/06/2009	
Latitude						-26.74223581	-26.74223581	-26.86851	-26.64981291	-26.99243382	-26.90024	-26.89485	-26.8864	-26.912381	-26.8766167	-26.666	-26.74223581	
Longitude						150.6799288	150.6799288	150.14921	150.1872157	151.0160259	150.36314	150.38665	150.36966	150.36535	150.4035	150.18441	150.6799288	
Elevation (mAHD)						308.58	308.58	287	295.85	323.98	296	296	300	311.53	292.78	301	308.58	
Screen Interval (Total Depth) (mbgl)						35.6-36.2	21.45-21.9	(27.65)	31.66	(27.75)	99	54-59	-	-	-	1187-1245	35.6-36.2	
Hydrostratigraphic Unit						Cainzoic	Cainozoic	Cainozoic	Cainozoic	Cainozoic	Gubberamunda	Gubberamunda	Gubberamunda	Walloons	Walloons	Precipice	Cainozoic	
Aquifer lithology						Sand and Clay	Fine Sand and clay	Sandy Clay	Sand and Gravel	Gravel	Sandstone	White sandy gravel	?	Coal	Coal	Sand (light)	Sand and clay	
Screen Construction Materials						PVC	PVC	PVC	PVC	PVC	Steel	PVC	PVC	Steel	Steel	Steel	PVC	
Field Results																		
Sample Collection Method						Low-flow	Low-flow	Low-flow	Bailed	Bailed	Existing Pump	Existing Pump	Existing Pump	Grab	Grab	Existing Pump	Low-flow	
SWL	mTOC	-	-	-	-	16.64	16.57	19.28	13.99	15.51	NA	NA	NA	NA	NA	NA	16.64	
EC	mS/cm	-	-	-	-	13.9	13.9	12.4	3.2	9.3	1	1.4	1.4	4.6	3.9	3.1	13.9	
pH	pH Units	-	<6	-	-	7.2	7.2	6.6	6.7	7.3	8.5	8.6	8.5	8	8.6	7.9	7.2	
Temperature	℃	-	-	-	-	23.7	25.2	19.2	20.9	22.3	25.2	15.5	22.9	36.9	27	32.6	23.7	
Laboratory Results																		
pH	pH Units	-	<6	-	0.1	7.5	7.6	6.9	6.9	7.1	8.8	8.3	8.6	8.5	8.9	8.4	7.6	1
Total Dissolved Solids	mg/L	-	-	2000	5	8500	8500	9000	1990	5400	840	810	830	2900	2400	1900	8400	1
Ion Balance (% Difference)	%	-	-	-	-	9.7	3.2	<1	5	3.8	3.2	3.2	3.2	7.3	2.3	5.6	15	43
Dissolved Gas																		0
Methane conc. of water @ 25℃	µg/L	-	-	-	-	4	3	78	2	<1	3200	590	2000	3000	3600	2400	4	0
Organic Analytes																		0
Sum of PAHs	µg/L	-	-	-	-	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	0
Total Reported Phenolics	µg/L	-	-	-	10	<2	<2	<10	20	20	<10	<10	<10	<10	<10	<10	<2	0
Dissolved Organic Carbon (mg/L)	µg/L	-	-	-	1	1.2	3	2	7	2	1.6	2	1.8	2.9	3.8	1.9	2.3	63
Dissolved Metals																		0
Arsenic	µg/L	7	100	500	1	6.2	6.6	6.8	*<20	*<20	<5	<5	<5	<5	<5	<5	5.9	5
Barium	µg/L	700	-	-	5	75	70	100	30	95	40	59	46	770	570	130	76	1
Beryllium	µg/L	-	100	-	1	<5	<5	<5	<1	<1	<5	<5	<5	<5	<5	<5	<5	0
Boron	µg/L	4000	500	5000	10	860	880	170	160	210	250	210	210	1200	770	1300	870	1
Cadmium	µg/L	2	10	100	0.1	<5	<5	<5	<0.1	<0.1	<5	<5	<5	<5	<5	<5	<5	0
Chromium	µg/L	-	100	1000	1	22	22	13	*<5	29	25	<5	<5	90	<5	<5	21	5
Cobalt	µg/L	-	50	1000	1	<5	<5	<5	42	5	<5	<5	<5	<5	<5	<5	<5	0
Copper	µg/L	2000	200	400	1	<5	7.1	<5	*<10	*<10	<5	<5	<5	<5	<5	<5	<5	0
Lead	µg/L	10	2000	100	1	<5	<5	<5	1	<1	<5	<5	<5	<5	<5	<5	<5	0
Manganese	µg/L	500	200	-	1	52	15	380	293	53	<5	<5	<5	<5	<5	<5	54	4
Molybdenum	µg/L	50	10	150	1	<5	<5	<5	2	<1	<5	<5	<5	<5	<5	<5	<5	0
Nickel	µg/L	20	200	1000	1	7.4	8	19	37	8	<5	<5	<5	<5	<5	<5	7.4	0
Selenium	µg/L	10	20	20	5	29	31	56	*<10	*<20	<5	<5	<5	9.8	6.9	<5	29	0
Silver	µg/L	100	-	-	0.1	<5	<5	8.9	<0.1	<0.1	<5	<5	<5	<5	<5	<5	<5	0
Strontium	µg/L	-	-	-	1	7800	7800	9500	294	10700	130	120	110	880	890	190	7700	1
Tin	µg/L	-	-	-	5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	0
Zinc	µg/L	-	2000	20000	5	39	36	31	167	45	18	5.5	<5	<5	7.8	<5	43	10
Mercury	µg/L	1	2	2	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0
Major Cations (Dissolved)																		0
Calcium	µg/L	-	-	1000000		178000	180000	396000	8300	266000	1620	2230	1660	2080	2760	1020	178000	0
Iron	µg/L	-	200	-	100	109	<100	12500	6550	710	<100	<100	<100	<100	<100	<100	125	14
Magnesium	µg/L	-	-	-	100	336000	305000	350000	42200	282000	329	821	465	764	835	167	365000	8
Potassium	µg/L	-	-	-	1000	3580	3180	12000	8000	6500	1190	1010	<1000	4620	3200	3840	3810	6
Sodium	µg/L	-	-	-	100	3170000	2920000	1960000	602000	1230000	332000	334000	331000	1320000	1030000	776000	3430000	8
Total Metals																		0
Arsenic	µg/L	7	100	500	5	-	-	5.5	*<20	*<20	<5	<5	<5	<5	<5	<5	-	0
Barium	µg/L	700	-	-	5	-	-	110	36	124	41	51	49	930	600	300	-	0
Beryllium	µg/L	-	100	-	1	-	-	<5	<1	<1	<5	<5	<5	<5	<5	<5	-	0
Boron	µg/L	4000	500	5000	10	-	-	160	160	230	190	240	220	940	870	1300	-	0
Cadmium	µg/L	2	10	100	0.5	-	-	<5	<0.5	<0.5	<5	<5	<5	<5	<5	<5	-	0
Chromium	µg/L	-	100	1000	5	-	-	<5	119	64	<5	11	6.9	<5	43	<5	-	0
Cobalt	µg/L	-	50	1000	5	-	-	<5	93	18	<5	<5	<5	<5	<5	<5	-	0
Copper	µg/L	2000	200	400	5	-	-	5.6	50	23	<5	<5	<5	<5	10	<5	-	0
Lead	µg/L	10	2000	100	5	-	-	<5	35	9	<5	<5	<5	<5	12	<5	-	0
Manganese	µg/L	500	200	-	5	-	-	390	377	260	<5	<5	<5	<5	15	<5	-	0
Molybdenum	µg/L	50	10	150	5	-	-	<5	<5	<5	<5	<5	<5	<5	<5	<5	-	0
Nickel	µg/L	20	200	1000	5	-	-	22	34	17	<5	<5	<5	<5	<5	<5	-	0
Selenium	µg/L	10	20	20	5	-	-	54	*<10	*<20	<5	<5	<5	8.6	7.6	<5	-	0
Silver	µg/L	100	-	-	0.5	-	-	9.3	<0.5	<0.5	<5	<5	<5	<5	<5	<5	-	0
Strontium	µg/L	-	-	-	10	-	-	9400	570	11100	140	140	110	1100	920	440	-	0
Tin	µg/L	-	-	-	5	-	-	<5	<5	<5	<5	<5	<5	<5	<5	<5	-	0
Zinc	µg/L	-	2000	20000	5	-	-	52	498	68	16	12	6	6.4	17	<5	-	0
Mercury	µg/L	1	2	2	0.1	-	-	<0.1	<0.1	0.6	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	-	0
Major Cations (Total)																		0
Calcium	µg/L	-	-	1000000	0.1	-	-	396000	13100	289000	1670	2250	1690	2400	3030	2280	-	0
Iron	µg/L	-	200	-	0.05	-	-	13400	11600	10200	<100	<100	<100	142	1120	<100	-	0
Magnesium	µg/L	-	-	-	0.1	-	-	350000	42500	307000	340	1070	467	800	861	267	-	0
Potassium	µg/L	-	-	-	0.1	-	-	12000	9300	10300	1330	1130	1060	4880	3330	4310	-	0
Sodium	µg/L	-	-	-	0.1	-	-	1960000	699000	1400000	338000	338000	338000	1360000	1070000	819000	-	0
Major Anions (Total)																		0
Chloride	mg/L	-	175	-	1	4100	4500	4000	532	3240	90	86	82	280	270	96	4200	2
Fluoride	mg/L	-	1	2	0.1	0.5	0.4	<0.5	0.1	<0.1	<0.5	<0.5	<0.5	3.4	3	8.8	0.5	0
Sulphate	mg/L	-	-	1000	2	390	390	440	663	323	<0.5	9.4	<0.5	<0.5	<0.5	<0.5	390	0
Bicarbonate as CaCO3	mg/L	-	-	-	5	791	787	283	282	471	591	656	639	2010	1610	1670	788	0
Carbonate as CaCO3	mg/L	-	-	-	5	<10	<10	<10	<5	<5	68	11	51	60	183	31	<10	0
Hydroxide as CaCO3	mg/L	-	-	-	5	<10	<10	<10	<5	<5	<10	<10	<10	<10	<10	<10	<10	0
Total Alkalinity as CaCO3	mg/L	-	-	-	5	791	787	283	282	471	660	667	690	2070	1790	1700	788	0
Nutrients																		0
Ammonia as N	mg/L	-	-	-	0.01	<0.02	<0.02	-	0.15	0.05	-	-	-	-	-	-	<0.02	0
Nitrate as N	mg/L	-	-	400	0.01	<0.01	0.01	-	-	-	-	-	-	-	-	-	0.02	67
Nitrite as N	mg/L	-	-	-	0.01	<0.01	<0.01	-	-	-	-	-	-	-	-	-	<0.01	0
Sulphur	µg/L	-	-	-		130000	130000	-	-	-	-	-	-	-	-	-	130000	0
Sulphide (Dissolved)	mg/L	-	-	-	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0

EQL - Estimated Quantification Limit, * increased due to matrix interference
NHMRC (2004) Australian Drinking Water Guidelines 6
ANZECC (2000) Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000) - Lowest available concentration. Generally the long-term trigger value (LTV) for heavy metals and metalloids (Irrigation) or poulty (livestock)

APLNG Groundwater Monitoring Program

Turinga House Bore

LATITUDE	*-26.8864*	**OWNER**	*Origin*	**CONSTRUCTED DEPTH (m)**	*NA*	**INSTRUMENTATION**	
LONGITUDE	*150.3696*	**USE**	*Stock and Domestic*	**SWL** (mTOC)	*NA*	**TYPE**	*NA*
ELEVATION (mAHD)	*300*	**UNIT**	*Gubberamunda*	**EC** (mS/cm)	*1.4*	**DEPTH**	*NA*

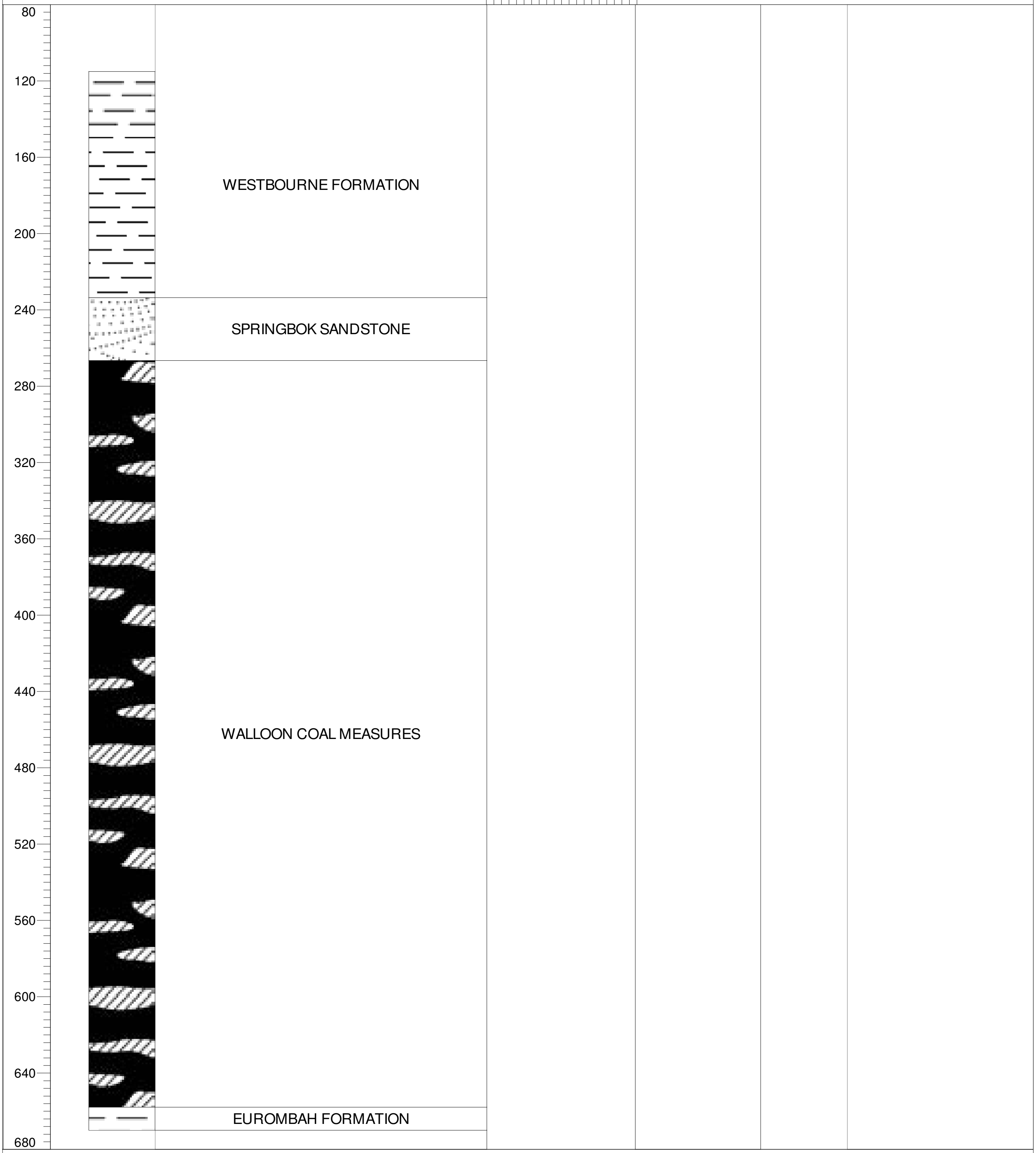
DEPTH (metres)	LITHOLOGY/FORMATION	GAMMA (API) 0 25 50 75 100	REMARKS	WELL CONSTRUCTION DETAILS
0				
0				
1				
1				
2				
2				
2				150mm PVC
3				
3				
4				
4				
4				
5				
5				

APLNG Groundwater Monitoring Program

Talinga 15

LATITUDE	*-26.9123*	**OWNER**	*Origin*	**CONSTRUCTED DEPTH (m)**	*665*	**INSTRUMENTATION**	
LONGITUDE	*150.3653*	**USE**	*CSG Extraction*	**SWL** (mTOC)	*NA*	**TYPE**	*NA*
ELEVATION (mAHD)	*311.53*	**UNIT**	*Walloons*	**EC** (mS/cm)	*4.6*	**DEPTH**	*NA*

DEPTH (metres)	LITHOLOGY/FORMATION	GAMMA (API) 0 25 50 75 100	REMARKS	WELL CONSTRUCTION DETAILS



APLNG Groundwater Monitoring Program

Talinga 2

LATITUDE	*-26.8766*	**OWNER**	*Origin*	**CONSTRUCTED DEPTH (m)**	*573*	**INSTRUMENTATION**	
LONGITUDE	*150.4035*	**USE**	*CSG Inactive*	**SWL** (mTOC)	*NA*	**TYPE**	*NA*
ELEVATION (mAHD)	*292.78*	**UNIT**	*Walloons*	**EC** (mS/cm)	*3.9*	**DEPTH**	*NA*

DEPTH (metres)	LITHOLOGY/FORMATION	GAMMA (API) 0 25 50 75 100	REMARKS	WELL CONSTRUCTION DETAILS

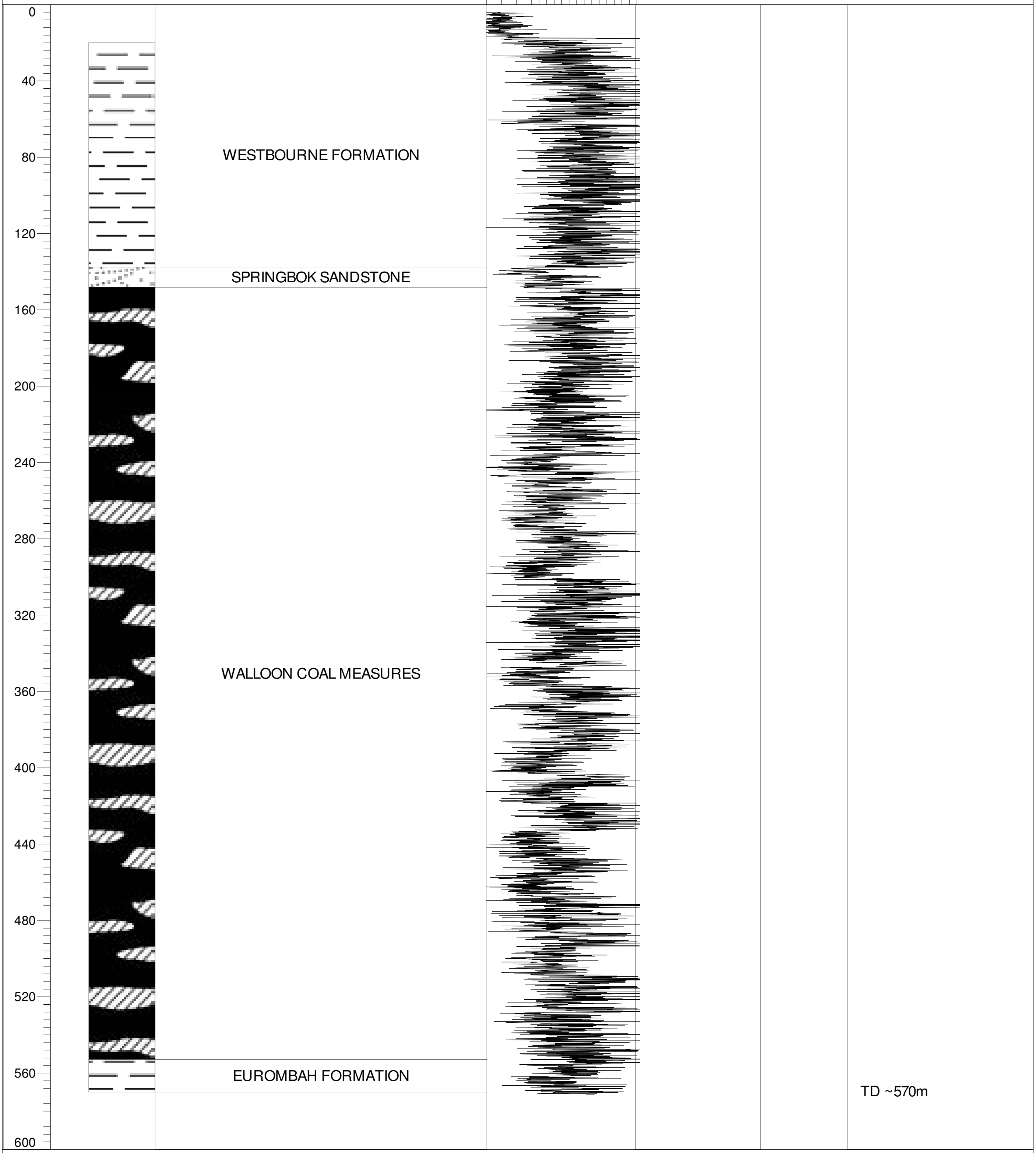


Table 1 - Australia Pacfici LNG Phase 1 Groundwater Monitoring Program - Summary of Field Results

Bore ID	Latitude	Longitude	Z55 Easting	Z55 Northing	Elevation	Owner	Use	Total Depth (m)	Formation Monitored	SWL (mTOC)	Gamma	CCTV	Sample Collection Method	EC (mS/cm)	pH	Temp (°C)	Lab Analysis	Instrumentation Type	Instrumentation Depth (mTOC)	Comments
42230203	-26.90	150.98	895414	7018421	326	DERM	Monitoring	34.4	Cainozoic	25.89	No	Partial	NA	-	-	-	NA	Levelogger M30	31.01	Casing in poor condition. Could not insert gamma, CCTV or sampling equipment
42230629	-26.86851	150.14921	812906	7024239	287	DERM	Monitoring	27.7	Cainozoic	19.28	Yes	Yes	Low-flow	12.4	6.6	19.2	Yes	Levelogger M30	27.53	Partial collapse, no screens observed, 20m shallower than DERM database
23457	-26.90	150.34	831783	7020262	309.7	Origin	Inactive	420	Gubberamunda/Westbourne/Springbok/Walloons	3.4	Yes	No	Grab	2.7	8.7	-	No			Excellent retrofit option
10925 Rockwood Old House Bore	-26.89915	150.36393	834164	7020293	306	Origin	Inactive	94	BMO	41.24	No	Yes	Grab	2.1	7.5	22.5	No	Levelogger M30	60.83	Old House Bore
58579 Rockwood Pump Bore	-26.90024	150.36314	834083	7020175	296	Origin	Stock Intensive	103	BMO	NA	No	Yes	Existing Pump	1	8.5	25.2	Yes			Rockwood Pumping Bore. Mono pump installed
42230209A	-26.74	150.68	866099	7037067	309	DERM	Monitoring	36.7	Cainozoic	16.64	Yes	Yes	Low-flow	13.9	7.2	23.7	Yes	Levelogger M30	30.97	
42230208	-26.78	150.67	864975	7032660	316	DERM	Monitoring	49.6	Cainozoic	25.29	No	Yes	NA	-	-	-	NA	Levelogger M30, Barologger	50.64	Bore severely out of plumb and some dislocated joins
23335	-26.96554	150.39488	837043	7012850	308	Dougall	Inactive	240	Gubberamunda	32.67	Yes	Partial	Grab	0.31	7.9	22.6		Levelogger M100	99.46	Casing shoe at 118m
Talinga 15	-26.912381	150.36535	834266	7018823	311.53	Origin	CSG Extraction	665	Walloons	NA	No	No	Grab	4.6	8	36.9	Yes			Active CSG well
30168 Rockwood Back Bore	-26.93085	150.3706	834734	7016761	300	Origin	Inactive	67	BMO	26.15	Yes	No	Grab	2	7.8	23	No	Levelogger M30	53.99	Rockwood Back Bore
Turinga House Bore	-26.8864	150.36966	834772	7021692	300	Origin	Stock and Domestic		BMO	NA	No	No	Existing Pump	1.4	8.5	22.9	Yes			Submersible pump installed
23642	-26.94098	150.35241	832896	7015686	325	Dougall	Inactive	215	Gubberamunda	48.35	Yes	No	Grab	0.2	7.1	22.9		Levelogger M100	85.18	Casing shoe at 97m
Talinga 2	-26.8766167	150.4035	838165	7022686	292.78	Origin	CSG Inactive	573	Walloons	NA	No	No	Grab	3.9	8.6	27	Yes			Shut-in CSG well
Condabri 4	-26.78	150.23	821188	7033849	308.3	Origin	CSG Inactive		Walloons	NA	No	No	NA							Excellent retrofit option
58410 Miles Town Bore	-26.666	150.18441	816968	7046602	301	Dalby Regional Council	Town Water Supply	1245	Precipice	NA	No	No	Existing Pump	3.1	7.9	32.6	Yes			Mono pump installed
42230004	-26.65	150.19	817569	7048362	296	DERM	Monitoring	31.7	Cainozoic	13.99	Yes	No	Bailed	3.2	6.7	20.9	Yes	Levelogger M30	30.78	
42231259	-26.99	151.02	899074	7008312	324	DERM	Monitoring	27.75	Cainozoic	15.51	No	No	Bailed	9.3	7.3	22.3	Yes	Levelogger M30	27.33	
42230202	-26.91	150.95	892396	7017405	321	DERM	Monitoring		Cainozoic	Dry	No	Yes	Grab	18.9	7.2	20.9	No			Bore Dry
42230005	-26.65	150.19	817569	7048362	296	DERM	Monitoring	18	Cainozoic	13.7	Yes	No	NA	-	-	-	NA			Part of nested site (42230004)
Turinga Windmill Bore	-26.90537	150.31536	829318	7019731	320	Origin	Inactive		BMO	NA	No	No	NA	-	-	-	NA			Windmill installed on bore. No access to water
10924 Old Forest Bore	-26.90537	150.31536	829318	7019731	300	Origin	Inactive	94.5	BMO	NA	No	No	NA	-	-	-	NA			Old bore in State Forest. Windmill installed on bore. No access to water
42230209B	-26.74	150.68	866099	7037067	309	DERM	Monitoring	22.5	Cainozoic	16.57	Yes	Yes	Low-flow	13.9	7.2	25.2	Yes			Part of nested site (42230209A)
9469 Rockwood Old Woolshed Bore	-26.91206	150.35893	833629	7018875	316	Origin	inactive	33.2	BMO	32.7	No	Yes	Grab	1.41	7.8	21.1				
Kainama 4	-27.00	150.80	877181	7007881	364.3	Origin	CSG Inactive		Walloons	0.3	No	No	NA	-	-	-	NA			CSG Well. Screw on cap. Oil emulsion on water surface
87755	-26.89485	150.38665	836436	7020710	296	Lloyd	Stock	59	BMO	NA	No	No	Existing Pump	1.4	8.6	15.5	Yes			Private well. Submersible pump installed
Talinga 3	-26.8829306	150.4054722	838342	7021981	297.93	Origin	CSG Inactive	349.92	Walloons	NA	No	No	NA	-	-	-	NA			Shut-in CSG well. No water flow
Talinga 16	-26.82	150.35	833012	7029105	300.9	Origin	CSG Monitoring	571	Walloons	NA	No	No	NA	-	-	-	NA			CSG monitoring well
Talinga 121	-26.81	150.43	841000	7030001	321.3	Origin	CSG Inactive	705.3	Walloons	0.15	No	No	Grab	2.6	-	-	NA			CSG Well. Screw on cap
Could Not Locate																				
42230190						DERM	Monitoring													Bore not located at DERM co-ordinates
42231257						DERM	Monitoring													PVC bore casing found in location provided. Bore dry. DERM to confirm location
42231258						DERM	Monitoring													Bore located within active mining area. DERM to confirm location
Lagoon Gully Monitoring Bore						CS Energy	Monitoring													Bore not located at available co-ordinates. Lagoon Gully production bores located.
No Land Access																				
Klines Road Regional Monitoring Bore						CS Energy	Monitoring													
87404						Stanbroke Pastoral Company	Stock Intensive													Stanbroke Pastoral Company Intensive Stock bore
42230214A						DERM	Monitoring													Sunwater land
42230211						DERM	Monitoring													Land access could not contact landowners. Back-up bore not required
Orana 5						Origin	CSG													Land Access granted but gate to property locked

Table 1 - Australia Pacfici LNG Phase 1 Groundwater Monitoring Program - Summary of Field Results

Bore ID	Latitude	Longitude	Z55 Easting	Z55 Northing	Elevation	Owner	Use	Total Depth (m)	Formation Monitored	SWL (mTOC)	Gamma	CCTV	Sample Collection Method	EC (mS/cm)	pH	Temp (°C)	Lab Analysis	Instrumentation Type	Instrumentation Depth (mTOC)	Comments
42230203	-26.90	150.98	895414	7018421	326	DERM	Monitoring	34.4	Cainozoic	25.89	No	Partial	NA	-	-	-	NA	Levelogger M30	31.01	Casing in poor condition. Could not insert gamma, CCTV or sampling equipment
42230629	-26.86851	150.14921	812906	7024239	287	DERM	Monitoring	27.7	Cainozoic	19.28	Yes	Yes	Low-flow	12.4	6.6	19.2	Yes	Levelogger M30	27.53	Partial collapse, no screens observed, 20m shallower than DERM database
23457	-26.90	150.34	831783	7020262	309.7	Origin	Inactive	420	Gubberamunda/Westbourne/Springbok/Walloons	3.4	Yes	No	Grab	2.7	8.7	-	No			Excellent retrofit option
10925 Rockwood Old House Bore	-26.89915	150.36393	834164	7020293	306	Origin	Inactive	94	BMO	41.24	No	Yes	Grab	2.1	7.5	22.5	No	Levelogger M30	60.83	Old House Bore
58579 Rockwood Pump Bore	-26.90024	150.36314	834083	7020175	296	Origin	Stock Intensive	103	BMO	NA	No	Yes	Existing Pump	1	8.5	25.2	Yes			Rockwood Pumping Bore. Mono pump installed
42230209A	-26.74	150.68	866099	7037067	309	DERM	Monitoring	36.7	Cainozoic	16.64	Yes	Yes	Low-flow	13.9	7.2	23.7	Yes	Levelogger M30	30.97	
42230208	-26.78	150.67	864975	7032660	316	DERM	Monitoring	49.6	Cainozoic	25.29	No	Yes	NA	-	-	-	NA	Levelogger M30, Barologger	50.64	Bore severely out of plumb and some dislocated joins
23335	-26.96554	150.39488	837043	7012850	308	Dougall	Inactive	240	Gubberamunda	32.67	Yes	Partial	Grab	0.31	7.9	22.6		Levelogger M100	99.46	Casing shoe at 118m
Talinga 15	-26.912381	150.36535	834266	7018823	311.53	Origin	CSG Extraction	665	Walloons	NA	No	No	Grab	4.6	8	36.9	Yes			Active CSG well
30168 Rockwood Back Bore	-26.93085	150.3706	834734	7016761	300	Origin	Inactive	67	BMO	26.15	Yes	No	Grab	2	7.8	23	No	Levelogger M30	53.99	Rockwood Back Bore
Turinga House Bore	-26.8864	150.36966	834772	7021692	300	Origin	Stock and Domestic		BMO	NA	No	No	Existing Pump	1.4	8.5	22.9	Yes			Submersible pump installed
23642	-26.94098	150.35241	832896	7015686	325	Dougall	Inactive	215	Gubberamunda	48.35	Yes	No	Grab	0.2	7.1	22.9		Levelogger M100	85.18	Casing shoe at 97m
Talinga 2	-26.8766167	150.4035	838165	7022686	292.78	Origin	CSG Inactive	573	Walloons	NA	No	No	Grab	3.9	8.6	27	Yes			Shut-in CSG well
Condabri 4	-26.78	150.23	821188	7033849	308.3	Origin	CSG Inactive		Walloons	NA	No	No	NA							Excellent retrofit option
58410 Miles Town Bore	-26.666	150.18441	816968	7046602	301	Dalby Regional Council	Town Water Supply	1245	Precipice	NA	No	No	Existing Pump	3.1	7.9	32.6	Yes			Mono pump installed
42230004	-26.65	150.19	817569	7048362	296	DERM	Monitoring	31.7	Cainozoic	13.99	Yes	No	Bailed	3.2	6.7	20.9	Yes	Levelogger M30	30.78	
42231259	-26.99	151.02	899074	7008312	324	DERM	Monitoring	27.75	Cainozoic	15.51	No	No	Bailed	9.3	7.3	22.3	Yes	Levelogger M30	27.33	
42230202	-26.91	150.95	892396	7017405	321	DERM	Monitoring		Cainozoic	Dry	No	Yes	Grab	18.9	7.2	20.9	No			Bore Dry
42230005	-26.65	150.19	817569	7048362	296	DERM	Monitoring	18	Cainozoic	13.7	Yes	No	NA	-	-	-	NA			Part of nested site (42230004)
Turinga Windmill Bore	-26.90537	150.31536	829318	7019731	320	Origin	Inactive		BMO	NA	No	No	NA	-	-	-	NA			Windmill installed on bore. No access to water
10924 Old Forest Bore	-26.90537	150.31536	829318	7019731	300	Origin	Inactive	94.5	BMO	NA	No	No	NA	-	-	-	NA			Old bore in State Forest. Windmill installed on bore. No access to water
42230209B	-26.74	150.68	866099	7037067	309	DERM	Monitoring	22.5	Cainozoic	16.57	Yes	Yes	Low-flow	13.9	7.2	25.2	Yes			Part of nested site (42230209A)
9469 Rockwood Old Woolshed Bore	-26.91206	150.35893	833629	7018875	316	Origin	inactive	33.2	BMO	32.7	No	Yes	Grab	1.41	7.8	21.1				
Kainama 4	-27.00	150.80	877181	7007881	364.3	Origin	CSG Inactive		Walloons	0.3	No	No	NA	-	-	-	NA			CSG Well. Screw on cap. Oil emulsion on water surface
87755	-26.89485	150.38665	836436	7020710	296	Lloyd	Stock	59	BMO	NA	No	No	Existing Pump	1.4	8.6	15.5	Yes			Private well. Submersible pump installed
Talinga 3	-26.8829306	150.4054722	838342	7021981	297.93	Origin	CSG Inactive	349.92	Walloons	NA	No	No	NA	-	-	-	NA			Shut-in CSG well. No water flow
Talinga 16	-26.82	150.35	833012	7029105	300.9	Origin	CSG Monitoring	571	Walloons	NA	No	No	NA	-	-	-	NA			CSG monitoring well
Talinga 121	-26.81	150.43	841000	7030001	321.3	Origin	CSG Inactive	705.3	Walloons	0.15	No	No	Grab	2.6	-	-	NA			CSG Well. Screw on cap
Could Not Locate																				
42230190						DERM	Monitoring													Bore not located at DERM co-ordinates
42231257						DERM	Monitoring													PVC bore casing found in location provided. Bore dry. DERM to confirm location
42231258						DERM	Monitoring													Bore located within active mining area. DERM to confirm location
Lagoon Gully Monitoring Bore						CS Energy	Monitoring													Bore not located at available co-ordinates. Lagoon Gully production bores located.
No Land Access																				
Klines Road Regional Monitoring Bore						CS Energy	Monitoring													
87404						Stanbroke Pastoral Company	Stock Intensive													Stanbroke Pastoral Company Intensive Stock bore
42230214A						DERM	Monitoring													Sunwater land
42230211						DERM	Monitoring													Land access could not contact landowners. Back-up bore not required
Orana 5						Origin	CSG													Land Access granted but gate to property locked

WorleyParsons APLNG Groundwater Monitoring Program

42231259

LATITUDE	*-26.9924*	**OWNER**	*DERM*	**CONSTRUCTED DEPTH (m)**	*27.75*	**INSTRUMENTATION**	
LONGITUDE	*151.016*	**USE**	*Monitoring*	**SWL** (mTOC)	*15.51*	**TYPE**	*Levelogger M30*
ELEVATION (mAHD)	*323.98*	**UNIT**	*Cainozoic*	**EC** (mS/cm)	*9.3*	**DEPTH**	*27.33*

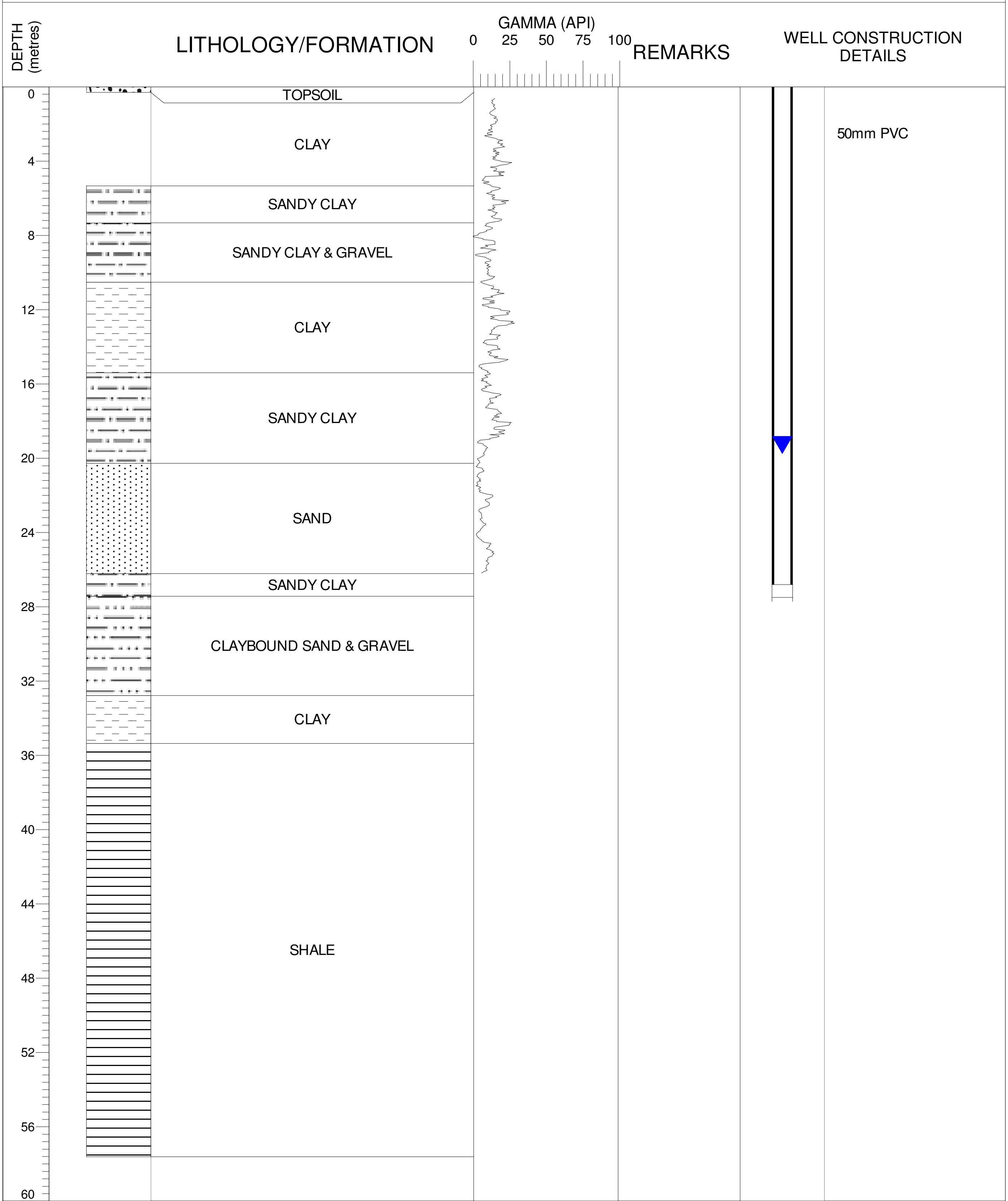
DEPTH (metres)	LITHOLOGY/FORMATION	GAMMA (API) 0 25 50 75 100	REMARKS	WELL CONSTRUCTION DETAILS
0	SOIL			50mm PVC
10	GRAVEL			
	CLAY			
20	GRAVEL			
	CLAY			
	GRAVEL BASE OF ALLUVIUM			
30				
	MUDSTONE			
40				
	SANDSTONE BASE OF WEATHERING			
50	MUDSTONE AND COAL			
	MUDSTONE			
60	SANDSTONE			
	COAL			
70				
	SANDSTONE			
80				
	MUDSTONE			
90				
	SANDSTONE			
100				
110				
	MUDSTONE			
120				
130				
	SANDSTONE			
140				
150				

WorleyParsons resources & energy

APLNG Groundwater Monitoring Program

42230629

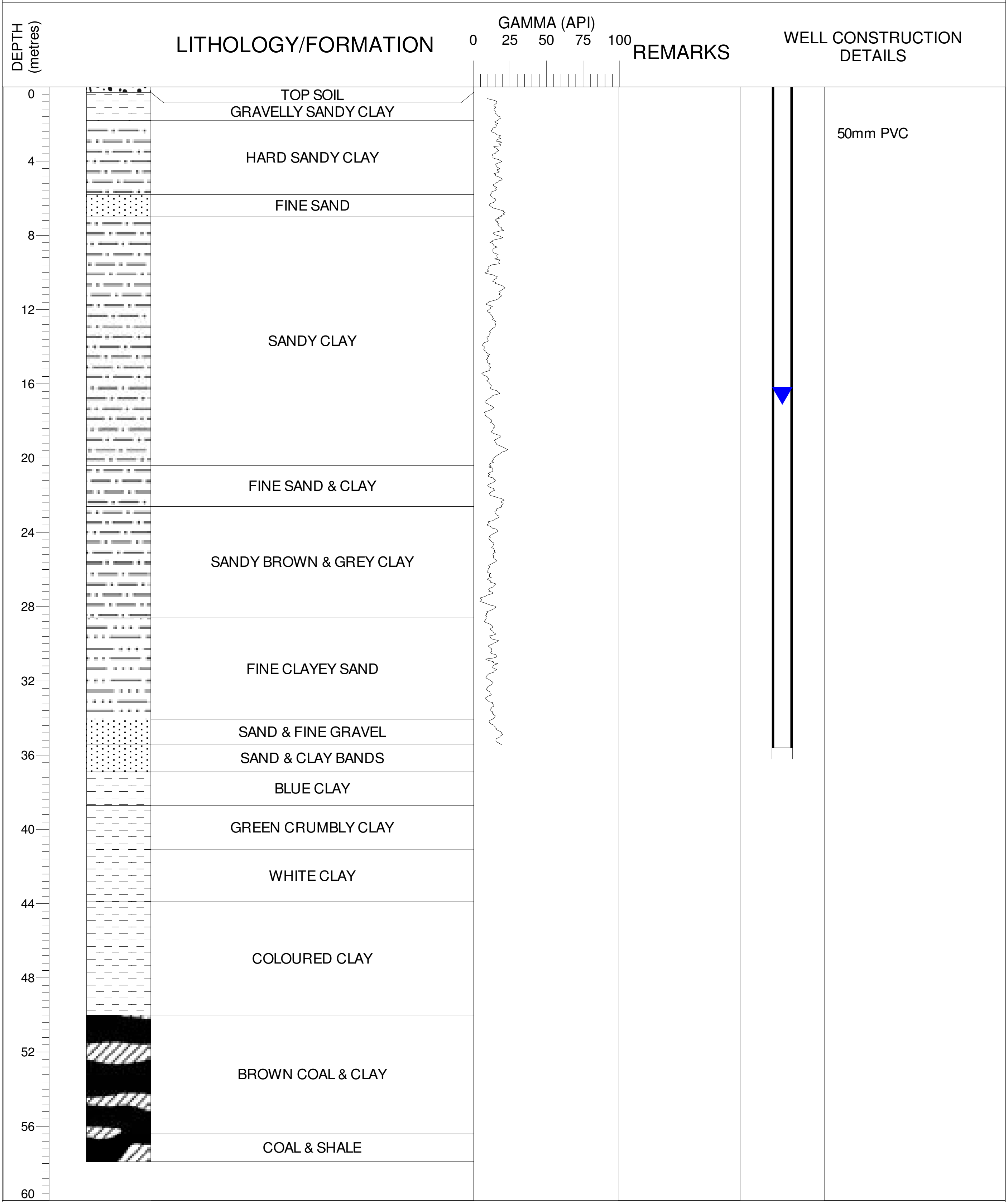
LATITUDE	-26.8685	OWNER	DERM	CONSTRUCTED DEPTH (m)	27.7	INSTRUMENTATION	
LONGITUDE	150.1492	USE	Monitoring	SWL (mTOC)	19.28	TYPE	Levelogger M30
ELEVATION (mAHD)	287	UNIT	Cainozoic	EC (mS/cm)	12.4	DEPTH	27.53



APLNG Groundwater Monitoring Program

42230209A

LATITUDE	*-26.7422*	**OWNER**	*DERM*	**CONSTRUCTED DEPTH (m)**	*36.7*	**INSTRUMENTATION**	
LONGITUDE	*150.6799*	**USE**	*Monitoring*	**SWL** (mTOC)	*16.64*	**TYPE**	*Levelogger M30*
ELEVATION (mAHD)	*308.58*	**UNIT**	*Cainozoic*	**EC** (mS/cm)	*13.9*	**DEPTH**	*30.97*



APLNG Groundwater Monitoring Program

42230203

LATITUDE	*-26.898869767*	**OWNER**	*DERM*	**CONSTRUCTED DEPTH (m)**	*34.4*	**INSTRUMENTATION**	
LONGITUDE	*150.979232761*	**USE**	*Monitoring*	**SWL** (mTOC)	*25.89*	**TYPE**	*Levelogger M30*
ELEVATION (mAHD)	*325.5*	**UNIT**	*Cainozoic*	**EC** (mS/cm)	*-*	**DEPTH**	*31.01*

DEPTH (metres)	LITHOLOGY/FORMATION	GAMMA (API) 0 25 50 75 100	REMARKS	WELL CONSTRUCTION DETAILS
0–1.5	TOP SOIL			
1.5–4.6	BROWN CLAY		*Casing disolocation - equipment could not pass*	50mm PVC
4.6–10.1	SANDY BROWN CLAY			
10.1–12.8	SAND			
12.8–19.2	HARD SANDY CLAY			
19.2–25	FINE SAND & CLAY			
25–27.4	BROWN GRAVELLY CLAY			
27.4–33.5	SANDY CLAY			
33.5–35.7	HARD CLAY & SAND			
35.7–36.3	SAND			
36.3–38.1	COLOURED SHALE			

APLNG Groundwater Monitoring Program

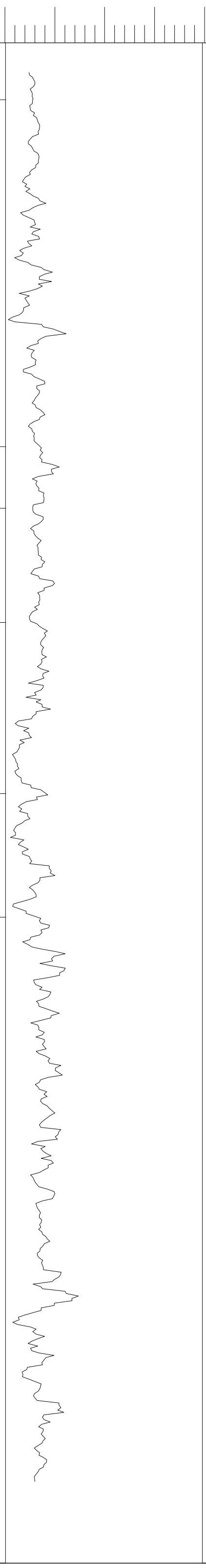
WorleyParsons resources & energy

42230004

LATITUDE	*-26.6498*	**OWNER**	*DERM*	**CONSTRUCTED DEPTH (m)**	*31.7*	**INSTRUMENTATION**	
LONGITUDE	*150.1872*	**USE**	*Monitoring*	**SWL** (mTOC)	*13.99*	**TYPE**	*Levelogger M30*
ELEVATION (mAHD)	*295.85*	**UNIT**	*Cainozoic*	**EC** (mS/cm)	*3.2*	**DEPTH**	*30.78*

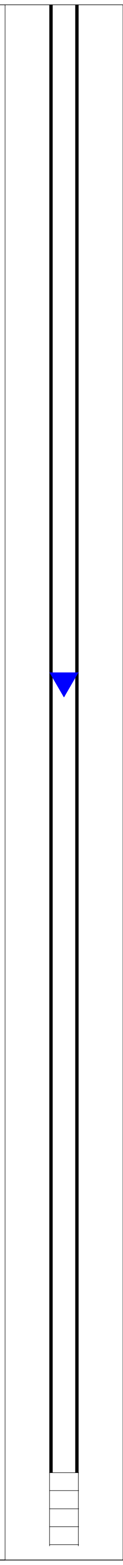
DEPTH (metres)	LITHOLOGY/FORMATION
0	BLACK SOIL
2–8	BROWN SANDY CLAY
	GRAVEL
10–12	GREY BROWN CLAY & GRAVEL BANDS
12–16	SAND & GRAVEL
16–18	BASALT BOULDERS

GAMMA (API)



REMARKS

WELL CONSTRUCTION DETAILS



50mm PVC

Depth scale: 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32

APLNG Groundwater Monitoring Program

87755

LATITUDE	*-26.8948*	**OWNER**	*Lloyd*	**CONSTRUCTED DEPTH (m)**	*59*	**INSTRUMENTATION**	
LONGITUDE	*150.3866*	**USE**	*Stock*	**SWL** (mTOC)	*NA*	**TYPE**	*NA*
ELEVATION (mAHD)	*296*	**UNIT**	*Gubberamunda*	**EC** (mS/cm)	*1.4*	**DEPTH**	*NA*

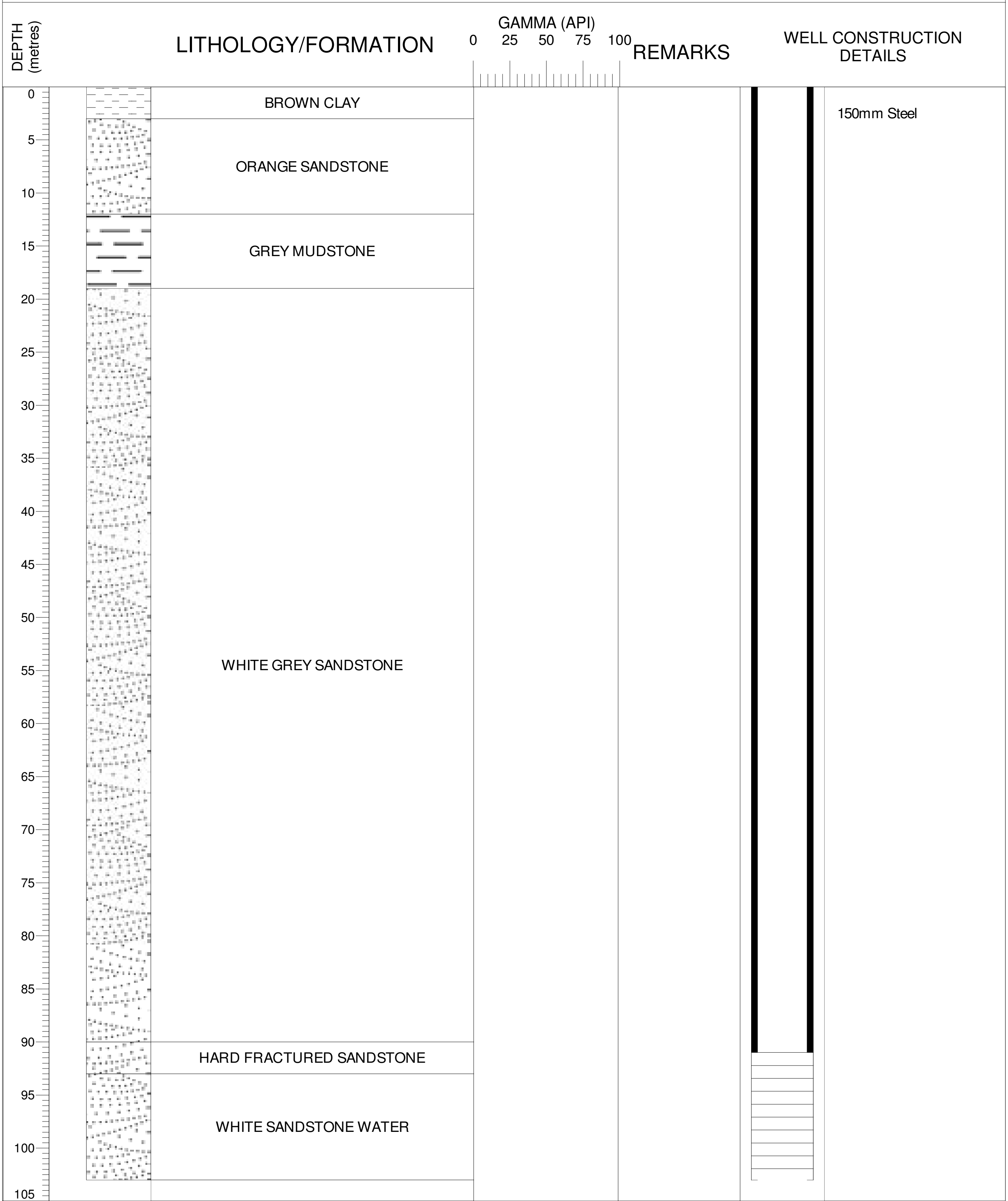
DEPTH (metres)	LITHOLOGY/FORMATION	GAMMA (API) 0 25 50 75 100	REMARKS	WELL CONSTRUCTION DETAILS
0–2	BROWN & YELLOW CLAY			150mm PVC
2–4	WHITE W/X SANDSTONE			
4–13	ORANGE SANDSTONE			
13–52	GREY SANDSTONE			
52–54	WHITE HARD FRACTURED SANDSTONE			
54–59	COARSE WHITE SANDY GRAVEL			

Depth scale: 0, 4, 8, 12, 16, 20, 24, 28, 32, 36, 40, 44, 48, 52, 56, 60

APLNG Groundwater Monitoring Program

58579 Rockwood Pump Bore

LATITUDE	*-26.9002*	**OWNER**	*Origin*	**CONSTRUCTED DEPTH (m)**	*103*	**INSTRUMENTATION**	
LONGITUDE	*150.3631*	**USE**	*Stock Intensive*	**SWL** (mTOC)	*NA*	**TYPE**	*NA*
ELEVATION (mAHD)	*296*	**UNIT**	*Gubberamunda*	**EC** (mS/cm)	*1*	**DEPTH**	*NA*



APLNG Groundwater Monitoring Program

58410 Miles Town Bore

LATITUDE	*-26.666*	**OWNER**	*Dalby RC*	**CONSTRUCTED DEPTH (m)**	*1245*	**INSTRUMENTATION**	
LONGITUDE	*150.1844*	**USE**	*Town Water Supply*	**SWL** (mTOC)	*NA*	**TYPE**	*NA*
ELEVATION (mAHD)	*301*	**UNIT**	*Precipice*	**EC** (mS/cm)	*3.1*	**DEPTH**	*NA*

DEPTH (metres) | LITHOLOGY/FORMATION | GAMMA (API) 0 25 50 75 100 | REMARKS | WELL CONSTRUCTION DETAILS

Depth scale: 0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300

LITHOLOGY/FORMATION:

- SANDSTONE (HARD WHITE FINE)
- COAL BANDS IN SHALE
- SHALE
- SAND - WATER STRUCK
- SANDY COAL
- 6 METRE BAND OF SAND
- COAL & SANDY SHALE
- SANDY SHALE
- COAL
- SANDY SHALE
- SAND - WATER STRUCK
- SHALE & COAL
- SAND - WATER STRUCK
- COAL & SHALE
- SAND - WATER STRUCK
- SHALE (LIGHT)
- SAND - WATER STRUCK
- SHALE & SANDSTONE
- 3 METRES OF WATER BEARING STRATA
- SHALE & COAL
- SANDY WATER
- SANDY SHALE
- SAND
- SHALE & COAL
- SAND TRACES OF COAL
- LIGHT GREY SHALE & SAND
- SAND - WATER STRUCK
- SANDY SHALE
- SAND
- SANDY SHALE
- SAND (DARK & GREY)
- SAND (LIGHT) - WATER STRUCK

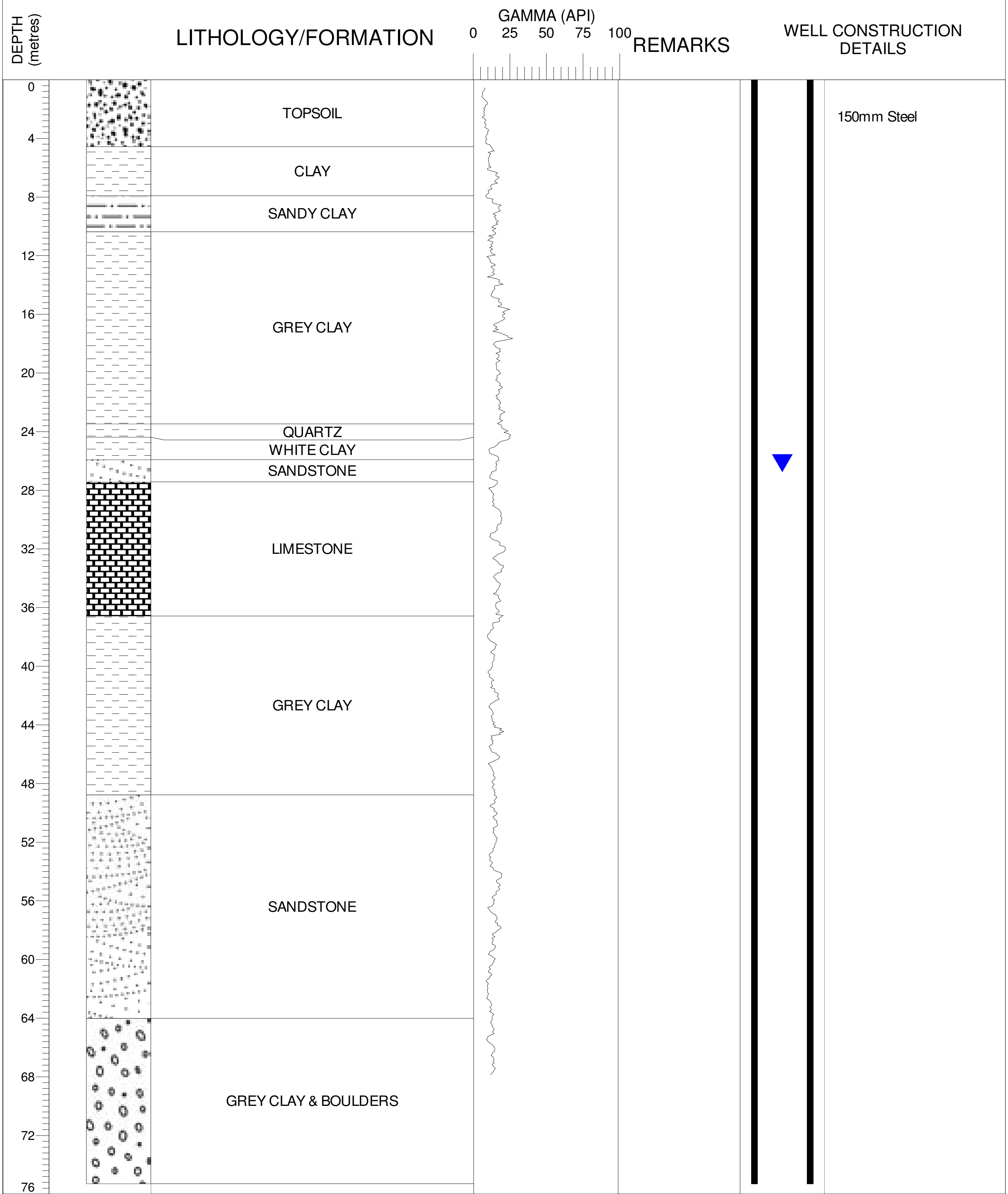
WELL CONSTRUCTION DETAILS:

- 273mm Steel
- 219mm Steel
- 168mm Steel
- Grout
- 168mm Steel Screens

APLNG Groundwater Monitoring Program

30168 Rockwood Back Bore

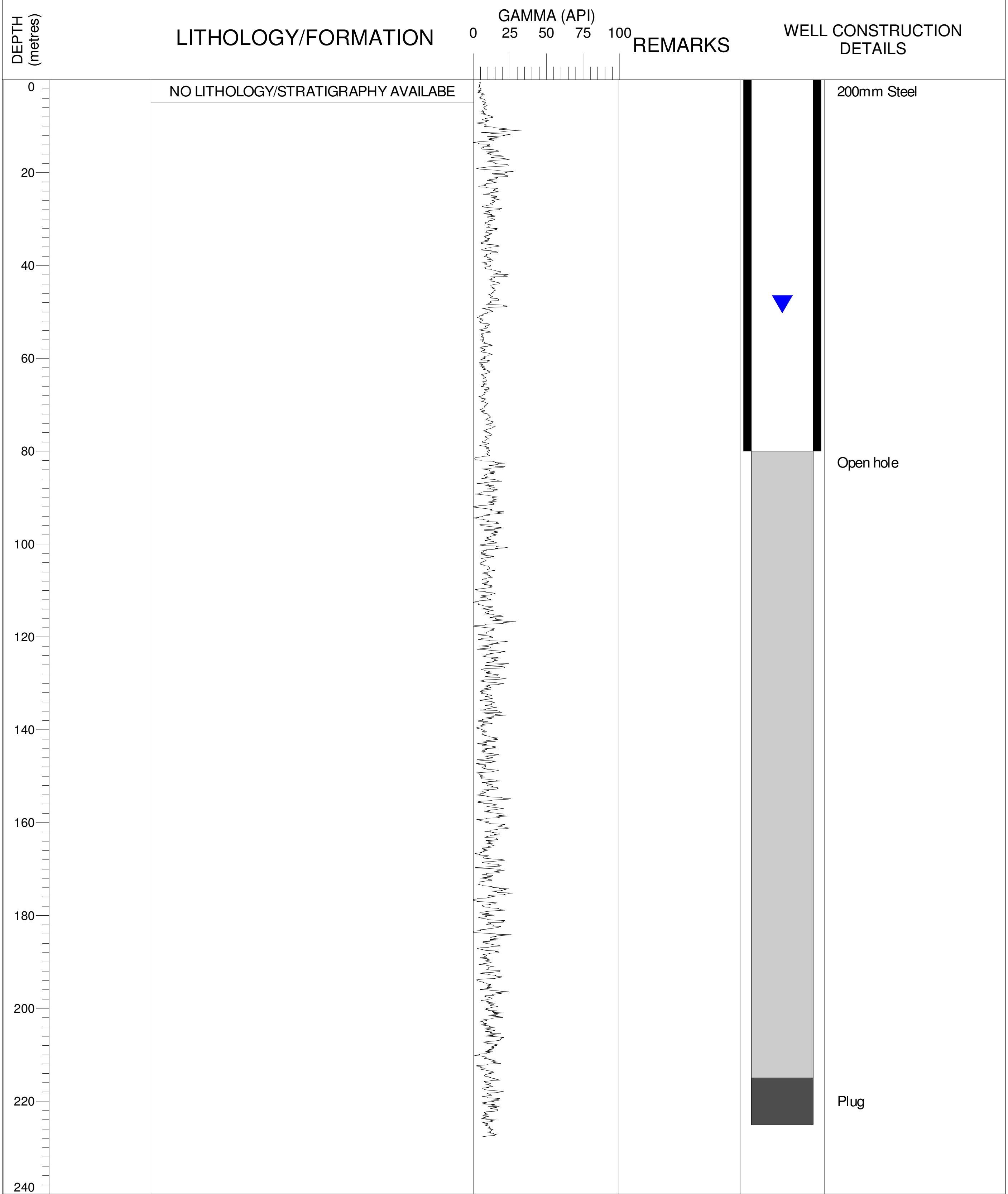
LATITUDE	*-26.9308*	**OWNER**	*Origin*	**CONSTRUCTED DEPTH (m)**	*67*	**INSTRUMENTATION**	
LONGITUDE	*150.3706*	**USE**	*Inactive*	**SWL** (mTOC)	*26.15*	**TYPE**	*Levelogger M30*
ELEVATION (mAHD)	*300*	**UNIT**	*Gubberamunda*	**EC** (mS/cm)	*2*	**DEPTH**	*53.99*



WorleyParsons APLNG Groundwater Monitoring Program

23642

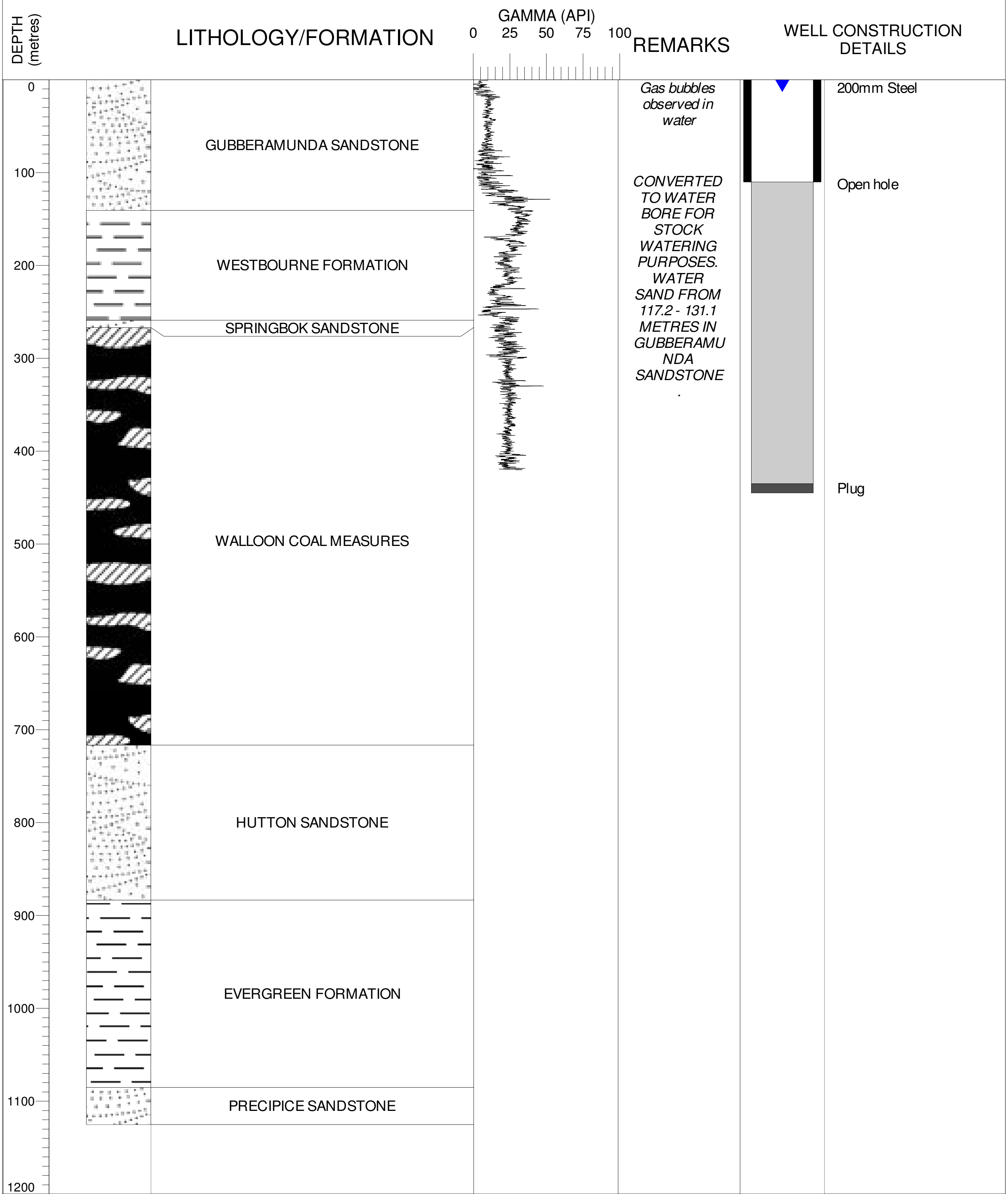
LATITUDE	*-26.9409*	**OWNER**	*Dougall*	**CONSTRUCTED DEPTH (m)**	*215*	**INSTRUMENTATION**	
LONGITUDE	*150.3524*	**USE**	*Inactive*	**SWL** (mTOC)	*48.35*	**TYPE**	*Levelogger M100*
ELEVATION (mAHD)	*325*	**UNIT**	*Gubberamunda*	**EC** (mS/cm)	*0.2*	**DEPTH**	*85.18*



APLNG Groundwater Monitoring Program

23457

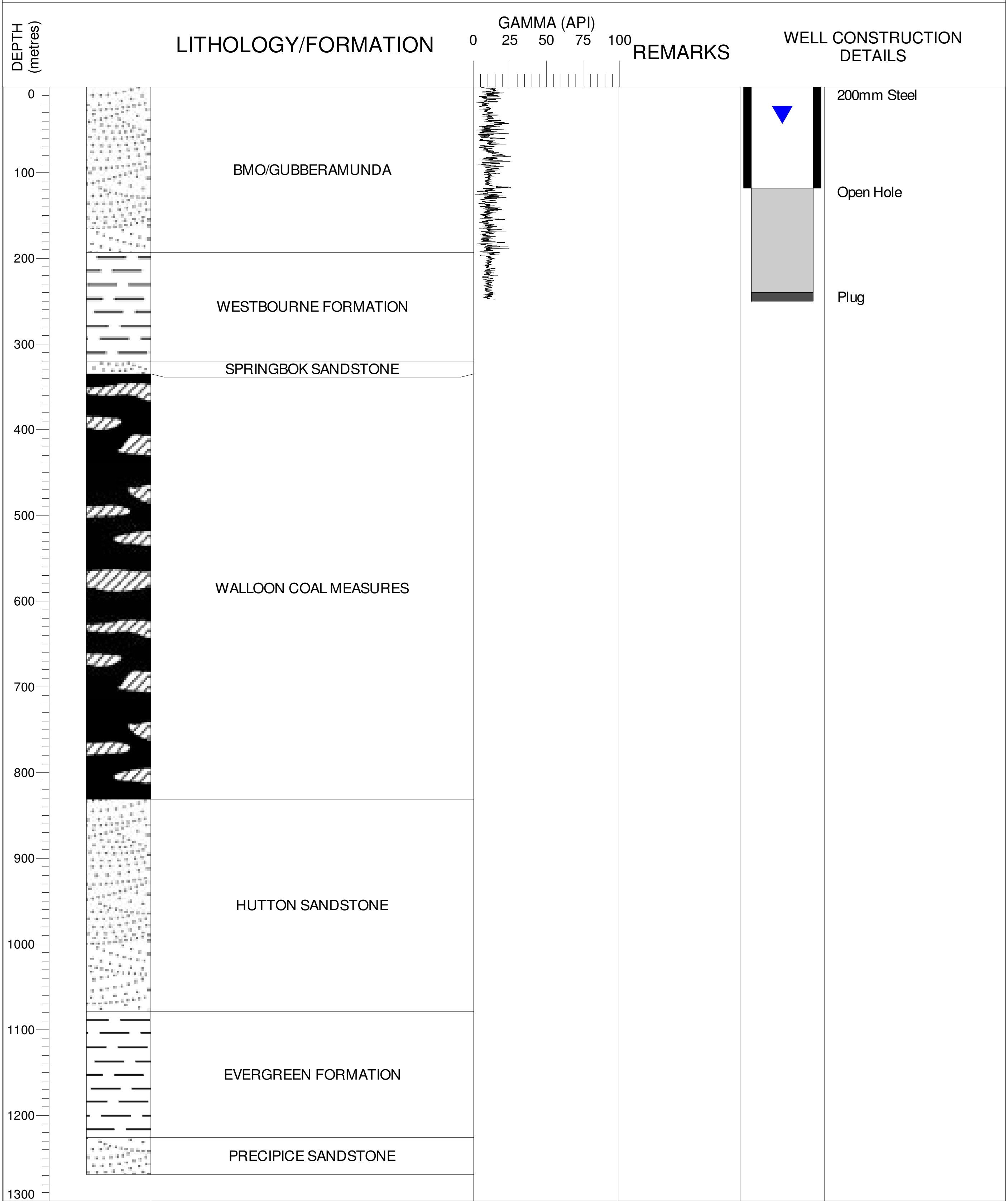
LATITUDE	*-26.904*	**OWNER**	*QGC*	**CONSTRUCTED DEPTH (m)**	*420*	**INSTRUMENTATION**	
LONGITUDE	*150.336*	**USE**	*Inactive*	**SWL** (mTOC)	*3.4*	**TYPE**	*NA*
ELEVATION (mAHD)	*309.7*	**UNIT**	*Multiple*	**EC** (mS/cm)	*2.7*	**DEPTH**	*NA*



APLNG Groundwater Monitoring Program

23335

LATITUDE	*-26.9655*	**OWNER**	*Dougall*	**CONSTRUCTED DEPTH (m)**	*240*	**INSTRUMENTATION**	
LONGITUDE	*150.3948*	**USE**	*Inactive*	**SWL** (mTOC)	*32.67*	**TYPE**	*Levelogger M100*
ELEVATION (mAHD)	*308*	**UNIT**	*Gubberamunda*	**EC** (mS/cm)	*0.3*	**DEPTH**	*99.46*



APLNG Groundwater Monitoring Program

10925 Rockwood Old House Bore

WorleyParsons resources & energy

LATITUDE	*-26.8991*	**OWNER**	*Origin*	**CONSTRUCTED DEPTH (m)**	*94*	**INSTRUMENTATION**	
LONGITUDE	*150.3639*	**USE**	*Inactive*	**SWL** (mTOC)	*41.24*	**TYPE**	*Levelogger M30*
ELEVATION (mAHD)	*306*	**UNIT**	*Gubberamunda*	**EC** (mS/cm)	*2.1*	**DEPTH**	*60.83*

DEPTH (metres)	LITHOLOGY/FORMATION	GAMMA (API) 0 25 50 75 100	REMARKS	WELL CONSTRUCTION DETAILS
0	SOIL, CLAY & SAND			150mm Steel
5				
10				
15				
20	HARD CLAY			
25				
30				
35	SANDSTONE			
40	PUGGY SANDSTONE			
45				
50	YELLOW SANDSTONE			
55				
60	PUGGY SANDSTONE			
65	HARD CLAY			
70				
75	HARD SANDSTONE			
80	SANDY CLAY			
85	HARD SANDSTONE			
	SANDY CLAY			
90	HARD SANDSTONE			
95				
100				

Appendix D Hydrochemistry characterisation

Environmental Impact Assessment

Hydrogeology – Hydrochemistry Characterisation

07-Jul-09

WorleyParsons Document Number - Alternate Document Number

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WORLEYPARSONS FORMAL REPORT TEMPLATE

REV	DESCRIPTION	ORIG	REVIEW	WORLEY-PARSONS APPROVAL	DATE	CLIENT APPROVAL	DATE
A	Issued for internal review	D Green	J Fennell	N/A	15-Jul-09	N/A	

Contents

1. Introduction

The Terms of Reference (ToR) for the Australia Pacific LNG project requires a description of the existing environment potentially affected by the proposed CSG development and operations. According to the ToR, the existing environment pertaining to water resources is to be characterised in the context of environmental values defined by the Environmental Protection (Water) Policy 1997 (EPP Water, 1997), and to be inclusive of an evaluation of both the quality and quantity of water resources in the project area. The characterisation will serve as a baseline from which to infer and monitor any impacts associated with the proposed Australia Pacific LNG project.

A primary objective of the current report is to describe the existing environment and environmental values with respect to groundwater quality within the Project area. The characterisation of groundwater quality has been conducted on the basis of existing and available data, together with data collected and analysed as part of the Phase 1 Groundwater Monitoring Program, supporting Australia Pacific's LNG application. The approach to characterising the groundwater quality has involved a range of statistical and trend analyses within and across particular hydrostratigraphic units.

The geochemical evaluation has also provided valuable insight to various attributes of the conceptual hydrogeological model in the Project area, in particular:

- regional groundwater flow patterns
- recharge and discharge processes
- groundwater – rock interaction, and
- the occurrence of inter-aquifer flow.

These processes are explored in the context of this geochemical evaluation and documented in the current report.

For clarification, the outcomes of the geochemical evaluation are documented according to the following chapters:

- Chapter 2 – Data Sources and Approach to Geochemical Characterisation
- Chapter 3 – Characterisation of Groundwater Chemistry
- Chapter 4 – Existing Environmental Values
- Chapter 5 – Summary

All figures associated with the report are provided in **Chapter 7** while a Compact Disc (CD) containing a database of the collective groundwater quality data is provided as an attachment to this report.

2. Approach to Geochemical Characterisation and Environmental Value Identification

2.1 Data Sources

For the purposes of the current assessment all available groundwater geochemical data within the Project area and its surrounds was sourced, collated, interrogated and interpreted. The sources of data included:

- the Queensland Government Department of Environment and Resource Management (DERM) Groundwater Database[1]
- Origin Energy exploration data, and
- Information collected from the Phase 1 Groundwater Monitoring Program.

2.2 Chemical Constituents

A number of chemical constituents formed the basis of the geochemical evaluation. These include:

- Field measured Electrical Conductivity (EC)
- Field measured pH
- Colour
- Turbidity
- Hardness
- Alkalinity
- Sodium Adsorption Ratio
- Total Dissolved Solids
- Major Cations
- Major Anions
- Silica
- Trace elements
- Nitrate and Phosphate

While the Queensland Government DERM Groundwater Database provided the bulk of the groundwater quality data, with over 11,000 groundwater sample results, the individual records rarely

[1] To encapsulate the project area and surrounds, groundwater geochemical data was accessed from the database between coordinates: 400000E – 1050000E and 6800000N – 7250000N.

included all the chemical parameters listed above. In particular, most groundwater samples were not subjected to trace element and nitrate and phosphate laboratory analysis.

2.3 Geochemical Characterisation Approach

In characterising the groundwater quality and its variability across the Australia Pacific LNG project area and its surrounds the following approach was adopted:

- All available groundwater quality data was collated from the various sources (listed in **Section 2.1**) into a collective database.
- The ion balance of each sample was calculated to evaluate the validity of laboratory analyses and the reported data. Groundwater sample results with ion balances in excess of +/-5% were discarded from the final database. Those groundwater sample results with very low pH (< pH 4) and very high pH (> pH 12) were also discarded from the final database.
- On the basis of the conceptual hydrogeological model developed for the project area, each groundwater bore (and accompanying groundwater sample) was classified according to the hydrostratigraphic unit in which the bore was screened and the groundwater sampled.
- For each hydrostratigraphic unit, the median and 20th and 80th percentile[2] of the concentrations of salinity and selected analytes[3] were calculated (according to the most recent geochemical sample of the bore) for the purposes of characterising the groundwater quality and its variability both regionally and across different units.
- Groundwater salinities and dominant hydrochemical facies[4] in each hydrostratigraphic unit were regionally mapped, and Piper diagrams[5] prepared, to evaluate regional scale salinity and facies trends that may inform potential relationships including: recharge processes, groundwater – rock interaction along flow paths, mixing of otherwise discrete water types and inter-aquifer flow.

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[2] The 20th and 80th percentile was chosen for the purposes of characterising “average” groundwater quality properties, rather than extreme end values represented by 5th and 95th percentiles.

[3] The selected analytes consisted of: pH, Sodium, Chloride, Sulphate, Nitrate, Iron, Manganese, Zinc, Aluminium, Boron and Copper. These analytes were chosen for having readily available records and as representing a reasonable measure of environmental values with reference to the guidelines adopted.

[4] Hydrochemical facies (or water types) are distinct zones that have cation and anion concentrations describable within defined geochemical composition categories.

[5] Piper diagrams are a graphical means of displaying the ratios of the principal ionic constituents in water. Piper diagrams have the potential to represent a large number of analyses and are convenient for illustrating differences between groundwater compositions within the project area or given formation.

2.4 Environmental Values and Assessment Guidelines

The environmental values of the groundwater in the Australia Pacific LNG project area have been assessed in accordance with the Environmental Protection (Water) Policy 1997 (EPP, 1997) and the Environmental Protection (Water) Amendment Policy (No.1) 2008 (EPP Water, 2008).

As stipulated in the Policy documents the following environmental values are to be enhanced or protected:

- biological integrity of an unmodified, highly valued or modified aquatic ecosystem
- suitability for primary, secondary and visual recreational use
- suitability for minimal treatment before supply of drinking water
- suitability for agriculture use
- suitability for aquaculture use
- suitability for producing aquatic food for human consumption
- suitability for industrial use, and
- cultural and spiritual values of the water.

With reference to the groundwater regime in the Australia Pacific LNG project area, the following three environmental values are considered to be of particular importance:

- "Biological integrity of aquatic ecosystems" in consideration of the effect of groundwater interaction with surface water bodies or groundwater dependent ecosystems.
- "Suitability for minimal treatment before supply as drinking water" in the event that groundwater is accessed for domestic use or municipal water supply.
- "Suitability for use in agriculture" in cases where groundwater is accessed for irrigation and/or livestock watering.

Accordingly, the guidelines adopted in evaluating these environmental values of the groundwater regime are presented in **Table 1**.

Table 1 Adopted Groundwater Quality Guidelines

Environmental Value	Adopted Guidelines
Biological integrity of aquatic ecosystems	ANZECC 2000 *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* Trigger Levels for Freshwater Ecosystems – 95% protection level of species
Suitability for minimal treatment before supply as drinking water	NHMRC 2004 *Australian Drinking Water Guidelines*
Suitability for use in agriculture (irrigation)	ANZECC 2000 *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* Short-term Trigger Values (STV) and Long-term Trigger Values (LTV) in Irrigation Water

Environmental Value	Adopted Guidelines
Suitability for use in agriculture (livestock watering)	ANZECC 2000 *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* Livestock Drinking Water Guidelines (Beef Cattle and Sheep)

3. Characterisation of Groundwater Chemistry

3.1 Hydrostratigraphic Unit Classification

The groundwater chemistry across the Australia Pacific LNG Project area has been characterised in the context of the hydrogeological conceptual model developed for the Environmental Impact Assessment (EIA). A comprehensive description of the hydrogeological conceptual model is provided in **Chapter 6** of the EIA technical document.

The hydrogeological conceptual model defines alternating hydrostratigraphic units consisting of major aquifers, watering bearing units and aquitard units (i.e. intervening low permeability layers). For the purposes of characterising the regional groundwater chemistry, each groundwater bore (and accompanying groundwater sample) was classified according to the hydrostratigraphic unit in which it was screened.

Most bores were designated to the following major aquifer or water bearing hydrostratigraphic units:

- Cainozoic units
- Bungil Formation, Mooga Sandstone and Orallo Formation (BMO Group)
- Gubberamunda Sandstone
- Springbok Sandstone
- Walloon Coal Measures
- Hutton Sandstone
- Precipice Sandstone

The characterisation of the groundwater chemistry is documented in the following sections in the context of these major hydrostratigraphic units.

For each hydrostratigraphic unit, the median and 20th and 80th percentile of the concentrations of salinity (as defined by total dissolved solids content) and selected analyte concentrations (according to the most recent geochemical sample in each bore) are described and presented in tabulated format (**Appendix 1**) with reference to the guidelines adopted to evaluate the environmental values of the water (**Section 2.4**). The groundwater salinity, Piper plots and regional hydrochemical facies trends are also described and presented in **Figure 1** to **Figure 21** to illustrate potential relationships including: recharge processes, groundwater – rock interaction along flow paths and inter-aquifer flow.

To assist in the characterisation and to serve as a comparison across units, the groundwater salinity statistics and dominant hydrochemical facies of each hydrostratigraphic unit are summarised in **Table 2**. It is notable, that for each hydrostratigraphic unit, the groundwater salinity data exhibits a positive skew, meaning the data sets generally contain a comparatively larger number of low salinity values relative to high salinity values.

Table 2 Groundwater Salinity and Hydrochemical Facies Summary

Hydrostratigraphic Unit	Salinity (Total Dissolved Solids mg/L)						Dominant Hydrochemical Facies
	Count	20th Percentile	80th Percentile	Medium	Mean	Standard Deviation	
Cainozoic Units	1,489	469	1,810	891	1,509	2,332	Na, Mg, Ca-Cl,HCO_3 and Na-Cl,HCO_3
BMO Formation	228	745	2,588	1,153	1,970	2,285	Na-HCO_3,Cl
Gubberamunda Sandstone	100	590	1,646	980	1,673	1,974	Na-HCO_3,Cl
Springbok Sandstone	8	533	1,615	575	948	598	Na-HCO_3,Cl
Walloon Coal Measures	162	591	3,564	1,463	2,547	3,044	Na-Cl,HCO_3, Na-HCO_3,Cl and Na-Cl
Hutton Sandstone	234	568	2,357	1,033	1,596	1,598	Na-HCO_3,Cl and Na-Cl,HCO_3
Precipice Sandstone	23	127	1,652	171	769	1,096	Na-HCO_3 and Na-Cl,HCO_3

3.2 Evolution of Geochemistry and Salinity Trends

Groundwater chemistry within the recharge zones of aquifer sequences in the Surat Basin (and the Great Artesian Basin as a whole) is largely inhomogeneous. The diversity of geochemical signatures within the recharge zones results from the range of processes contributing to recharge, together with localised evapotranspiration, deposition of marine aerosols via rainfall, leaching of salts during recharge and the numerous water-rock interactions that occur initially as infiltrating water equilibrates with the subsurface materials (Radke et al., 2000).

In the transition to confined aquifer conditions, local homogenisation of the geochemical signature may occur, although regional heterogeneity remains significant throughout the Great Artesian Basin (Radke et al., 2000).

Following the infiltration of rainfall, the evolutionary path of groundwater begins through low salinity, slightly acidic groundwater, to Ca,Mg-HCO_3,Cl groundwater and finally to Na-HCO_3-Cl dominant groundwater. This trend is generally expressed in the dominant hydrochemical facies of each confined aquifer system in the Surat Basin (**Table 2**). Further detail concerning the geochemical evolution of groundwater in the Surat Basin is provided below.

Initially, Carbon Dioxide (CO_2) (up to three orders of magnitude above atmospheric levels) is acquired by waters near the recharge area, owing to plant respiration and oxidation of organic matter in the soil zone. In turn, silicate (i.e. plagioclase or orthoclase) and carbonate minerals may dissolve, contributing to elevated alkalinity levels and Na, Ca and Mg ion concentrations. As the groundwater progresses basinwards, cation exchange of the Na present in aquifer materials for Ca and Mg in solution occurs. This may lead to the subsequent conversion of Na-Smectite to Kaolinite, releasing Na to solution (Herczeg et al., 1991).

With the removal of Ca (and Mg) from the groundwater by exchange with Na in clay minerals within the aquifer framework, H^+ ions are released, further promoting carbonate dissolution (Radke et al., 2000). As a consequence of these processes the groundwater evolves towards elevated Na and HCO_3 concentrations. The geochemical signature may, however, be overprinted to some extent by the diffusion of Cl (and other soluble ions) from overlying or underlying aquitards with marginal marine depositional histories (i.e. Rolling Downs Group, Bungil Formation, Westbourne Formation and

Evergreen Formation) (Radke et al., 2000). Leaching of soluble ions from these formations may be responsible for the elevated Cl concentrations in the groundwater geochemistry records (**Table 2**) and the general increase in salinity along the flow paths of aquifers in the Great Artesian Basin. The increasing salinity trend may also be a consequence of mixing of dilute recharge waters with saline waters present within deeper parts of the basin and the dissolution or weathering of evaporates, carbonate minerals or incongruent dissolution of feldspars, micas or clay minerals along the flow path (Herczeg et al., 1991).

The following sections provide a summary of the geochemical characterisation of each aquifer unit of the Surat Basin within the project area.

3.3 Cainozoic Units

The median and 20th and 80th percentile of the concentrations of salinity and selected analytes for groundwater samples derived from the Cainozoic units are presented in **Table 3** (**Appendix 1**), while the regional scale salinity trend, piper diagram and regional hydrochemical facies trend are illustrated in **Figure 1**, **Figure 2** and **Figure 3**, respectively.

As demonstrated in the figures, groundwater quality information for the Cainozoic age aquifers across the Australia Pacific LNG's development area is largely absent due to the unit's very limited occurrence. The Cainozoic age Upper Condamine River alluvial plain aquifer is a major groundwater resource to the southeast of Chinchilla and it is in this region that the majority of groundwater quality data is clustered.

The Cainozoic age unit within this region generally contains good quality (marginally alkaline) groundwater with a median salinity of less than 900mg/L TDS. The salinity can however be highly variable, regularly exceeding concentrations of 3,000mg/L TDS in the Millmerran, Toowoomba and Dalby regions. The hydrochemical facies are similarly variable, interchanging between Na, Mg, Ca-Cl,HCO_3 and Na-Cl,HCO_3 water types.

Due to the clustered and variable nature of the chemistry data, no spatial groundwater quality trends are discernable. As discussed in **Section 3.2**, groundwater chemistry within recharge zones is largely heterogeneous as a consequence of shallow groundwater processes such as local recharge and localised occurrences of discharge systems, deposition of marine aerosols via rainfall, evapo-transpiration, rock-water interactions and possibly in this region; irrigation induced salinity.

Elevated nitrate concentrations (with a median concentration of 2.6mg/L NO_3 as N) are present in the Cainozoic age unit possibly as a result of anthropogenic influences. Nitrate is a common derivative of fertiliser application to soils and is soluble and mobile in groundwater.

3.4 BMO Group

The median and 20th and 80th percentile of the concentrations of salinity and selected analytes for groundwater samples derived from the BMO Group are presented in **Table 4** (**Appendix 1**), while the regional scale salinity trend, Piper diagram and regional hydrochemical facies trend are illustrated in **Figure 4**, **Figure 5** and **Figure 6**, respectively.

The BMO Group (in particular, the Mooga Sandstone aquifer sequence) is restricted to the north-western sections of Australia Pacific LNG's development areas. Within this region the Mooga Sandstone aquifer is relatively thin (at approximately 20 metres) and only attains reasonably

thicknesses down-dip, southwest of the project area. It is within this region that groundwater bores target the Mooga Sandstone unit and provide a moderate coverage of groundwater quality data.

The Mooga Sandstone unit within this region contains reasonably good quality (marginally alkaline) groundwater with a median salinity of 1,153mg/L TDS, although salinities exceeding 3,000mg/L TDS are common around the Roma and Miles townships. The dominant hydrochemical facies for the Mooga Sandstone unit is Na-HCO_3,Cl.

As for the Cainozoic age unit, no regional spatial groundwater quality trends are discernable due to the clustered and variable nature of the data assessed. On the basis of the variable quality it may be inferred that the groundwater quality, particularly between Roma and Miles, is to some extent controlled by similar shallow groundwater processes as indicated for the Cainozoic age unit. The aquifer is generally overlain by the Rolling Downs Group (aquitard) or the Cainozoic age units and it may also be possible that the sandstone unit is receiving variable quality infiltration and/or ion diffusion from one or both of these overlying units.

Elevated nitrate concentrations (with median concentrations of 1.3mg/L NO_3 as N) are present in the outcropping and subcropping areas of the BMO Group, possibly as a consequence of fertiliser application in this area.

3.5 Gubberamunda Sandstone

The median and 20th and 80th percentile of the concentrations of salinity and selected analytes for groundwater samples derived from the Gubberamunda Sandstone are presented in **Table 5** (**Appendix 1**), while the regional scale salinity, Piper diagram and regional hydrochemical facies trend are illustrated in **Figure 7**, **Figure 8** and **Figure 9**, respectively.

The Gubberamunda Sandstone unit is regionally extensive, being present across Australia Pacific LNG's development areas and to the west and south west. The groundwater chemistry records demonstrate the aquifer porewater is alkaline in character and of good quality with salinities consistently below 2,000mg/L TDS. The groundwater salinity can be very low near direct recharge sources to the north of Roma (i.e. at or below 500mg/L TDS). The groundwater quality marginally declines along a flowpath that extends towards the south and south-west.

The groundwater salinity is more variable in proximity to Australia Pacific LNG's development areas and to the south. The unit sub-crops and eventually outcrops in this region and it may be possible that the porewater quality is to some extent controlled by shallow groundwater processes (as documented for the BMO and Cainozoic units). Where overlain, the aquifer may also be receiving variable quality infiltration and/or ion diffusion from younger units (i.e. Cainozoic, Rolling Downs Group, BMO Formation).

In proximity to the recharge source (to the north of Roma) and in downgradient areas, the major water type is regularly Na-HCO_3,Cl. Geochemical processes potentially contributing to the dominance of Na and HCO_3 in groundwaters of the GAB are documented in **Section 3.2**. In proximity to Australia Pacific LNG's development areas and to the south, the water type while consistently Na dominated, can interchange between HCO_3 and Cl dominance. Shallow groundwater processes or other processes such as: ion-exchange, leaching of soluble ions, mixing of different water types and/or precipitation/dissolution of minerals, may be contributing to this variability in anion dominance.

Elevated nitrate concentrations (with median concentrations of 1.0mg/L NO_3 as N) are present in the subcropping and outcropping areas of the Gubberamunda Sandstone, possibly as a consequence of fertiliser application to the soils and its subsequent leaching to aquifer.

3.6 Springbok Sandstone

The median and 20th and 80th percentile of the concentrations of salinity and selected analytes for groundwater samples derived from the Springbok Sandstone are presented in **Table 6** (**Appendix 1**), while the regional scale salinity, piper diagram and regional hydrochemical facies trend are illustrated in **Figure 10**, **Figure 11** and **Figure 12**, respectively.

With increasing depth in the stratagraphic sequence, the occurrence of groundwater bores (and associated groundwater quality data) becomes relatively sparse and the interpretations of quality trends are more speculative. Those bores screened within the Springbok Sandstone aquifer are generally situated to the southwest of Australia Pacific LNG's project area where the unit achieves a reasonable thickness at depths less than 1,000 metres.

The groundwater chemistry records demonstrate the aquifer is marginally alkaline and of very good quality with a median groundwater salinity of 575mg/L TDS. Direct recharge sources to the Springbok Sandstone are likely to reside north-west of Injune where the unit sub-crops and eventually outcrops in absence of the overlying Westbourne Formation (aquitard). The low salinity (Na-HCO_3,Cl and Na-Cl,HCO_3 type) groundwater is maintained along a flowpath extending towards the south and south-west and may imply the sequence is well leached and/or highly transmissive. Although based on limited data, it may be possible to infer that the groundwater interchanges from Na-Cl,HCO_3 to Na-HCO_3,Cl along the flow path. Such a trend (if real) may be occurring as a consequence of any number of processes including: small amounts of carbonate dissolution occurring within the unit during groundwater flow; the by-product of which is elevated HCO_3 concentrations, ion-exchange, leaching of soluble ions, mixing of different water types and/or precipitation/dissolution of minerals.

3.7 Walloon Coal Measures

The median and 20th and 80th percentile of the concentrations of salinity and selected analytes for groundwater samples derived from the Walloon Coal Measures are presented in **Table 7** (**Appendix 1**), while regional scale salinity, Piper diagram and regional hydrochemical facies trend are illustrated in **Figure 13**, **Figure 14** and **Figure 15**, respectively.

A total of 149 groundwater sample results sourced from bores screened within the Walloon Coal Measures in proximity to the project area and its surrounds are available in the database. The bores are generally situated to the north-east of Australia Pacific LNG's development areas, coinciding with the sub-crop regions of the Walloon Coal Measures, where the target aquifer is located at reasonably shallow depths. Recorded groundwater salinities are highly variable; ranging from 250 to 16,000mg/L TDS. The median groundwater salinity of this interval (1,463mg/L TDS) is comparatively elevated with respect to overlying and underlying aquifers. The porewater is dominated by Na and Cl ions (i.e. Na-Cl,HCO_3 and Na-Cl types), with the Na-HCO_3,Cl water type accounting for approximately 20% of the geochemical record.

The localised pockets of low salinity groundwater may be representative of discrete recharge zones for the Walloon Coal Measures. A combination of water-rock interaction, shallow water processes and infiltration from poorer quality overlying units (i.e. Cainozoic units) may be responsible for the variable salinity and water types in this unit.

On the basis of the clustered nature of the quality data, the variable nature of the lithology in the unit, both laterally and vertically, and the presence of discontinuous coal seams, the inference of water quality trends in the Walloon Coal Measures is, however, speculative at best.

3.8 Hutton Sandstone

The median and 20th and 80th percentile of the concentrations of salinity and selected analytes for groundwater samples derived from the Hutton Sandstone are presented in **Table 8** (**Appendix 1**), while the regional scale salinity, Piper diagram and hydrochemical facies trend are illustrated in **Figure 16**, **Figure 17** and **Figure 18**, respectively.

A total of 235 groundwater sample results sourced from bores screened within the Hutton Sandstone unit in proximity to the project area and its surrounds are available in the database. The bores are concentrated to the north and east of Australia Pacific LNG's development areas, in regions were the Marburg Sandstone (a subset of the Hutton Sandstone's hydrostratigraphic classification) is relatively accessible at shallow depths. Groundwater is marginally alkaline and the salinity is generally maintained below 3,000mg/L TDS across the project area. The recorded median salinity for this interval is 1,033mg/L TDS.

The groundwater salinity is generally lower in the aquifer's recharge (outcrop) areas, in the proximity of Injune and dominated by a Na-HCO_3,Cl water type. The groundwater quality is inferred to degrade towards the south-east, possibly as a consequence of infiltration of poorer quality water from overlying units (i.e. Cainozoic and Walloons Coal Measures) in areas where the overlying Eurombah Formation (aquitard) is thin or absent, mixing of different water types, and/or weathering reactions along the flow path. One or more of these processes is likely to be contributing to the alternating of water types along the flow path, which generally vary between Na-HCO_3,Cl and Na-Cl,HCO_3 types.

Elevated nitrate concentrations (with median concentrations of 1.4mg/L NO_3 as N) are present in the outcropping and subcropping areas of the Hutton Sandstone, possibly as a consequence of fertiliser application to the soils and its subsequent leaching to aquifer.

3.9 Precipice Sandstone

The median and 20th and 80th percentile of the concentrations of salinity and selected analytes for groundwater samples derived from the Precipice Sandstone are presented in **Table 9** (**Appendix 1**), while the regional scale salinity, Piper diagram and hydrochemical facies trend are illustrated in **Figure 19**, **Figure 20** and **Figure 21**, respectively.

With only 24 groundwater samples sourced from bores screened in the Precipice Sandstone unit within the project area and surrounds, the characterisation of groundwater quality and trends is very limited. According to the data available, the aquifer is likely to be pH neutral with groundwater salinities varying between 100 and 3,000mg/L TDS. Groundwater salinities are substantially lower (< 500mg/L TDS) in the aquifer's recharge areas, north of Injune and Taroom, where the water type is dominated by Na-HCO_3.

Further downgradient, in proximity to Miles and Chinchilla, the groundwater salinity is higher at levels between 1,000 and 5,000mg/L TDS, interchanging between Na-HCO_3,Cl and Na-Cl,HCO_3 types. The inferred deterioration of groundwater quality and variability in water type may be a consequence of any number of processes such as: ion diffusion from the Evergreen Formation, infiltration of poorer quality water from overlying units (i.e. Cainozoic, Walloons Coal Measures and Hutton Sandstone), mixing of

different water types and/or precipitation/mineral dissolution along the flow path. It is notable that the overlying Evergreen Formation is thin and/or absent in this area which may provide a conduit for poorer quality water to infiltrate.

3.10 Potential for Inter-Aquifer Flow

The potential for inter-aquifer flow across the aquifer units of the Surat Basin is discussed in **Chapter 6** of the EIA technical document. As indicated, groundwater flow is predominantly sub-horizontal, with limited flow occurring perpendicular to the bedding plane of the aquifers, in the vertical direction. Significant inter-aquifer flow may, however, occur locally in areas of direct aquifer connectivity, for instance, in locations where intervening aquitards narrow (particularly, around the margins of the basin) or as a consequence of structural controls (i.e. in fault or fold zones where vertical dislocations promote vertical or sub-vertical hydraulic conduits). There is currently insufficient regional scale potentiometry data to evaluate vertical hydraulic gradients and the associated potential for vertical groundwater movement across units within the project area.

Furthermore, due to the relative consistency of the hydrochemical facies across the hydrostratigraphic units of the Surat Basin and the limited availability of regional groundwater quality data (particularly for the deeper aquifers), geochemical based inferences concerning the occurrence and level of inter-aquifer flow or mixing cannot be made.

It is envisioned that direct recharge of aquifers in and around Injune and Taroom is contributing to localised occurrences of low salinity groundwater in the Gubberamunda Sandstone, Springbok Sandstone, Hutton Sandstone and Precipice Sandstone aquifers. In general, groundwater quality in each of these aquifers changes from fresher to more saline conditions across Australia Pacific LNG's development areas (between Roma and Toowoomba). It may be possible that poorer quality groundwater from overlying aquifers is infiltrating as a consequence of the inferred narrowing or absence of major confining aquitards (i.e. Rolling Downs Group, Westbourne, Eurombah and Evergreen Formations). Alternatively, structural controls (i.e. fault or fold zones) may be partly responsible where vertical dislocations facilitate vertical or sub-vertical hydraulic conduits. Other processes that may be contributing to the deteriorating groundwater quality in this region include: ion diffusion from overlying or underlying aquitards with marginal marine depositional histories, ion-exchange, leaching of soluble ions, mixing of different water types, and/or water-rock interactions along flow paths.

4. Existing Environmental Values

The environmental values of the groundwater in Australia Pacific LNG's project area have been assessed according to the values identified in the Environmental Protection (Water) Policy 1997 (EPP, 1997) and the Environmental Protection (Water) Amendment Policy (No.1) 2008 (EPP Water, 2008).

A discussion of each environmental value is provided below in the context of the project area and the relevant guideline values adopted.

For each hydrostratigraphic unit, the median and 20th and 80th percentile of the concentrations of salinity and selected analytes (according to the most recent geochemical sample in each bore) are presented in **Table 3** to **Table 9** (**Appendix 1**) with reference to the guidelines adopted to evaluate the environmental values of the water.

Biological integrity of a pristine or modified aquatic ecosystem

Groundwater in most hydrostratigraphic units of the Surat Basin contains elevated levels of trace elements (including zinc and copper), and in some instances nitrate, which exceed the ANZECC 2000 guideline Trigger Levels for Freshwater Ecosystems (at 95% protection). Accordingly, any controlled, or uncontrolled, discharge of associated CSG water may potentially affect the biological integrity of any receiving surface water system. Importantly, however, discharge of associated CSG water to surface water systems will not occur during any period of operation, and hence, such impacts are not expected.

Where surface water and groundwater systems are hydraulically connected there may be a potential for any affected groundwater to indirectly impact upon the environmental values of connected surface water systems. As such, appropriate management, mitigation and monitoring measures will be required in all aspects of the project's operation to minimise the potential for groundwater and any connected surface water systems to be affected with regards to this environmental value.

Furthermore, any existing Groundwater Dependent Ecosystems within the Australia Pacific LNG project area will be identified and monitored to ensure the construction and operational activities of the project do not adversely impact these ecosystems.

Notably, Stygofauna, a type of Groundwater Dependent Ecosystem, are classified as any fauna that live within a groundwater system. Stygofauna commonly include aquatic groundwater invertebrates (i.e. fish, worms, snails, arachnids, mites and insects) though terrestrial air-breathing subterranean animals may also be included in this classification. These species may be present within freshwater aquifers and within the pore spaces of limestone, calcrete or laterite, marine caves and along coasts.

Stygofauna have been the subject of extensive investigation in countries such as America, France, Slovenia and numerous other European countries, due to the presence and accessibility of favourable habitat (i.e. cave systems) and the large diversity and numbers of fauna identified. In contrast, Australian Stygofauna species are relatively poorly investigated and understood.

The nature of the geology and shallow groundwater systems in the project area (i.e. absence of limestone, marine caves, variable groundwater salinity) are unlikely to be conducive to large scale populations of Stygofauna species. If however, there is considered to be a significant risk to shallow

groundwater levels and/or quality as a consequence of the project's operation, it may be necessary to conduct a baseline Stygofauna survey to identify the relevance of this environmental value.

Suitability for recreational use

The environmental values associated with recreational use are more applicable to surface water than groundwater systems. Where surface water and groundwater systems are hydraulically connected however there may be a potential for any affected groundwater to indirectly impact upon the recreational values of connected surface water systems. As such, appropriate management, mitigation and monitoring measures will be required in all aspects of the project's operation to minimise the potential for groundwater and any connected surface water systems to be affected with regards to this environmental value.

Suitability for minimal treatment before supply as drinking water

Groundwater salinities within and in proximity to the Australia Pacific LNG project area are commonly in excess of 500mg/L TDS; the upper limit for the Australian Drinking Water Guidelines (2004), determined on the basis of taste. Elevated salinities, together with concentrations of trace elements (including iron and boron) that regularly exceed guideline values, are likely to preclude the use of groundwater as a drinking water source without some form of shandying (with lower salinity water) and/or pre-treatment.

On a regional scale, groundwater is accessed at various locations from the Cainozoic age Condamine-Alluvium, Mooga Sandstones, Gubberamunda Sandstone, Hutton Sandstone and Precipice Sandstone for town water supply purposes. In most instances the groundwater is not accessed for continuous supply, but for drought relief purposes only. If accessed, the groundwater is generally shandied with lower salinity surface water to reduce the salinity to an acceptable level for drinking water purposes.

Suitability for use in agriculture, aquaculture, aquatic food for human consumption

The majority of registered bores present in the Australia Pacific LNG project area access groundwater for irrigation and stock watering purposes, indicating the quality is likely to be suitable for these uses.

With reference to irrigation, appropriate groundwater salinities will be largely governed by the crop and soil type and irrigation regime. While groundwater salinities in the region may be suitable or marginally elevated for irrigation purposes, shandying with fresher surface waters may provide an opportunity to expand the potential irrigation uses.

The available groundwater quality data for the region indicate the groundwater resources are likely to be generally suitable for stock watering purposes. Similarly, the groundwater is likely to be appropriate for aquaculture and aquatic food for human consumption.

Suitability for industrial use

Groundwater resources within and in proximity to the Australia Pacific LNG project area are expected to be suitable for a range of industrial uses including; cooling water, process water, utility water and

wash water. Each industry will have specific quality requirements and constraints that will determine the suitability of employing the treated or untreated groundwater resource.

Cultural and spiritual values

The hydrogeological assessment has not identified any groundwater resources recognised for their cultural or spiritual value. Artesian conditions may give rise to local scale permanent water pools and/or springs. Such features may have important cultural significance, and if present, will require careful investigation as part of the CSG planning process.

In summary, the assessment identified six environmental values of relevance to the groundwater regime within Australia Pacific LNG's project area. These include: suitability for minimal treatment before supply as drinking water, biological integrity (maintaining water qualities to enable the survival of plants and animals present in surface waters and groundwaters), suitability for recreational use, suitability for cultural and spiritual values and suitability for livestock drinking water use and suitability for irrigation (agriculture) use.

5. Conclusions

In accordance with the Terms of Reference (ToR) for the Australia Pacific LNG project, the groundwater quality of the existing environment potentially affected by the proposed CSG operations have been assessed and are described in the current report. Over 11,000 chemistry records, belonging to seven hydrostratigraphic (aquifer/water bearing) units of the Surat Basin, have been assessed for the purposes of characterising the groundwater regime within Australia Pacific LNG's project area and identifying relevant environmental values. A summary of the key findings of the review is provided below.

- Most aquifer or water bearing units in the project area contain groundwater of meteoric origin and are marginally alkaline with median salinities recorded below 1,500mg/L TDS.
- Groundwater chemistry within the shallower aquifer systems (comprising the Cainozoic units and the Mooga Sandstone) is largely heterogeneous, possibly as a consequence of shallow groundwater processes such as local recharge and discharge systems and localised occurrences of deposition of marine aerosols via rainfall, evapo-transpiration, rock-water interactions and possibly in this region; irrigation induced salinity.
- Groundwater salinities in the Gubberamunda Sandstone, Springbok Sandstone, Hutton Sandstone and Precipice Sandstone aquifers are typically very low in proximity to direct recharge sources in and around Injune and Taroom, to the north of Australia Pacific LNG's development areas.
- Groundwater quality in the deeper confined aquifers generally deteriorates across Australia Pacific LNG's development areas (between Roma and Toowoomba) and it may be possible that poorer quality groundwater from other water bearing aquifers is infiltrating. It may be possible that poorer quality groundwater from overlying aquifers is infiltrating as a consequence of the inferred narrowing or absence of major confining aquitards (i.e. Rolling Downs Group, Westbourne, Eurombah and Evergreen Formations). Alternatively, structural controls (i.e. fault or fold zones) may be partly responsible where vertical dislocations facilitate vertical or sub-vertical hydraulic conduits. Other processes that may be contributing to the deteriorating groundwater quality in this region include: ion diffusion from overlying or underlying aquitards with marginal marine depositional histories, ion-exchange, leaching of soluble ions, mixing of different water types, and/or water-rock interactions along flow paths.
- In most hydrostratigraphic units the dominant water type is Na-HCO_3,Cl (or a close variant). The dominance of bicarbonate in the groundwater (and its common derivative from soil zone CO_2 as a result of plant respiration and oxidation of organic matter) may be a consequence of the proximity of the recharge zones to the north and northwest of Australia Pacific LNG's development areas. Bicarbonate concentrations may also be elevated as a consequence of the dissolution of carbonates by oxygenated recharge waters, mixing of different water types and/or precipitation/dissolution of minerals. The dominance of Na is likely to be related to the weathering of Na bearing silicate minerals, cation exchange and conversion of Na-Smectite to Kaolinite and release of Na to solution. The geochemical signature may, however, be overprinted to some extent by the diffusion of Cl (and other soluble ions) from overlying or underlying aquitards with marginal marine depositional histories.

- The assessment identified six environmental values of relevance to the groundwater regime within Australia Pacific LNG's project area. These include: suitability for minimal treatment before supply as drinking water, biological integrity (maintaining water qualities to enable the survival of plants and animals present in surface waters), suitability for recreational use, suitability for cultural and spiritual values and suitability for livestock drinking water use and suitability for irrigation (agriculture) use.

6. References

ANZECC and ARMCANZ. 2000, *The Australian and New Zealand Guidelines for Fresh and Marine Water Quality*. National Water Quality Management Strategy.

Freeze, R.A. and J.A. Cherry. 1979, *Groundwater*. Prentice-Hall, Inc., Englewood Cliffs, NJ, 604 pp.

Herczeg, A.L., Torgersen, T., Chivas, A.R. and Habermehl, M.A. 1991, *Geochemistry of ground waters from the Great Artesian Basin, Australia*. Journal of Hydrology, 126 (1991), pp 225-245.

National Health and Medical Research Council and Natural Resource Management Ministerial Council. 2004, *Australian Drinking Water Guidelines*. National Water Quality Management Strategy.

Radke, B.M., Ferguson, J., Cresswell, R.G., Ransley, T.R. and Habermehl, M.A. 2000, *Hydrochemistry and Implied Hydrodynamics of the Cadna-owie – Hooray Aquifer, Great Artesian Basin, Australia*. Bureau of Rural Science, Canberra.

Queensland Parliamentary Council. 2008, *Environmental Protection (Water) Amendment Policy (No.1) 2008*. Subordinate Legislation 2008 No.433.

Queensland Parliamentary Council. 2009, *Environmental Protection (Water) Policy 1997*. Reprint No.3C.

7. Figures

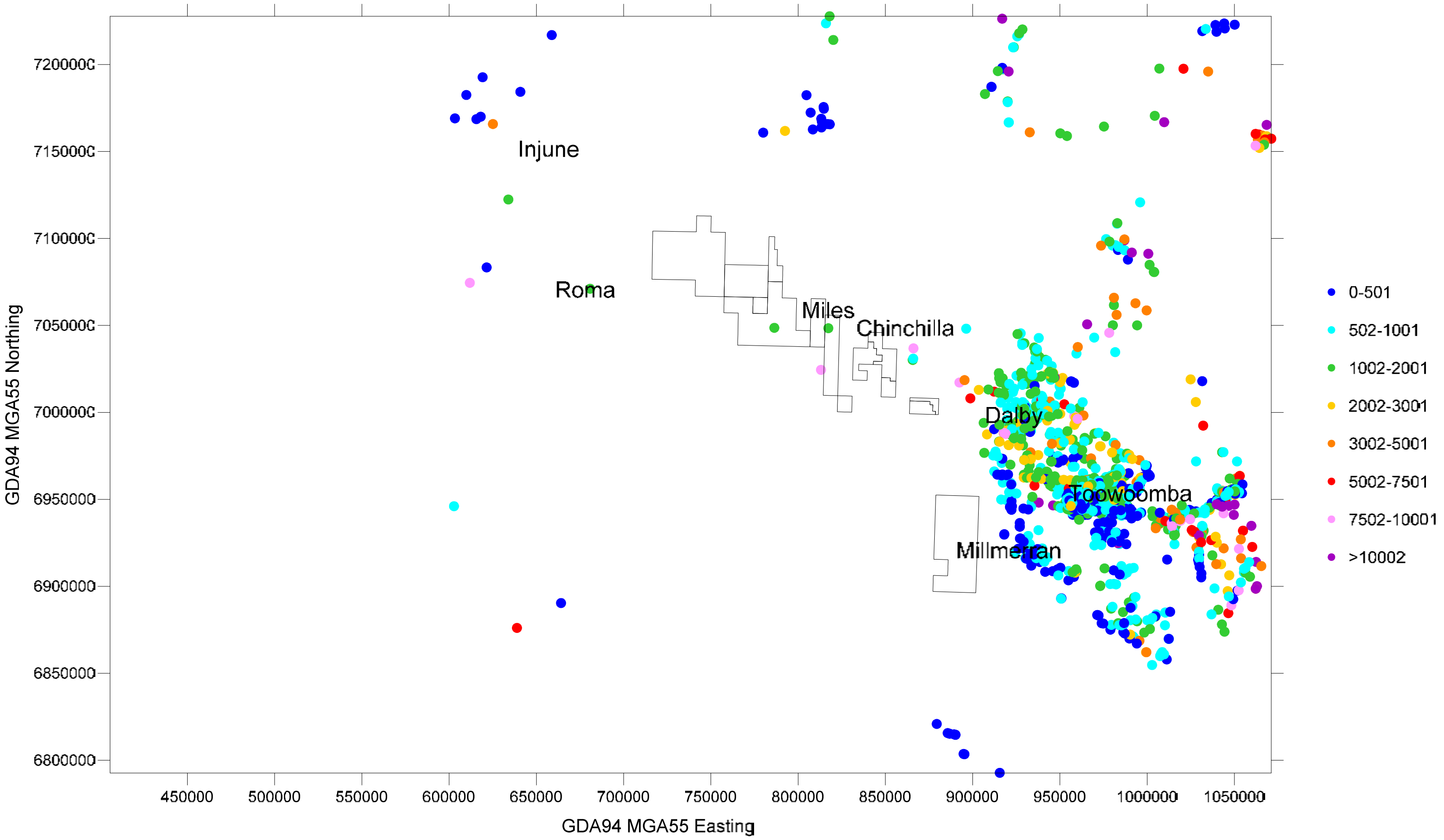

Figure 1 Regional Groundwater Salinity - Cainozoic Units

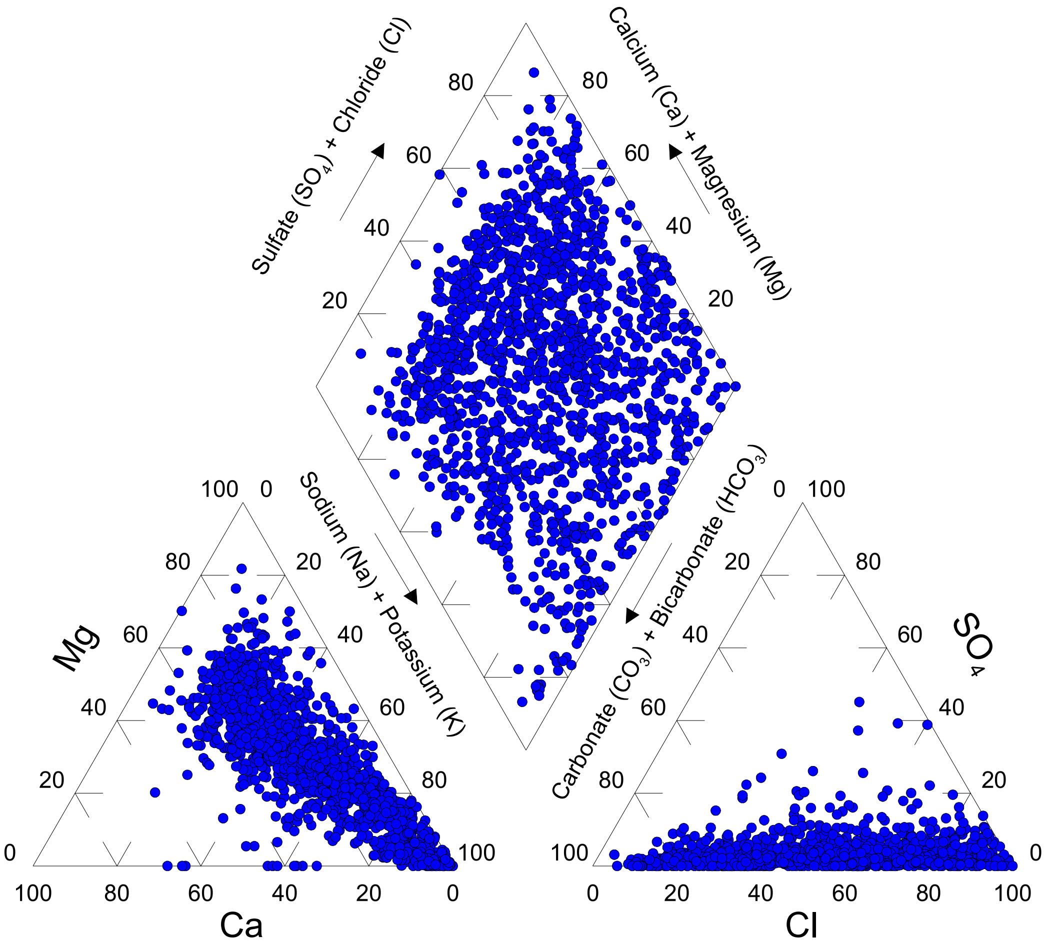

Figure 2 Piper Plot - Cainozoic Units

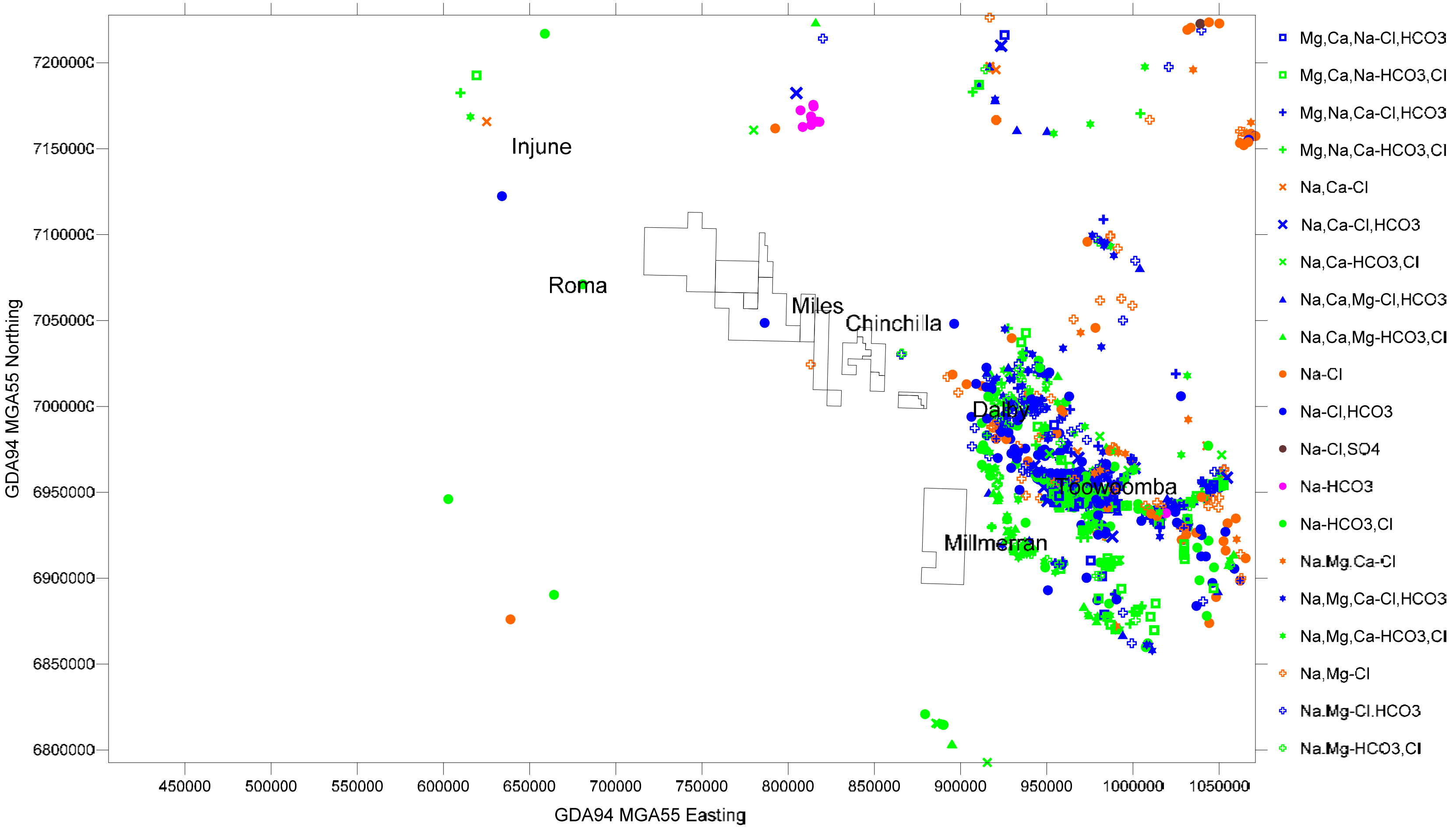

Figure 3 Hydrochemical Facies - Cainozoic Units

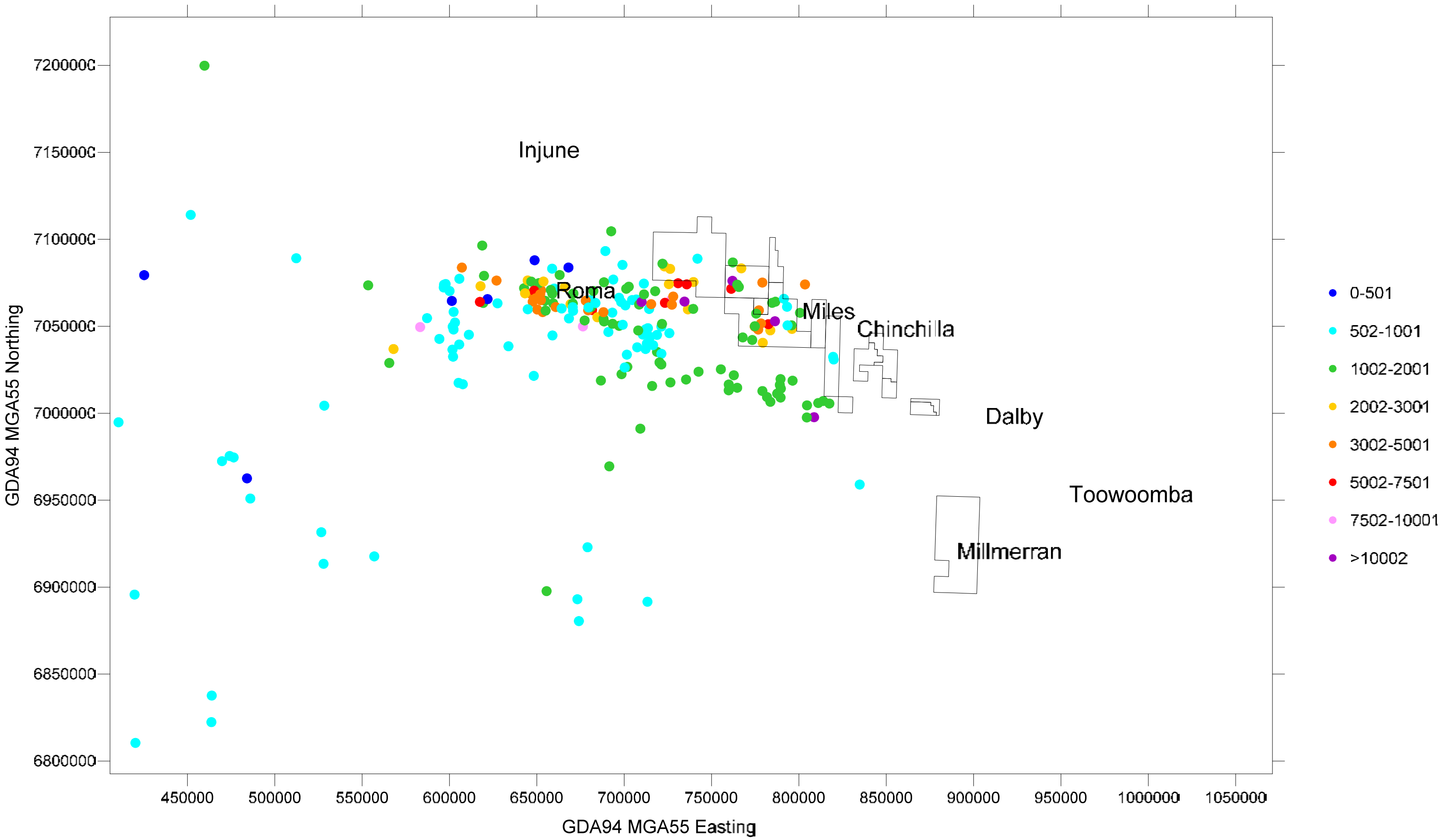

Figure 4 Regional Groundwater Salinity – BMO Formation

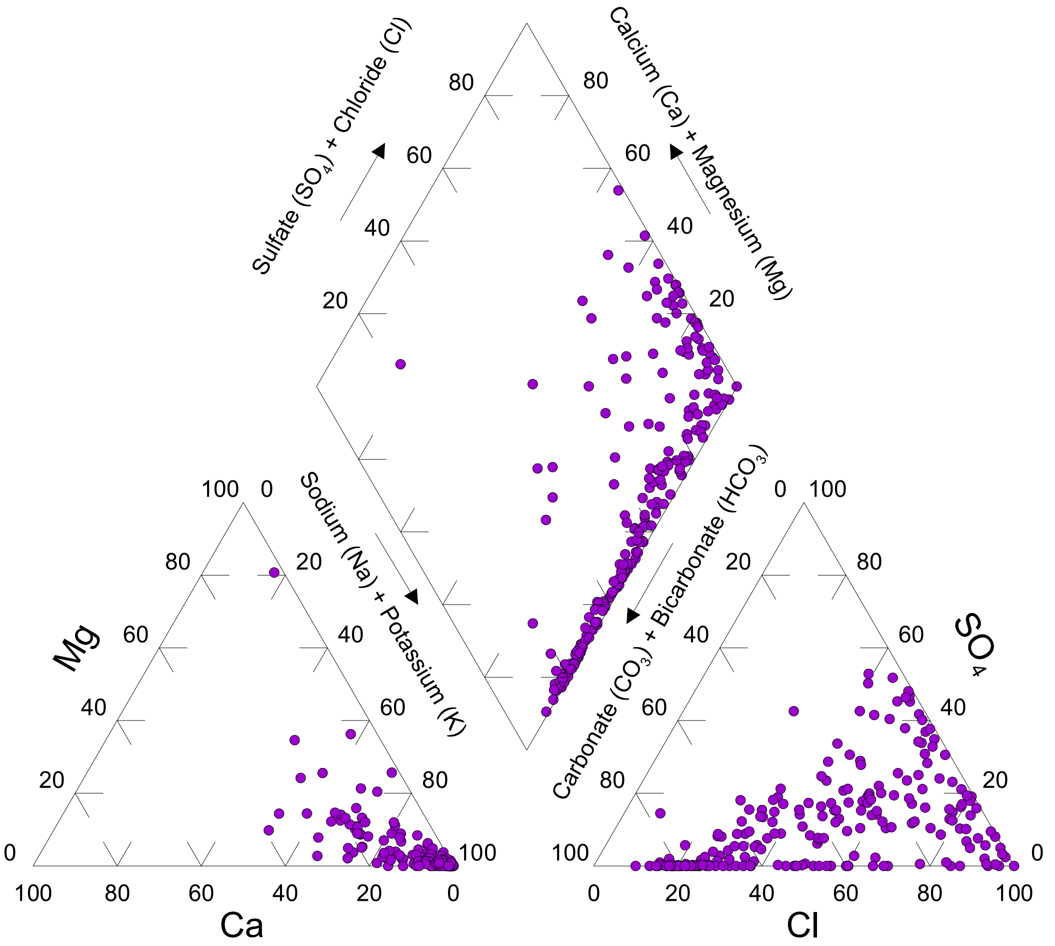

Figure 5 Piper Plot - BMO Formation

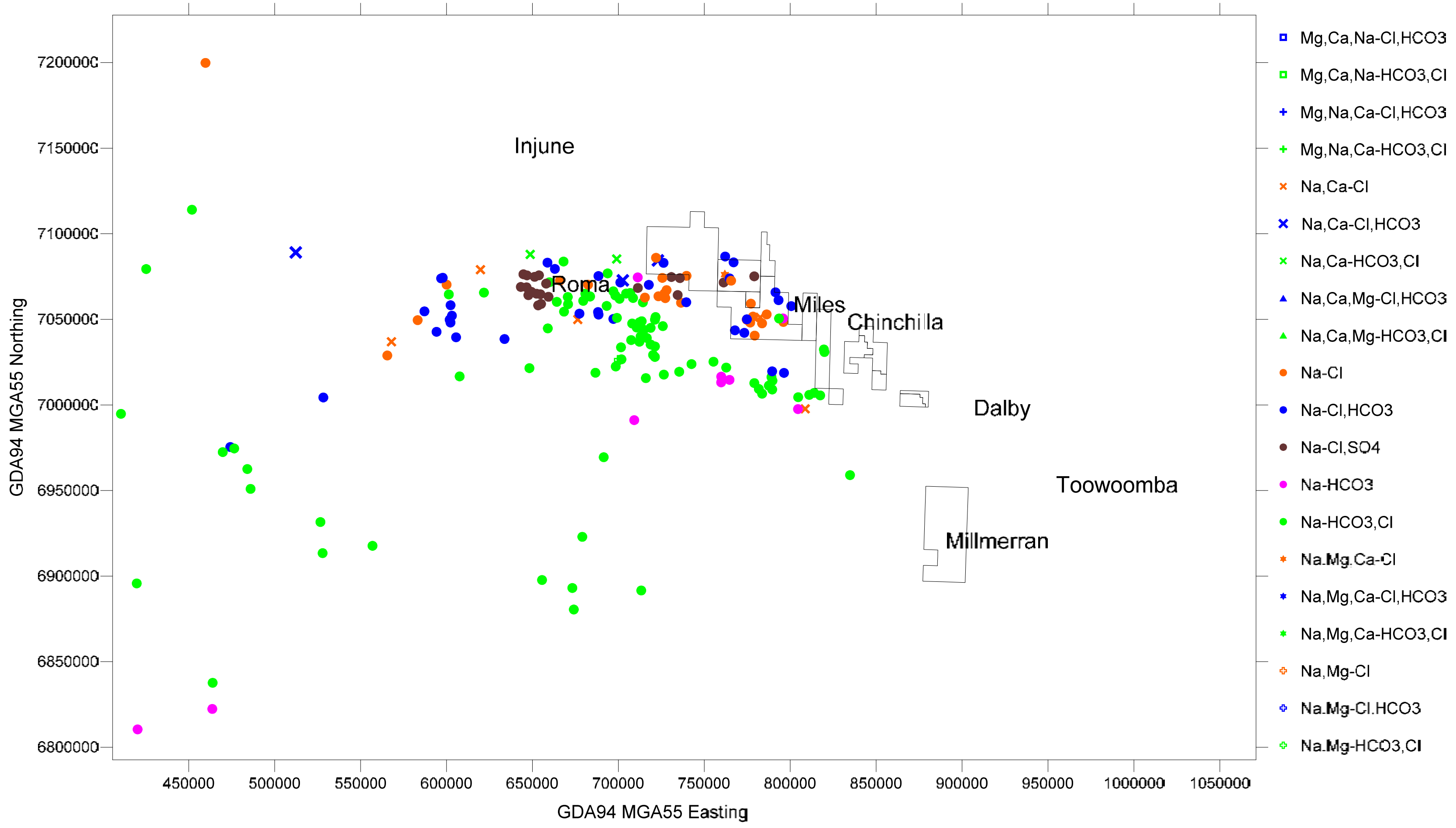

Figure 6 Hydrochemical Facies – BMO Formation

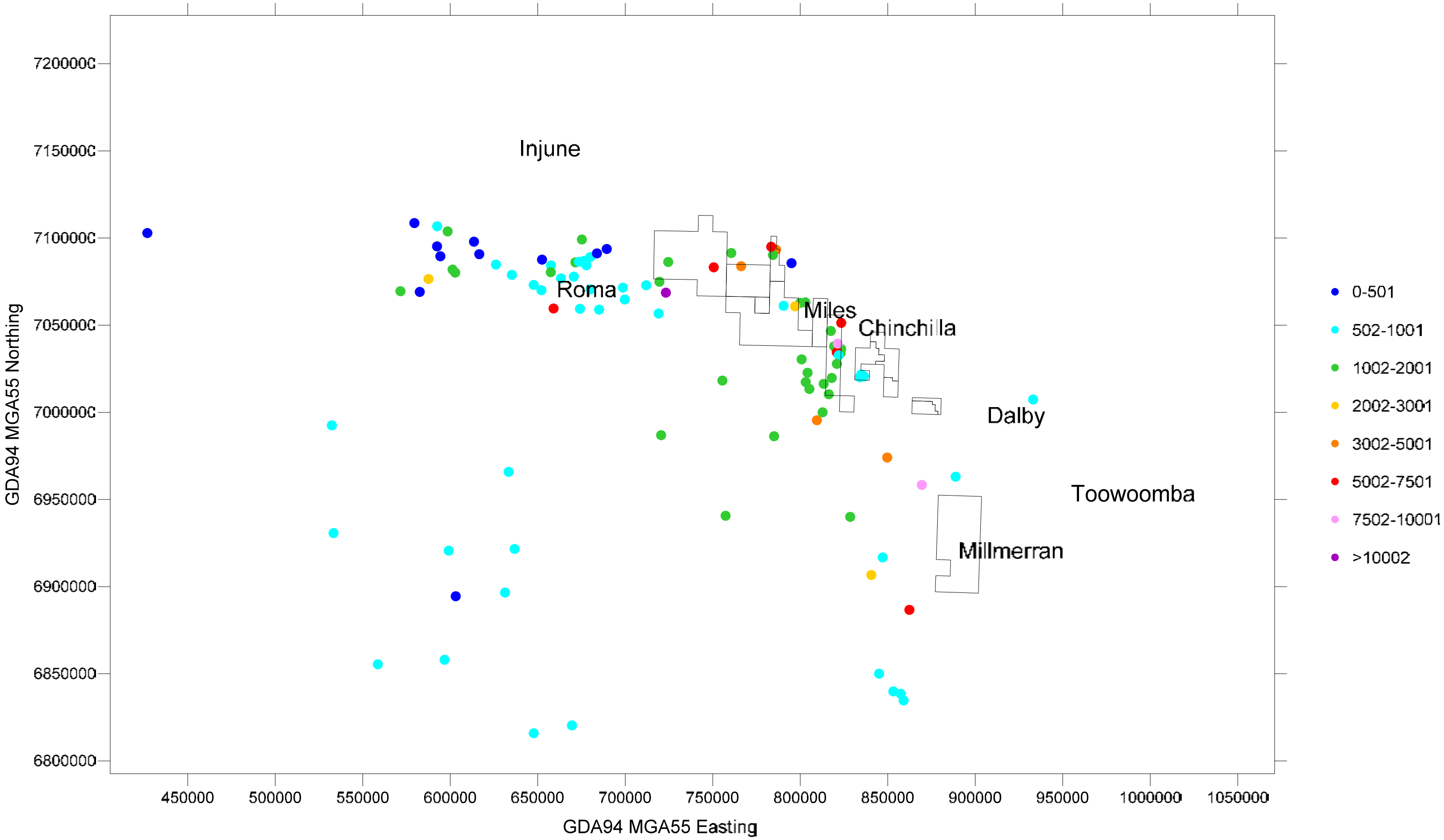

Figure 7 Regional Groundwater Salinity – Gubberamunda Sandstone

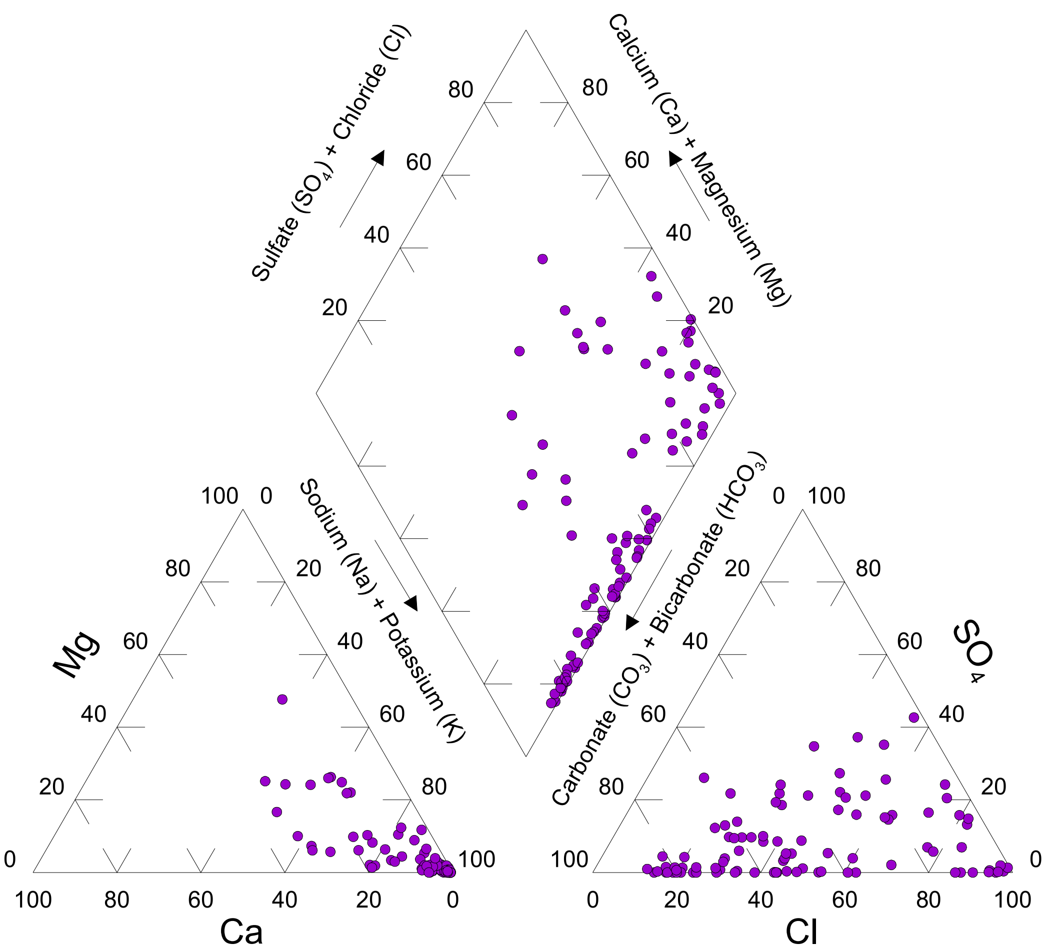

Figure 8 Piper Plot - Gubberamunda Sandstone

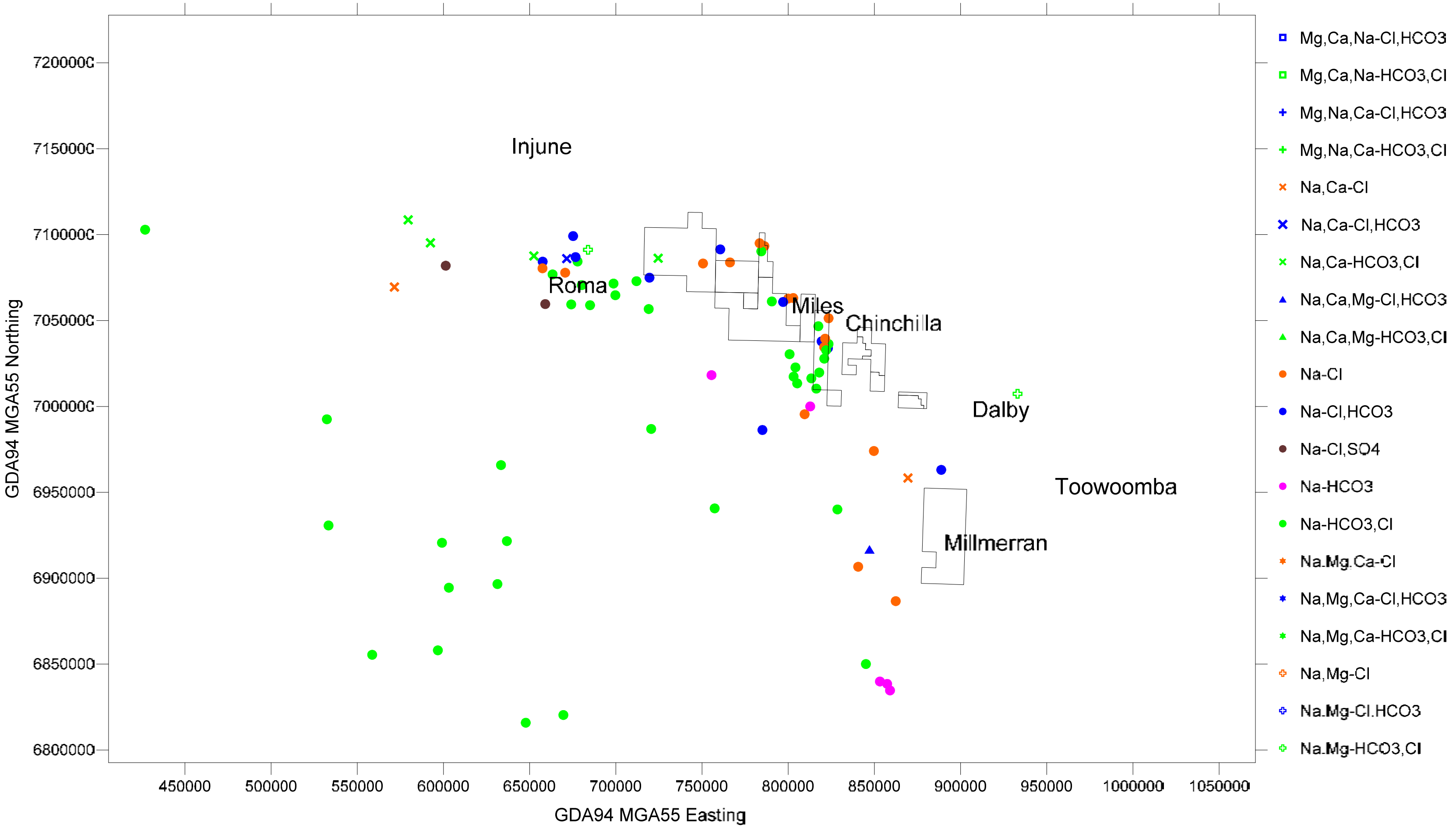

Figure 9 Hydrochemical Facies – Gubberamunda Sandstone

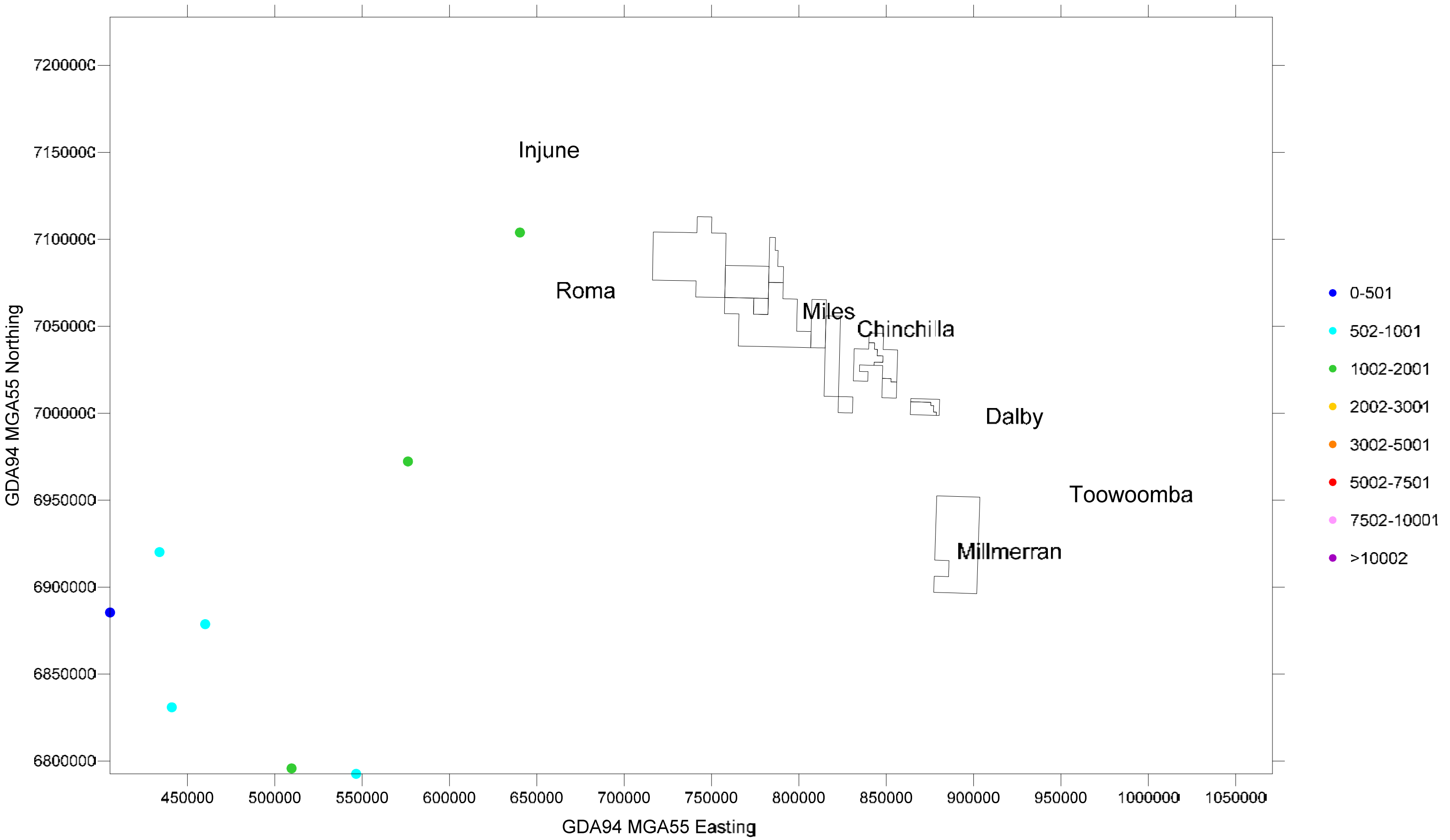

Figure 10 Regional Groundwater Salinity – Springbok Sandstone

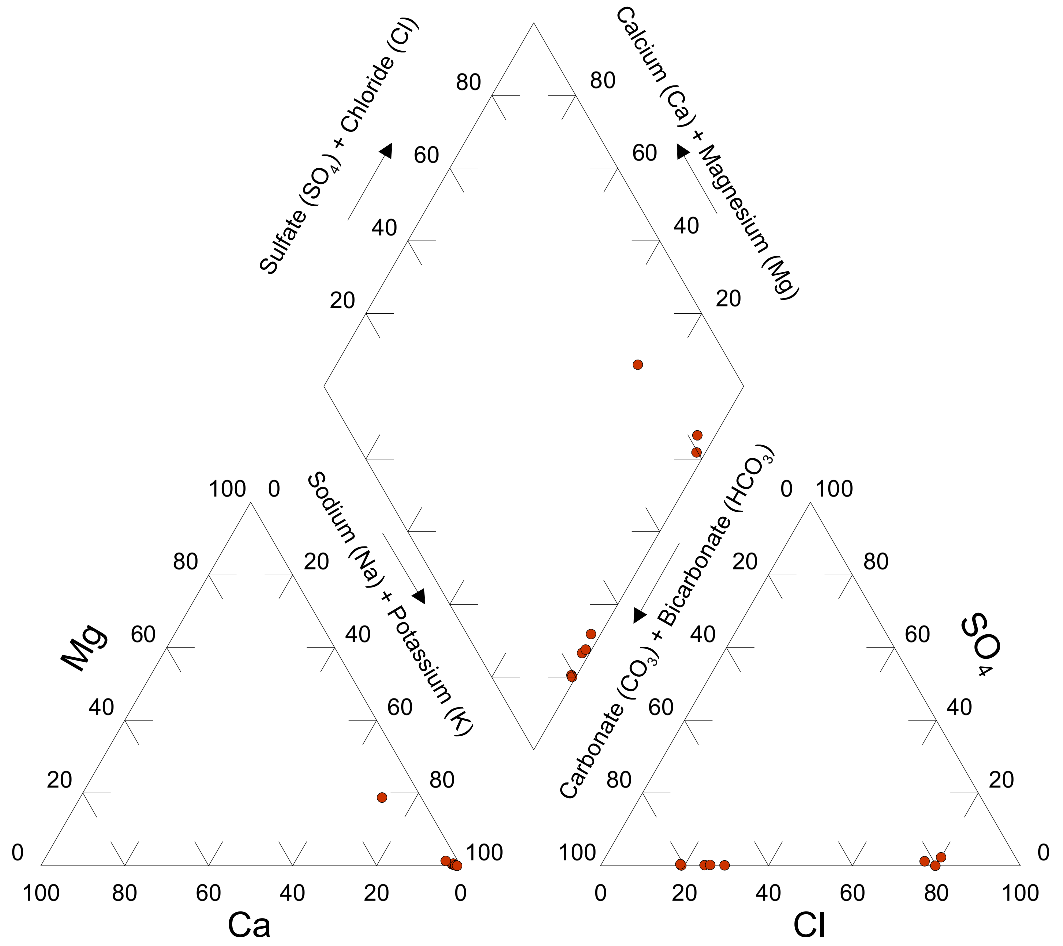

Figure 11 Piper Plot - Springbok Sandstone

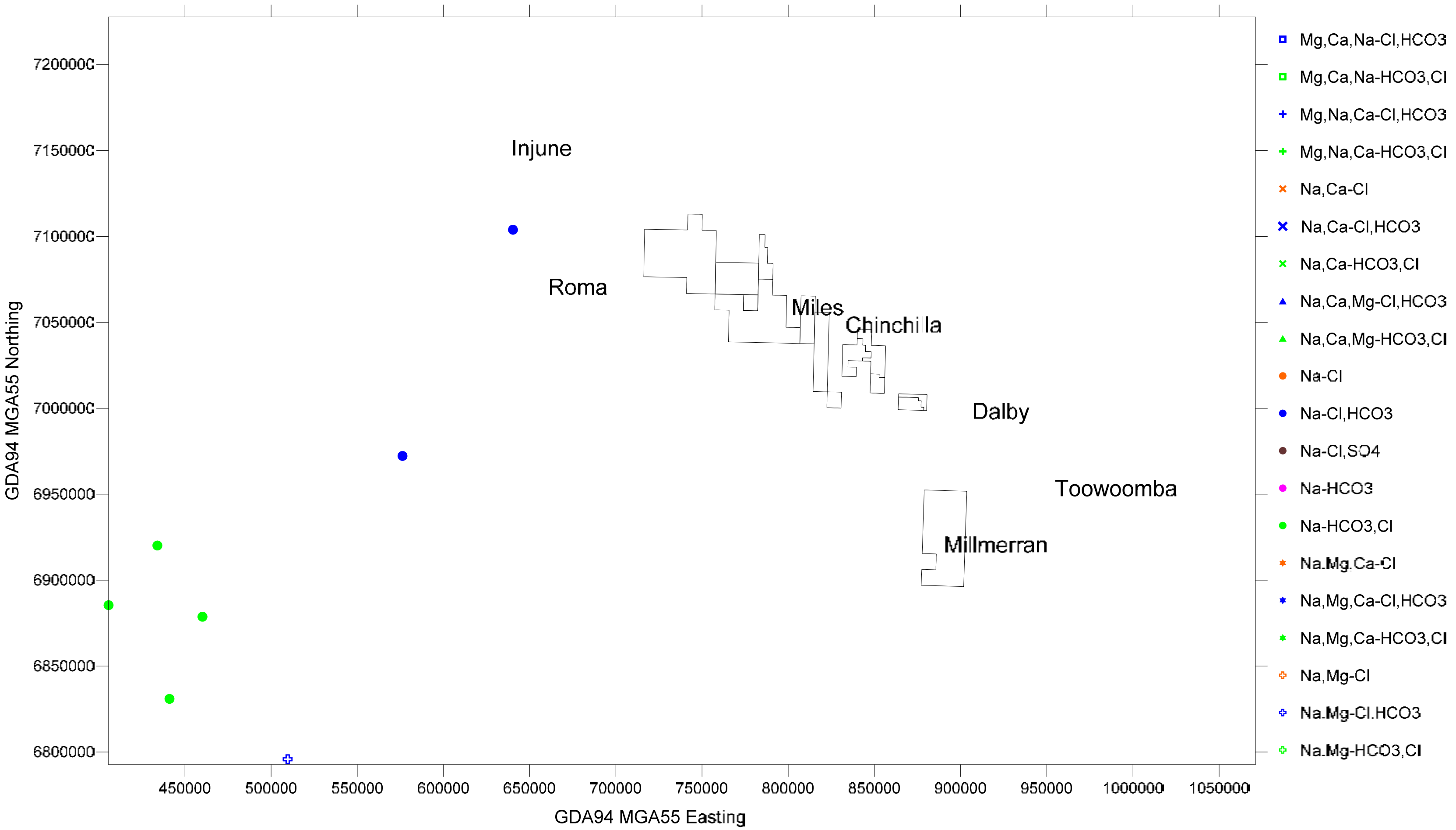

Figure 12 Hydrochemical Facies – Springbok Sandstone

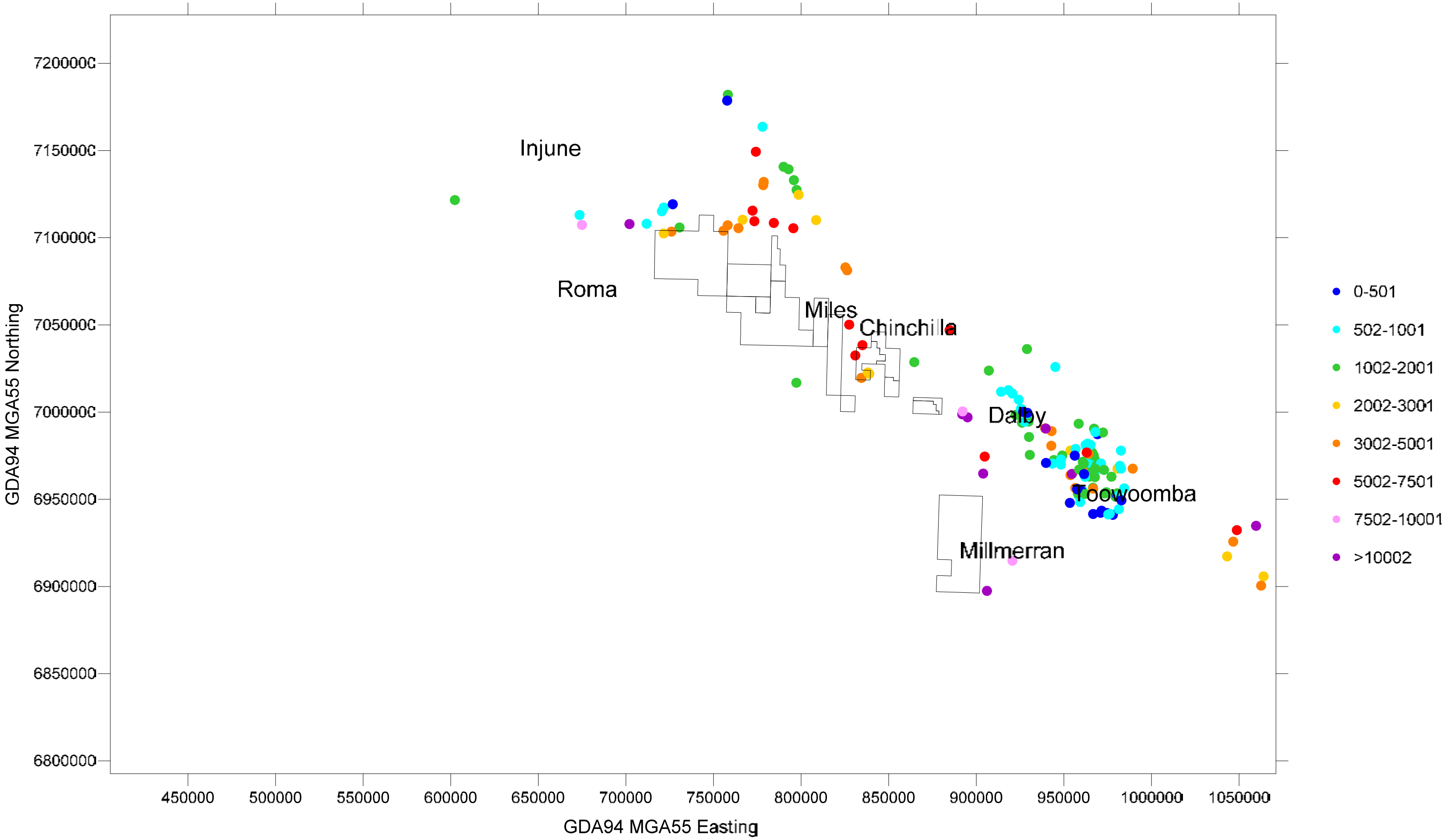

Figure 13 Regional Groundwater Salinity – Walloon Coal Measures

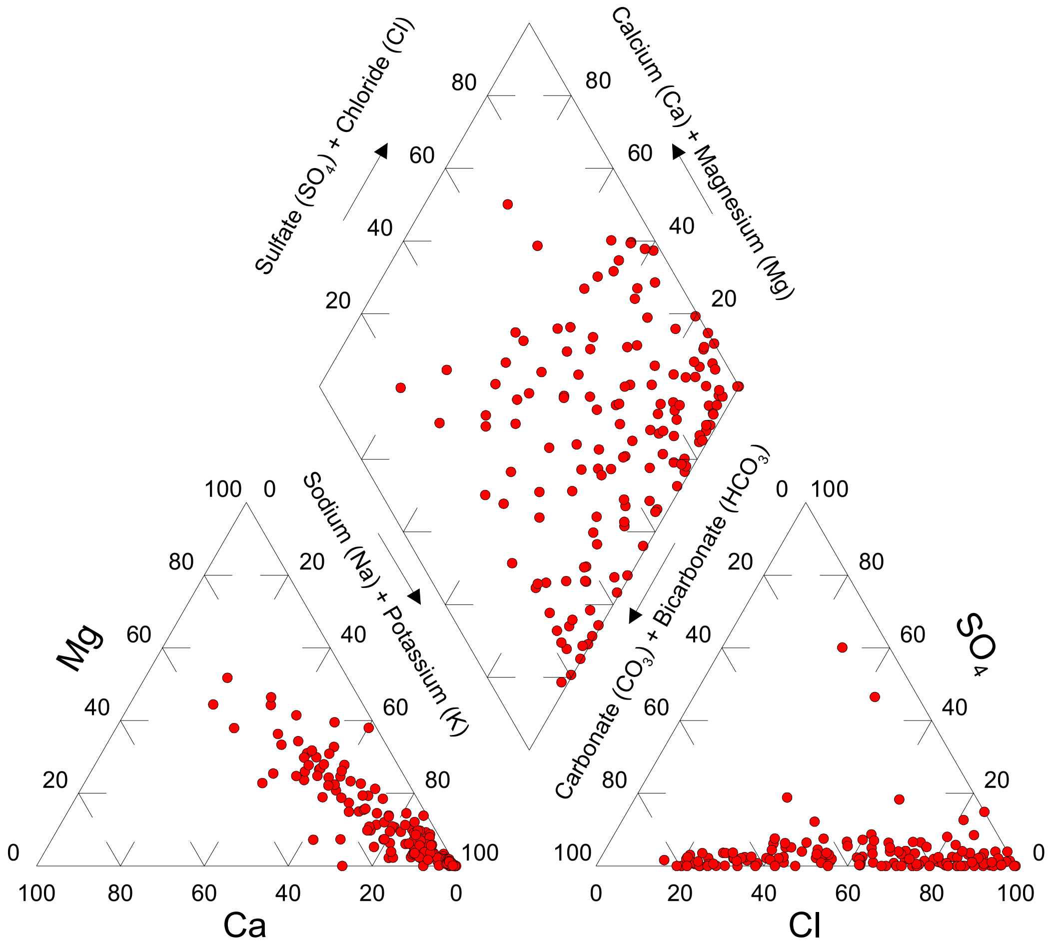

Figure 14 Piper Plot - Walloon Coal Measures

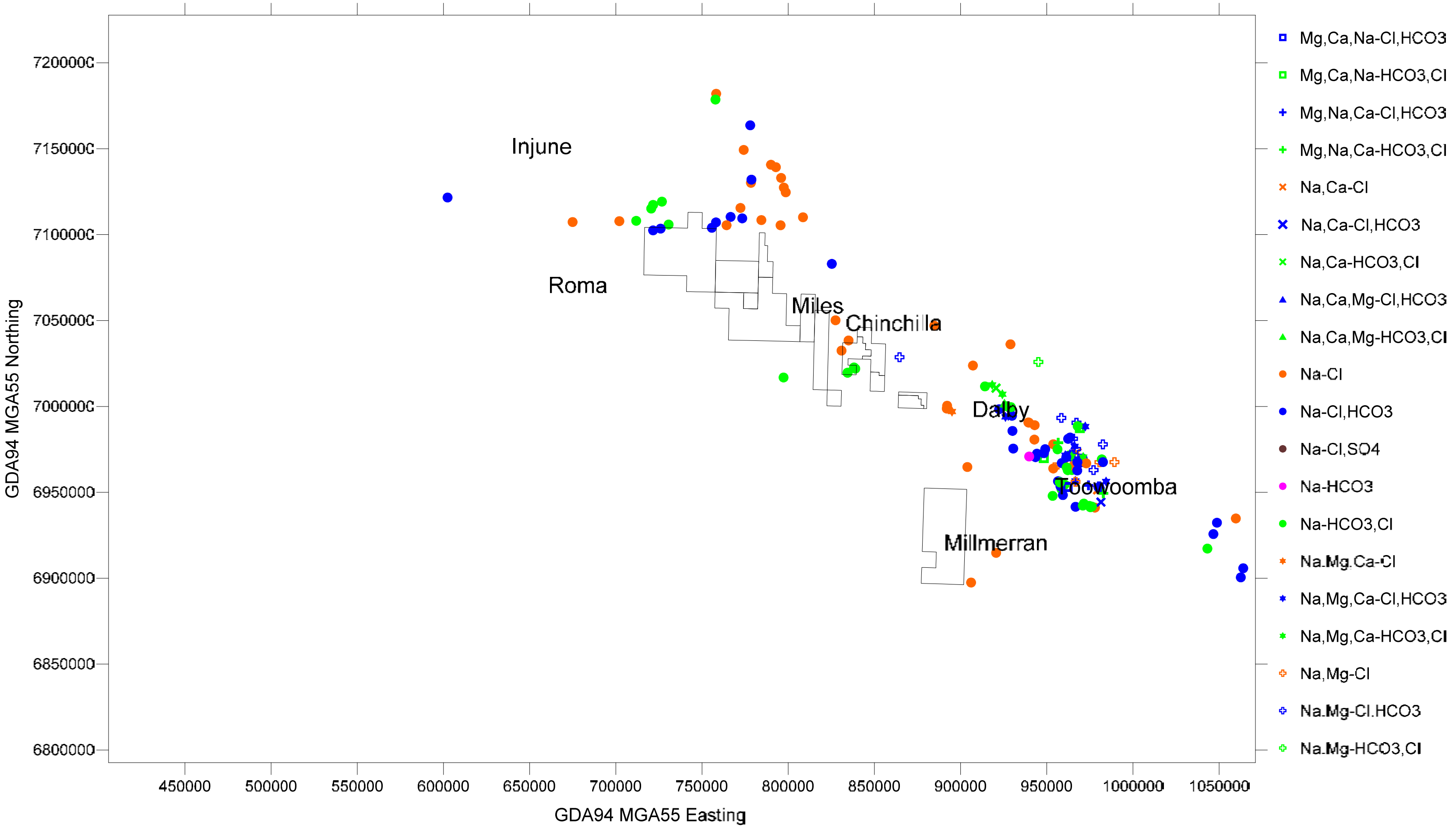

Figure 15 Hydrochemical Facies – Walloon Coal Measures

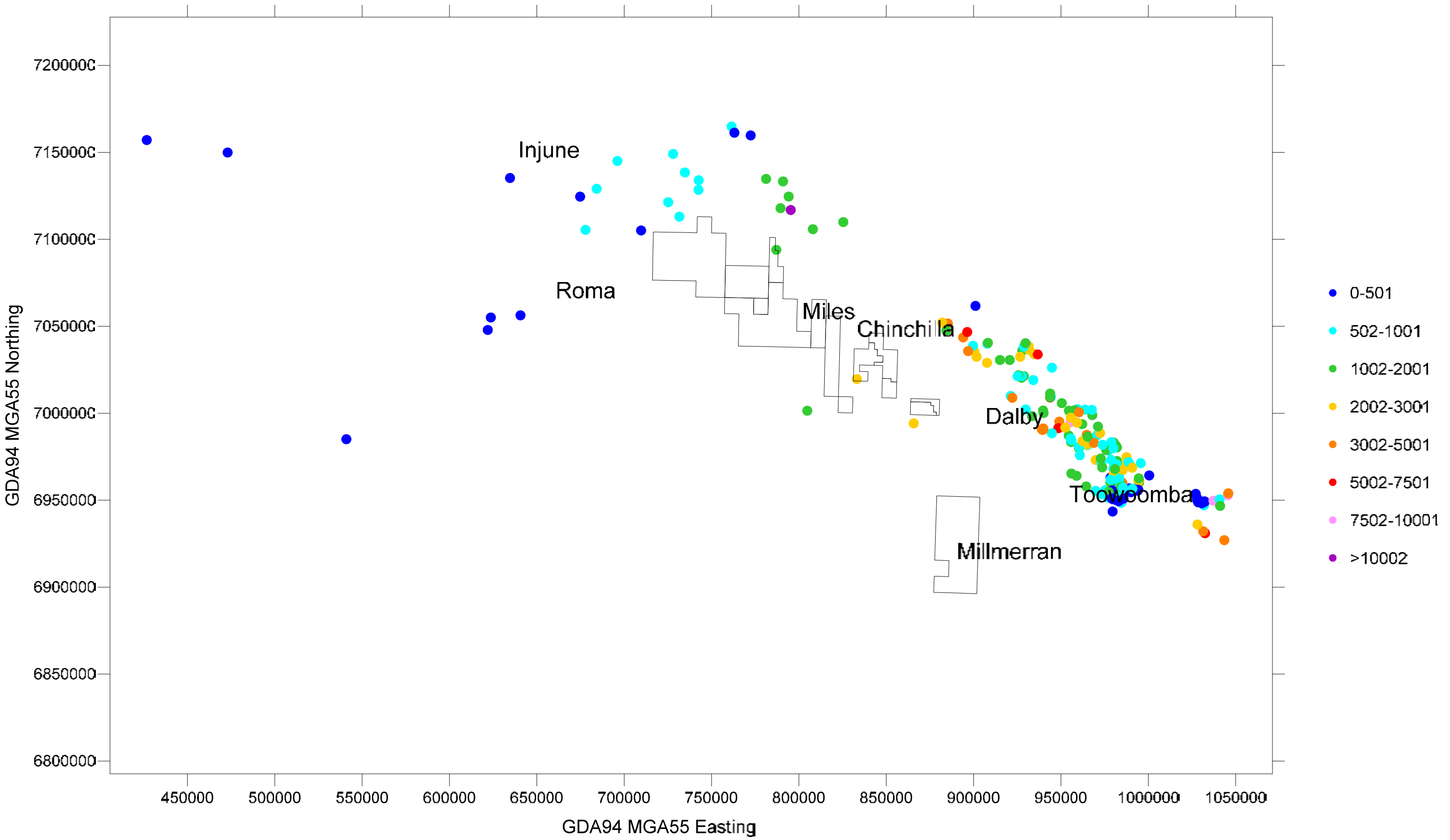

Figure 16 Regional Groundwater Salinity – Hutton Sandstone

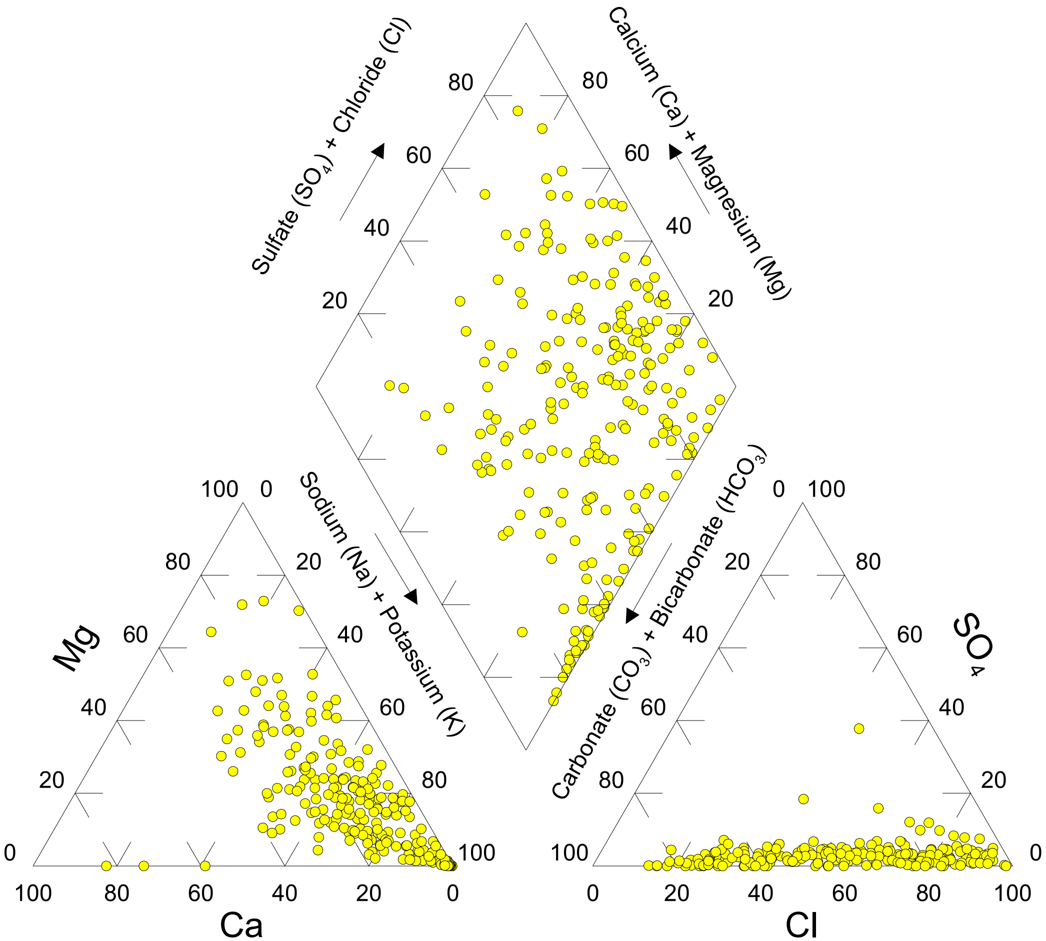

Figure 17 Piper Plot - Hutton Sandstone

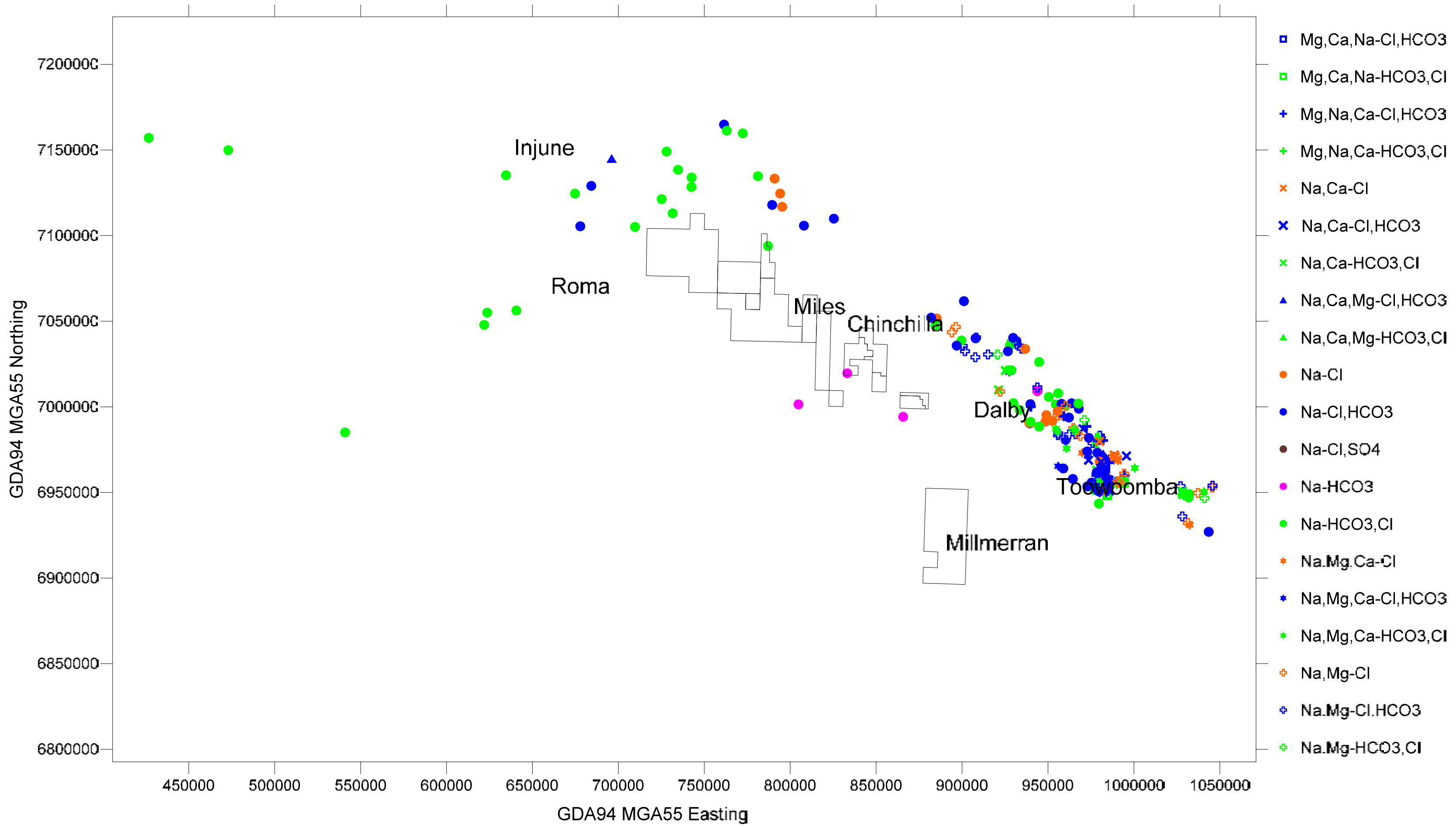

Figure 18 Hydrochemical Facies – Hutton Sandstone

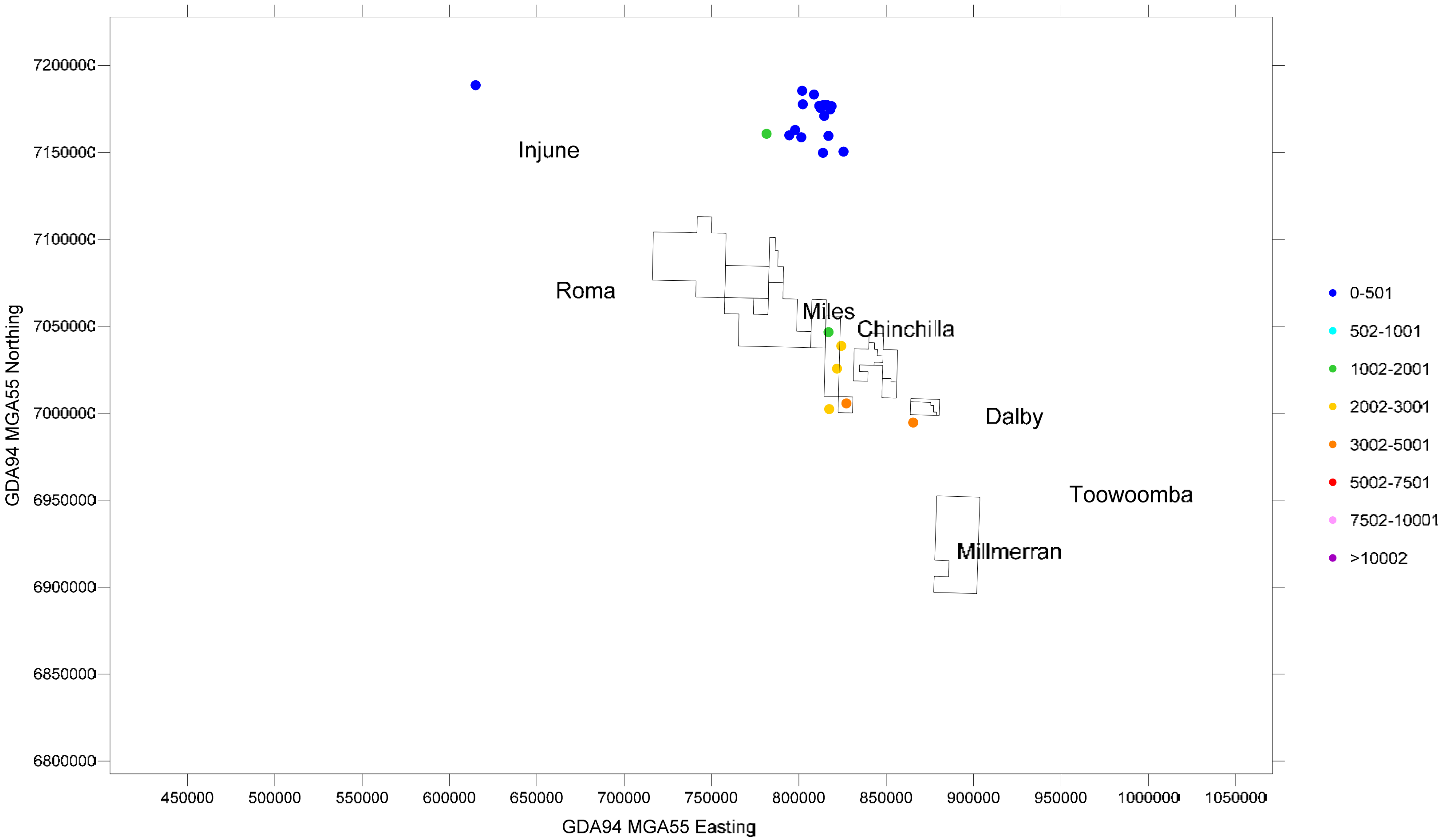

Figure 19 Regional Groundwater Salinity – Precipice Sandstone

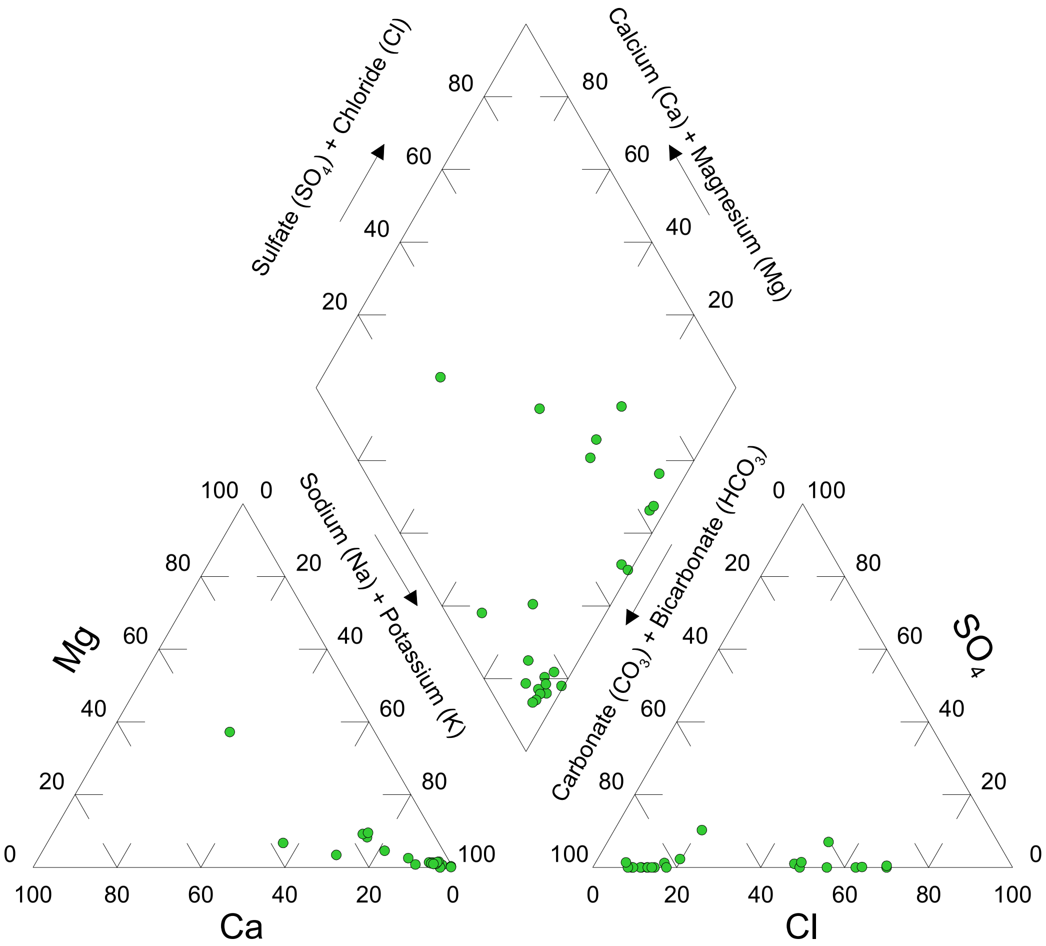

Figure 20 Piper Plot - Precipice Sandstone

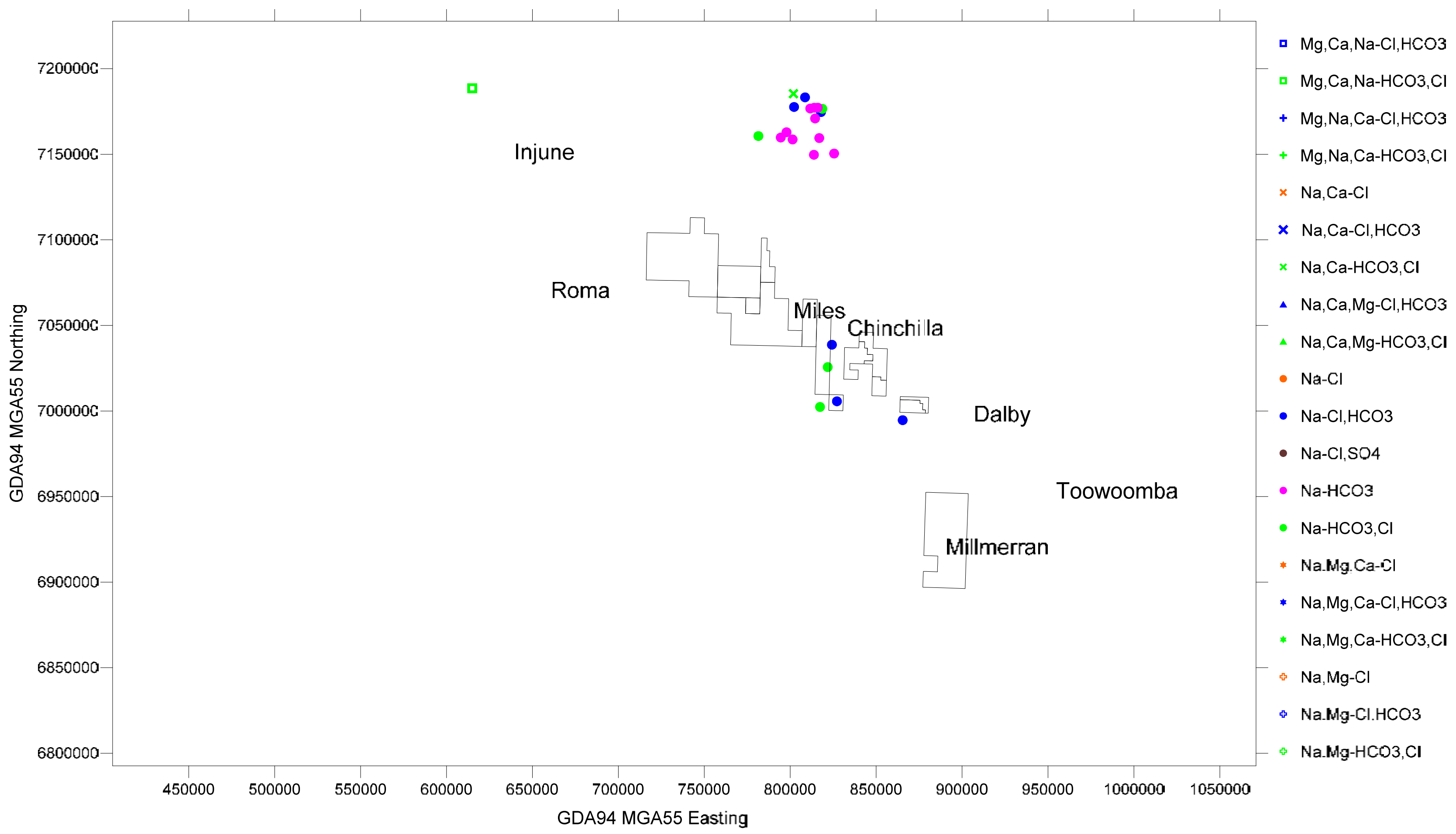

Figure 21 Hydrochemical Facies – Precipice Sandstone

Appendix 1 - Groundwater Quality Data

Table 3 Selected Groundwater Quality Data with Reference to Guidelines – Cainozioc Unit

Analyte	Unit	ANZECC 2000 Freshwater Guidelines (95% protection) (1)	NHMRC 2004 Drinking Water Guidelines (2)	ANZECC 2000 Irrigation Guidelines (LTV) (3)	ANZECC 2000 Irrigation Guidelines (STV) (3)	ANZECC 2000 Livestock Drinking Water Guidelines (Beef) (4)	ANZECC 2000 Livestock Drinking Water Guidelines (Sheep) (4)	Number of Samples	20th Percentile	80th Percentile	Medium (P50)	Standard Deviation
TDS	mg/L	-	500 (7)	Crop & Soil Dependent	Crop & Soil Dependent	4,000 (5) 5,000 (6)	5,000 (5) 10,000 (6)	1,489	469	1,810	891	2,332
pH		-	6.5-8.5	6-8.5	6-8.5	6-8.5	6-8.5	1,441	7.6	8.3	8.0	0.5
Sodium	mg/L	-	180 (7)	-	-	-	-	1,497	75	374	152	581
Chloride	mg/L	-	250 (7)	-	-	-	-	1,497	98	768	280	1,345
Sulphate	mg/L	-	500	-	-	2,000 (8)	2,000 (8)	1,349	7	54	15	158
Nitrate	mg/L	0.7	50	-	-	1,500 (8)	1,500 (8)	1,049	0.5	13.0	2.6	31.3
Iron	mg/L	-	0.3 (7)	0.2	10	-	-	718	0.010	0.050	0.020	0.902
Manganese	mg/L	1.9	0.5	0.2	10	-	-	658	0.010	0.050	0.020	0.874
Zinc	mg/L	0.008	3 (7)	2	5	20	20	214	0.010	0.030	0.010	0.364
Aluminium	mg/L	0.055	-	5	20	5	5	177	0.050	0.050	0.050	0.493
Boron	mg/L	0.37	0.004	0.5	-	5	5	226	0.030	0.180	0.070	0.125
Copper	mg/L	0.0014	2	0.2	5	1	0.4	201	0.020	0.030	0.030	0.031

Notes:
(1) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality - Trigger Levels for Freshwater Ecosystems – 95% protection level of species
(2) NHMRC 2004 Australian Drinking Water Guidelines
(3) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality - Short-term Trigger Values (STV) and Long-term Trigger Values (LTV) in Irrigation Water
(4) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality Livestock Drinking Water Guidelines (Beef Cattle and Sheep)
(5) Upper limit for no adverse affect to livestock. (6) Lower range at which point a loss of production and a decline in livestock condition and health would be expected.
(7) Aesthetic guideline value determined on the basis of taste. (8) Toxicity threshold.
Shaded cells indicate the concentration of the analyte exceeds one or more guideline value.

Table 4 Selected Groundwater Quality Data with Reference to Guidelines – BMO Formation

Analyte	Unit	ANZECC 2000 Freshwater Guidelines (95% protection) (1)	NHMRC 2004 Drinking Water Guidelines (2)	ANZECC 2000 Irrigation Guidelines (LTV) (3)	ANZECC 2000 Irrigation Guidelines (STV) (3)	ANZECC 2000 Livestock Drinking Water Guidelines (Beef) (4)	ANZECC 2000 Livestock Drinking Water Guidelines (Sheep) (4)	Number of Samples	20th Percentile	80th Percentile	Medium (P50)	Standard Deviation
TDS	mg/L	-	500 (7)	Crop & Soil Dependent	Crop & Soil Dependent	4,000 (5) 5,000 (6)	5,000 (5) 10,000 (6)	228	745	2,588	1,153	2,285
pH		-	6.5-8.5	6-8.5	6-8.5	6-8.5	6-8.5	138	7.7	8.6	8.3	0.6
Sodium	mg/L	-	180 (7)	-	-	-	-	229	271	884	429	651
Chloride	mg/L	-	250 (7)	-	-	-	-	229	135	1,005	260	1,274
Sulphate	mg/L	-	500	-	-	2,000 (8)	2,000 (8)	172	20	501	120	459
Nitrate	mg/L	0.7	50	-	-	1,500 (8)	1,500 (8)	57	0.5	3.0	1.3	4.8
Iron	mg/L	-	0.3 (7)	0.2	10	-	-	55	0.010	0.142	0.050	0.677
Manganese	mg/L	1.9	0.5	0.2	10	-	-	45	0.010	0.032	0.010	0.288
Zinc	mg/L	0.008	3 (7)	2	5	20	20	11	0.010	0.030	0.020	0.009
Aluminium	mg/L	0.055	-	5	20	5	5	9	0.020	0.050	0.050	0.017
Boron	mg/L	0.37	0.004	0.5	-	5	5	16	0.250	1.120	0.415	0.960
Copper	mg/L	0.0014	2	0.2	5	1	0.4	11	0.020	0.030	0.030	0.011

Notes:
(1) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality - Trigger Levels for Freshwater Ecosystems – 95% protection level of species
(2) NHMRC 2004 Australian Drinking Water Guidelines
(3) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality - Short-term Trigger Values (STV) and Long-term Trigger Values (LTV) in Irrigation Water
(4) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality Livestock Drinking Water Guidelines (Beef Cattle and Sheep)
(5) Upper limit for no adverse affect to livestock. (6) Lower range at which point a loss of production and a decline in livestock condition and health would be expected.
(7) Aesthetic guideline value determined on the basis of taste. (8) Toxicity threshold.
Shaded cells indicate the concentration of the analyte exceeds one or more guideline value
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Table 5 Selected Groundwater Quality Data with Reference to Guidelines – Gubberamunda Sandstone

Analyte	Unit	ANZECC 2000 Freshwater Guidelines (95% protection) (1)	NHMRC 2004 Drinking Water Guidelines (2)	ANZECC 2000 Irrigation Guidelines (LTV) (3)	ANZECC 2000 Irrigation Guidelines (STV) (3)	ANZECC 2000 Livestock Drinking Water Guidelines (Beef) (4)	ANZECC 2000 Livestock Drinking Water Guidelines (Sheep) (4)	Number of Samples	20th Percentile	80th Percentile	Medium (P50)	Standard Deviation
TDS	mg/L	-	500 (7)	Crop & Soil Dependent	Crop & Soil Dependent	4,000 (5) 5,000 (6)	5,000 (5) 10,000 (6)	100	590	1,646	980	1,974
pH		-	6.5-8.5	6-8.5	6-8.5	6-8.5	6-8.5	72	7.8	8.7	8.4	0.6
Sodium	mg/L	-	180 (7)	-	-	-	-	100	216	602	332	632
Chloride	mg/L	-	250 (7)	-	-	-	-	100	87	639	190	1,094
Sulphate	mg/L	-	500	-	-	2,000 (8)	2,000 (8)	79	7	127	42	363
Nitrate	mg/L	0.7	50	-	-	1,500 (8)	1,500 (8)	31	0.5	2.3	1.0	16.7
Iron	mg/L	-	0.3 (7)	0.2	10	-	-	25	0.010	0.112	0.020	0.081
Manganese	mg/L	1.9	0.5	0.2	10	-	-	21	0.010	0.030	0.010	0.068
Zinc	mg/L	0.008	3 (7)	2	5	20	20	6	0.010	0.018	0.010	0.069
Aluminium	mg/L	0.055	-	5	20	5	5	4	N/a	N/a	0.050	0.033
Boron	mg/L	0.37	0.004	0.5	-	5	5	9	0.206	1.310	0.240	1.321
Copper	mg/L	0.0014	2	0.2	5	1	0.4	5	N/a	N/a	0.010	0.011

Notes:
(1) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality - Trigger Levels for Freshwater Ecosystems – 95% protection level of species
(2) NHMRC 2004 Australian Drinking Water Guidelines
(3) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality - Short-term Trigger Values (STV) and Long-term Trigger Values (LTV) in Irrigation Water
(4) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality Livestock Drinking Water Guidelines (Beef Cattle and Sheep)
(5) Upper limit for no adverse affect to livestock. (6) Lower range at which point a loss of production and a decline in livestock condition and health would be expected.
(7) Aesthetic guideline value determined on the basis of taste. (8) Toxicity threshold.
Shaded cells indicate the concentration of the analyte exceeds one or more guideline value.

Table 6 Selected Groundwater Quality Data with Reference to Guidelines – Springbok Sandstone

Analyte	Unit	ANZECC 2000 Freshwater Guidelines (95% protection) (1)	NHMRC 2004 Drinking Water Guidelines (2)	ANZECC 2000 Irrigation Guidelines (LTV) (3)	ANZECC 2000 Irrigation Guidelines (STV) (3)	ANZECC 2000 Livestock Drinking Water Guidelines (Beef) (4)	ANZECC 2000 Livestock Drinking Water Guidelines (Sheep) (4)	Number of Samples	20th Percentile	80th Percentile	Medium (P50)	Standard Deviation
TDS	mg/L	-	500 (7)	Crop & Soil Dependent	Crop & Soil Dependent	4,000 (5) 5,000 (6)	5,000 (5) 10,000 (6)	8	533	1,615	575	598
pH		-	6.5-8.5	6-8.5	6-8.5	6-8.5	6-8.5	8	8.0	8.6	8.4	0.4
Sodium	mg/L	-	180 (7)	-	-	-	-	8	213	579	227	202
Chloride	mg/L	-	250 (7)	-	-	-	-	8	64	798	97	386
Sulphate	mg/L	-	500	-	-	2,000 (8)	2,000 (8)	7	1	16	1	12
Nitrate	mg/L	0.7	50	-	-	1,500 (8)	1,500 (8)	1	N/a	N/a	0.5	
Iron	mg/L	-	0.3 (7)	0.2	10	-	-	5	N/a	N/a	0.030	0.015
Manganese	mg/L	1.9	0.5	0.2	10	-	-	1	N/a	N/a	0.010	
Zinc	mg/L	0.008	3 (7)	2	5	20	20	3	N/a	N/a	0.010	0.006
Aluminium	mg/L	0.055	-	5	20	5	5	2	N/a	N/a	0.010	0.000
Boron	mg/L	0.37	0.004	0.5	-	5	5	4	N/a	N/a	0.325	0.239
Copper	mg/L	0.0014	2	0.2	5	1	0.4	4	N/a	N/a	0.010	0.000

Notes:
(1) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality - Trigger Levels for Freshwater Ecosystems – 95% protection level of species
(2) NHMRC 2004 Australian Drinking Water Guidelines
(3) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality - Short-term Trigger Values (STV) and Long-term Trigger Values (LTV) in Irrigation Water
(4) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality Livestock Drinking Water Guidelines (Beef Cattle and Sheep)
(5) Upper limit for no adverse affect to livestock. (6) Lower range at which point a loss of production and a decline in livestock condition and health would be expected.
(7) Aesthetic guideline value determined on the basis of taste. (8) Toxicity threshold.
Shaded cells indicate the concentration of the analyte exceeds one or more guideline value.

Table 7 Selected Groundwater Quality Data with Reference to Guidelines – Walloon Coal Measures

Analyte	Unit	ANZECC 2000 Freshwater Guidelines (95% protection) (1)	NHMRC 2004 Drinking Water Guidelines (2)	ANZECC 2000 Irrigation Guidelines (LTV) (3)	ANZECC 2000 Irrigation Guidelines (STV) (3)	ANZECC 2000 Livestock Drinking Water Guidelines (Beef) (4)	ANZECC 2000 Livestock Drinking Water Guidelines (Sheep) (4)	Number of Samples	20th Percentile	80th Percentile	Medium (P50)	Standard Deviation
TDS	mg/L	-	500 (7)	Crop & Soil Dependent	Crop & Soil Dependent	4,000 (5) 5,000 (6)	5,000 (5) 10,000 (6)	162	591	3,564	1,463	3,044
pH		-	6.5-8.5	6-8.5	6-8.5	6-8.5	6-8.5	147	7.7	8.4	8.1	0.6
Sodium	mg/L	-	180 (7)	-	-	-	-	164	165	1,202	426	1,043
Chloride	mg/L	-	250 (7)	-	-	-	-	164	153	1,717	499	1,834
Sulphate	mg/L	-	500	-	-	2,000 (8)	2,000 (8)	129	8	84	23	350
Nitrate	mg/L	0.7	50	-	-	1,500 (8)	1,500 (8)	78	0.5	5.8	1.4	14.6
Iron	mg/L	-	0.3 (7)	0.2	10	-	-	63	0.010	0.100	0.040	0.699
Manganese	mg/L	1.9	0.5	0.2	10	-	-	53	0.010	0.106	0.030	0.412
Zinc	mg/L	0.008	3 (7)	2	5	20	20	13	0.010	0.030	0.010	1.084
Aluminium	mg/L	0.055	-	5	20	5	5	10	0.050	0.776	0.050	2.645
Boron	mg/L	0.37	0.004	0.5	-	5	5	12	0.168	0.452	0.255	0.207
Copper	mg/L	0.0014	2	0.2	5	1	0.4	11	0.030	0.030	0.030	0.010

Notes:
(1) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality - Trigger Levels for Freshwater Ecosystems – 95% protection level of species
(2) NHMRC 2004 Australian Drinking Water Guidelines
(3) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality - Short-term Trigger Values (STV) and Long-term Trigger Values (LTV) in Irrigation Water
(4) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality Livestock Drinking Water Guidelines (Beef Cattle and Sheep)
(5) Upper limit for no adverse affect to livestock. (6) Lower range at which point a loss of production and a decline in livestock condition and health would be expected.
(7) Aesthetic guideline value determined on the basis of taste. (8) Toxicity threshold.
Shaded cells indicate the concentration of the analyte exceeds one or more guideline value.

Table 8 Selected Groundwater Quality Data with Reference to Guidelines – Hutton Sandstone

Analyte	Unit	ANZECC 2000 Freshwater Guidelines (95% protection) (1)	NHMRC 2004 Drinking Water Guidelines (2)	ANZECC 2000 Irrigation Guidelines (LTV) (3)	ANZECC 2000 Irrigation Guidelines (STV) (3)	ANZECC 2000 Livestock Drinking Water Guidelines (Beef) (4)	ANZECC 2000 Livestock Drinking Water Guidelines (Sheep) (4)	Number of Samples	20th Percentile	80th Percentile	Medium (P50)	Standard Deviation
TDS	mg/L	-	500 (7)	Crop & Soil Dependent	Crop & Soil Dependent	4,000 (5) 5,000 (6)	5,000 (5) 10,000 (6)	234	568	2,357	1,033	1,598
pH		-	6.5-8.5	6-8.5	6-8.5	6-8.5	6-8.5	229	7.5	8.3	7.9	0.6
Sodium	mg/L	-	180 (7)	-	-	-	-	237	150	662	272	477
Chloride	mg/L	-	250 (7)	-	-	-	-	237	140	1,102	340	943
Sulphate	mg/L	-	500	-	-	2,000 (8)	2,000 (8)	212	7	53	20	61
Nitrate	mg/L	0.7	50	-	-	1,500 (8)	1,500 (8)	126	0.5	5.9	1.4	81.5
Iron	mg/L	-	0.3 (7)	0.2	10	-	-	91	0.010	0.120	0.030	1.055
Manganese	mg/L	1.9	0.5	0.2	10	-	-	87	0.010	0.100	0.030	0.584
Zinc	mg/L	0.008	3 (7)	2	5	20	20	13	0.010	0.040	0.020	0.220
Aluminium	mg/L	0.055	-	5	20	5	5	10	0.028	0.050	0.050	0.016
Boron	mg/L	0.37	0.004	0.5	-	5	5	8	0.024	0.128	0.080	0.075
Copper	mg/L	0.0014	2	0.2	5	1	0.4	8	0.024	0.036	0.030	0.030

Notes:
(1) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality - Trigger Levels for Freshwater Ecosystems – 95% protection level of species
(2) NHMRC 2004 Australian Drinking Water Guidelines
(3) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality - Short-term Trigger Values (STV) and Long-term Trigger Values (LTV) in Irrigation Water
(4) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality Livestock Drinking Water Guidelines (Beef Cattle and Sheep)
(5) Upper limit for no adverse affect to livestock. (6) Lower range at which point a loss of production and a decline in livestock condition and health would be expected.
(7) Aesthetic guideline value determined on the basis of taste. (8) Toxicity threshold.
Shaded cells indicate the concentration of the analyte exceeds one or more guideline value.

Table 9 Selected Groundwater Quality Data with Reference to Guidelines – Precipice Sandstone

Analyte	Unit	ANZECC 2000 Freshwater Guidelines (95% protection) (1)	NHMRC 2004 Drinking Water Guidelines (2)	ANZECC 2000 Irrigation Guidelines (LTV) (3)	ANZECC 2000 Irrigation Guidelines (STV) (3)	ANZECC 2000 Livestock Drinking Water Guidelines (Beef) (4)	ANZECC 2000 Livestock Drinking Water Guidelines (Sheep) (4)	Number of Samples	20th Percentile	80th Percentile	Medium (P50)	Standard Deviation
TDS	mg/L	-	500 (7)	Crop & Soil Dependent	Crop & Soil Dependent	4,000 (5) 5,000 (6)	5,000 (5) 10,000 (6)	23	127	1,652	171	1,096
pH		-	6.5-8.5	6-8.5	6-8.5	6-8.5	6-8.5	29	6.8	7.8	7.4	0.7
Sodium	mg/L	-	180 (7)	-	-	-	-	29	31	633	50	430
Chloride	mg/L	-	250 (7)	-	-	-	-	29	9	148	15	413
Sulphate	mg/L	-	500	-	-	2,000 (8)	2,000 (8)	12	1	19	3	11
Nitrate	mg/L	0.7	50	-	-	1,500 (8)	1,500 (8)	6	0.5	0.5	0.5	0.1
Iron	mg/L	-	0.3 (7)	0.2	10	-	-	17	0.010	0.508	0.100	2.873
Manganese	mg/L	1.9	0.5	0.2	10	-	-	18	0.010	0.106	0.020	0.077
Zinc	mg/L	0.008	3 (7)	2	5	20	20	4	N/a	N/a	0.100	0.078
Aluminium	mg/L	0.055	-	5	20	5	5	1	N/a	N/a	0.050	
Boron	mg/L	0.37	0.004	0.5	-	5	5	5	N/a	N/a	0.500	1.115
Copper	mg/L	0.0014	2	0.2	5	1	0.4	5	N/a	N/a	0.010	0.011

Notes:
(1) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality - Trigger Levels for Freshwater Ecosystems – 95% protection level of species
(2) NHMRC 2004 Australian Drinking Water Guidelines
(3) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality - Short-term Trigger Values (STV) and Long-term Trigger Values (LTV) in Irrigation Water
(4) ANZECC 2000 Australian and New Zealand Guidelines for Fresh and Marine Water Quality Livestock Drinking Water Guidelines (Beef Cattle and Sheep)
(5) Upper limit for no adverse affect to livestock. (6) Lower range at which point a loss of production and a decline in livestock condition and health would be expected.
(7) Aesthetic guideline value determined on the basis of taste. (8) Toxicity threshold.
Shaded cells indicate the concentration of the analyte exceeds one or more guideline value.

Appendix E Abbreviations & Glossary

Abbreviations

Abbreviation	Meaning
API	American Petroleum Institute units
BMO	Bungil Formation, Mooga Sandstone and Orallo Formation
BOM	Bureau of Meteorology
BOP	Blow out protector
CBL	Cement bond log
CSG	coal seam gas
Cl	chlorine
CMP	Construction management plan
CO_2	Carbon dioxide
CST	Cement stage tool
DEM	digital elevation model
DERM	department of environment and resource management
DST	drill stem test
ECP	External casing packer
ENSO	El Niño Southern Oscillation
EPA	Environmental Protection Agency
EPP	Environmental Protection Policy
FEFLOW	Finite Element subsurface FLOW system
GAB	Great Artesian Basin
GABCC	Great Artesian Basin Coordinating Committee
GWBD	Groundwater bore database
GDE	Groundwater dependent ecosystem
GMA	Groundwater management area
GMF	Groundwater management/monitoring framework
GMU	Groundwater management unit
HCO_3	Bicarbonate
HDD	horizontal directional drilling
HDPE	high-density polyethylene
IPO	Interdecadal Pacific Oscillation

Abbreviation	Meaning
K	Hydraulic conductivity
km	kilometer
LCL	Lower Control Limit
MGA	Map Grid Australia
LNG	liquefied natural gas
mAHD	meters above australian height datum
Mbgl	meters below ground level
mD	millidarcy
m/day	meters per day
mg/L	milligrams per litre
ML	megalitres
ML/d	megalitres per day
Na	Sodium
NATA	National Association of Testing Authorities
NRME	Natural Resources Mines and Energy
TDS	total dissolved solids.
RO	Reverse osmosis
ROW	Right of way
RWL	reduced water level
RO	reverse osmosis
SCADA	Supervisory Control and Data Acquisition
ToR	terms of reference
UCL	Upper Control Limit
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WERD	Water Entitlements Register Database
WTF	Water treatment facility
µS/cm	microsiemens per centimetre

Glossary

Term	Description
AHD	Australian Height Datum
Alluvial	Applying to the environments, actions, and products of rivers or streams.
Alluvium	Clay or silt or gravel (sediment) carried by rivers or streams and deposited where the stream slows down.
Analyte	Substance or chemical constituent that is determined in an analytical procedure,
Anisotropy	The property of being anisotropic; having a different value when measured in different directions.
Anticline	A fold in which the older rocks occupy the core
Aquiclude	Impermeable beds of geologic material that hinder or prevent groundwater movement. Theoretical only as all material have some intrinsic permeability
Aquifer	A water-saturated geologic unit that is capable of transmitting significant or usable quantities of groundwater under ordinary hydraulic gradients.
Aquitard	A water-saturated sediment or rock whose permeability is so low it cannot transmit any useful amount of water. An aquitard allows some measure of leakage between the aquifer interval it separates.
Artesian	A condition which applies to aquifers which are confined by layers of low-permeability, and where the hydraulic head in the aquifer is higher than the overlying ground surface. Wells penetrating such aquifers may result in groundwater flowing at the surface without pumping
Associated CSG water	Water extracted from the coal seams to allow depressurisation, gas desorption and gas extraction
Baseflow	Amount of groundwater flowing into a river.
Basin	A topographic depression containing, or capable of containing, sediment.
Bedrock	The solid rock that underlies unconsolidated surficial sediments.
Bore/borehole	A hole drilled into the ground for exploratory purposes. See "wellbore"
Boundary Condition	Specific condition at the edge or surface of a system.
Boggomoss	
Brackish Water	Water that contains relatively low concentrations of soluble salts. Brackish water is saltier than fresh water, but not as salty as salt water.
Bulls eye	Center of a target of concentric circles
Buried Valley	An eroded depression in the sol or bedrock within which sediments significant permeability (e.g. sand) or low permeability (e.g. till, clay) accumulate.
Cainozoic	The period in geologic time between 65 million years ago and the present
Catchment	The area of land drained by a creek or river system, or a place set aside for

Term	Description
	collecting water which runs off the surface of the land. Catchments provide the source of water for the dams and reservoirs in which our drinking water is collected.
Channel	An eroded depression in the soil or bedrock surface within which alluvial deposits accumulate (i.e. gravel, sands, silt, clay).
Climate Change	Any change in global temperatures and precipitation over time due to natural variability or to human activity
Climate Variability	Deviations of climate statistics over a given period of time (such as a specific month, season or year) from the long-term climate statistics relating to the corresponding calendar period
Coal Seam	A layer, vein, or deposit of coal.
Confined Aquifer	Exists where the groundwater is bounded between layers of impermeable substances like clay or dense rock. When tapped by a well, water in confined aquifers is forced up, sometimes above the soil surface. This is how a flowing artesian well is formed.
Confining Layer	Geologic material with little permeability or hydraulic conductivity. Water does not pass through this layer or the rate of movement is extremely slow.
Consolidated Rock	Tightly bound geologic formation composed of sandstone, limestone, granite, or other rock.
Contaminant	A substance that is present in an environmental medium in excess of natural baseline concentration.
Cretaceous	The period in geologic time between 140 and 65 million years ago; also, the corresponding system of rocks deposited during that time range.
Cuesta	A ridge with a steep face on one side and a gentle slope on the other.
Darcy's law	A groundwater movement equation formulated by Henry Darcy during the mid-1800s based on experiments on the flow of water through beds of sand. Darcy's Law forms the scientific basis of fluid permeability used in earth science.
Datalogger	An electronic device that records data over time or in relation to location either with a built in instrument or sensor or via external instruments and sensors
Depletion	The loss of water from surface water reservoirs or groundwater aquifers at a rate greater than that of recharge.
Depressurization	The lowering of the groundwater piezometric surface over the desired area.
Devonian	The period in geologic time between 408.5 and 362.5 million years ago; also, the corresponding system of rocks deposited during that time range.
Discharge	An outflow of water from a stream, pipe, groundwater aquifer, or watershed; the opposite of recharge.
Discharge Area	The area or zone where groundwater emerges from the aquifer. The outflow maybe into a stream, lake, spring, wetland, etc.
Dissolved Solids	Minerals and organic matter dissolved in water

Term	Description
Drawdown	A lowering of the groundwater level caused by pumping.
Drift Deposits	Any sediment laid down by, or in association with, the activity of glaciers and ice sheets.
EC	Electrical Conductivity. Usually measure in siemens per unit length (e.g. millisiemens per centimeter)
Effective Porosity	The percentage of the total volume of a given mass of soil or rock that consists of interconnected void spaces.
Ephemeral River	Rivers are generally storm-event driven and flow occurs less than 20% of the time; these rivers have limited baseflow component with no groundwater discharge during the no flow period.
Erosion	The process by which material, such as rock or soil, is worn away or removed by wind or water.
Evapotranspiration	The process by which water is discharged to the atmosphere as a result of evaporation from the soil and surface-water bodies and transpiration by plants. Transpiration is the process by which water passes through living organisms, primarily plants, into the atmosphere.
Facies	Features of a rock type or water type from which its origins can be inferred
Fault	A crack in the earth's crust resulting from the displacement of one side with respect to the other.
Fault Line	Line determined by the intersection of a geological fault and the earth's surface.
FEFLOW	3D finite element groundwater modeling software
Field	A geographical area under which an oil or gas reservoir lies.
Filtering	The soil's ability to attenuate substances by retaining chemicals or dissolved substances on the soil particle surface, transforming chemicals through microbial biological processing, retarding movement, and capturing solid particles; also the use of an artificial filter to remove particulate matter from a water sample prior to chemical analysis
Filtration	Separation of a solid and a liquid by using a porous substance that only lets the liquid pass through.
Floodplain	An area of land periodically indundated by floodwater
Flow Rate	The time required for a volume of groundwater to move between points. Typically groundwater moves very slowly—sometimes as little as millimeters per year.
Fluvial	Material deposited by moving water.
Fluvial Deposits	Particles of minerals or rocks which are transported by a river and deposited along its valley.
Fluvial Deposits	All material, past and present, deposited by flowing water.
Flux	The rate of flow of energy or particles across a given surface.

Term	Description
Formation	A geologic unit of distinct rock types that is large enough in scale to be mappable over a region.
Fresh Water	Water that is not salty, especially when considered as a natural resource.
GABHYD	Groundwater flow model of the Great Artesian Basin
GABLOG	A project undertaken to geophsycially log existing water bores in the Great Artesian Basin
Gamma Log	Gamma logs record the level of natural occurring gamma ray emissions from rocks around boreholes. The gamma ray signal is comprised of gamma ray emissions from at different energy levels from the radioactive isotopes of the elements potassium (^{40}K), Thorium (^{232}Th) and Uranium (^{238}U) and the daughter products in the decay of each series. In sedimentary rock sequences, relatively high natural gamma counts are recorded in shales and other clay rich sediment (due to the affinity of clay minerals for potassium) and relatively low counts are recorded in clean quartz sandstones and limestones.
Gaining Stream	A stream in which groundwater discharges contribute significantly to the streamflow volume. The same stream could be both a gaining stream and a losing stream, depending on the conditions.
Grading	The process of levelling off to a smooth horizontal or sloping surface.
Groundwater	All the water contained in the pores/voids within unconsolidated sediments or consolidated rocks (i.e. bedrock).
Group	A grouping of geological or hydrogeological formations
Half graben	A topographic depression that forms as a result of movement on a fault plane
Hydraulic Conductivity	The ease with which water moves through soil or rock. A coefficient (“K”) depends on the physical properties of formation and fluid. “K” is the rate of flow per unit cross-sectional area under the influence of a unit gradient, and has the dimension of $length^3/length^2$ x time or length/time (e.g. m/s).
Hydraulic Gradient	The change in hydraulic head or water level over a distance. Usually expressed in meters/meter. For example, a hydraulic gradient of 0.01 indicates a one-metre drop in water level over a distance of 100 m. The hydraulic gradient is the driving force that causes groundwater to flow.
Hydraulic Head	A measure of the groundwater pressure in an aquifer. Hydraulic head is determined from water level measurements in wells.
Hydrocarbons	An organic compound containing only carbon and hydrogen.
Hydrochemical Type	The definition of a chemical composition of groundwater based on the relative percentages of major cation and anion concentrations.
Hydrogeology	The science that relates geology, fluid movement (i.e. water) and geochemistry to understand water residing under the earth’s surface. Groundwater as used here includes all water in the zone of saturation beneath the earth’s surface, except water chemically combined in minerals.

Term	Description
Hydrological Cycle	The paths water takes through its various states--vapor, liquid, solid--as it moves throughout the oceans, atmosphere, groundwater, streams, etc.
Hydrological Integrity	The ability of a landscape to maintain proper drainage and groundwater-surface water interaction to support healthy ecological functioning and aquatic habitat.
Hydrostatic Head	The force (pressure) exerted by a body of fluid at rest.
Hydrostratigraphic Unit	Geological units that are not solely based on lithologic characteristics but also include characteristics related to water movement, occurrence and storage
Impermeable Layer	A layer of material (such as clay) in an aquifer through which water does not pass.
Ion diffusion	A process whereby ions in groundwater are transported in response to differences in chemical concentration. Movement is from high concentration to low concentration.
Ion-exchange	A chemical process in which cations of like charge are exchanged equally between a sediment and the groundwater.
Indicators	Anything that is used to measure the condition of something of interest. Indicators are often used as variables in the modelling of changes in complex environmental systems.
Infiltration	Flow of water from the land surface into the subsurface. Infiltration is the main factor in recharge of groundwater reserves.
Instream Flow Needs (IFN)	The amount of water required in a river to sustain a healthy aquatic ecosystem, and/or meet human needs such as recreation, navigation, waste assimilation or aesthetics
Interfluve	A ridge or area of land dividing two river valleys
Irrigation	The controlled application of water to cropland, hay fields, and/or pasture to supplement that supplied by nature.
Isotropy	The condition in which the properties of a system or a parameter do not vary with direction.
Isopach	A line on a map representing points of equal thickness
Jurassic	The period in geologic time between 208 and 145.6 million years ago; also, the corresponding system of rocks deposited during that time range.
Kriging	A group of geostatistical techniques to interpolate the value of a random field (e.g., the elevation, z, of the landscape as a function of the geographic location) at an unobserved location from observations of its value at nearby locations.
Lacustrine Deposits	Sedimentary material laid down in a lake environment.
Lagoon	A body of water enclosed by a barrier, such as a water storage pond
Leachate	Liquids that have percolated through a soil and that carry substances in solution or suspension.
Limestone	A sedimentary rock rich in calcium carbonate.

Term	Description
Lithic	Formed of rock
Lithology	The systematic description of sediment and rocks, in terms of composition, texture and internal structure
Losing stream	A stream that is losing water to (or recharging) the groundwater system. The same stream could be both a gaining stream and a losing stream, depending on the conditions.
Mesa	An elevated area of land with a flat top and sides that are usually steep cliffs. Spanish for “table”
Mesozoic	The middle of the three Phanerozoic eras; it lasted from 245 Ma to 65 Ma
Metamorphic Rock	A rock derived from pre-existing rocks by way of mineralogical, chemical, or structural changes. These changes come in response to marked changes in temperature, pressure, shearing stress, or the chemical environment.
Meteoric Water	Water derived from the earth's atmosphere.
Monitoring Well	A constructed controlled point of access to an aquifer which allows groundwater observations. Small diameter observation wells are often called piezometers.
Mound Spring	Mound springs are geomorphic formations raised above the surrounding land surface formed by a deposit of minerals and sediment brought up from artesian aquifers or confining beds by water at certain natural discharge points in the Great Artesian Basin. Other spring systems not raised above the surrounding land surface also occur throughout the Basin.
Nutrients	Any substance that promotes growth with living organisms. The term is generally applied to nitrogen and phosphorus in wastewater, but is also applied to other essential and trace elements.
Orogenic	The process of mountain forming
Overburden	Any loose material which overlies bedrock (often used as a synonym for Quaternary sediments and/or surficial deposits) or any barren material, consolidated or loose, that overlies an ore body.
Overwithdrawal	Withdrawal (removal) of groundwater over a period of time that exceeds the recharge rate of the supply aquifer. Also referred to as mining the aquifer.
Oxidation	A chemical reaction in which ions are transferring electrons, to increase positive valence.
Palaeochannel	A buried stream channel
Paludal	Pertaining to a depositional environment or organisms from a marsh. It also refers to the type of environment in which palustrine sediments can accumulate.
Peat	Unconsolidated soil material consisting largely of undecomposed, or only slightly decomposed, organic matter.
Pelagic	The portion of a lake that is not littoral and comprises those areas offshore more than 3 m deep.

Term	Description
Perched Aquifer	Localized zone of saturation above the main water table created by an underlying layer of impermeable material
Percolation	The movement of water through the openings in rock or soil.
Permeability	A physical property of the porous medium. Has dimensions Length^2. When measured in cm^2, the value of permeability is very small, therefore more practical units are commonly used - darcy (D) or millidarcy (mD). One darcy is equivalent to 9.86923×10^{-9} cm².
Permeability	A measure of the ability of a porous medium to transmit a fluid (any fluid). Similar to hydraulic conductivity that describes the ability of a porous medium to transmit water specifically.
pH	The logarithm of the reciprocal of hydrogen-ion concentration in gram atoms per litre; provides a measure on a scale from 0 to 14 of the acidity or alkalinity of a solution (where 7 is neutral and greater than 7 is more basic and less than 7 is more acidic).
Phenols	Oxygen –substituted benzenes, commonly derived from the degradation of natural organic matter, the distillation of wood and coal, and the refining of oil. This particular class of organic compounds is ubiquitous in nature, and is common in groundwater.
Piezometeric Head	The elevation to which water will rise in a piezometer connected to a point in an aquifer. Differences in piezometric head determine the hydraulic gradient and therefore the direction of groundwater flow.
Plug and abandon	To fill a depleted well or dry hole completely with cement or with impermeable plugs (cement or other) inserted at appropriate depths to inhibit movement of water or gas between geological formations. Surface equipment is also removed from the wellhead.
Plume	In groundwater a plume is an underground pattern of contaminant concentrations created by the movement of groundwater beneath a contaminant source. Contaminants spread mostly laterally in the direction of groundwater movement. The source site has the highest concentration, and the concentration decreases away from the source.
Pollution	An alteration in the character or quality of the environment, or any of its components, that renders it less suited for certain uses. The alteration of the physical, chemical, or biological properties of water by the introduction of any substance that renders the water harmful to use.
Polycyclic Aromatic Hydrocarbons (PAH)	A group of over 100 different organic compounds composed of several benzene rings.
Pore Water Pressure	Pressure exerted by fluid in the void space of soil or rock. It is usually expressed with respect to atmospheric pressure so that positive pressures indicate that the porous medium is saturated and negative pressures indicate that it is unsaturated.
Porosity	The ratio of the volume of void or air spaces in a rock or sediment to the total

Term	Description
	volume of the rock or sediment. The capacity of rock or soil to hold water varies with the material. For example, saturated small grain sand contains less water than coarse gravel.
Potentiometric surface	An imaginary surface that everywhere coincides with the static level of the water in a given water bearing formation. The surface to which the water from a given interval will rise under its full hydraulic head.
Precipitation	The part of the hydrologic cycle when water falls, in a liquid or solid state, from the atmosphere to Earth (rain, snow, sleet).
Primary Aquifer	An aquifer in which water moves through the original interstices of the geological formation.
Quaternary	The most recent geologic time, encompassing the last two million years.
Radius of Influence	Radial distance to points where hydraulic head is noticeably affected by a pumping well.
Recharge	The infiltration of water into the soil zone, unsaturated zone and ultimately the saturated zone. This term is commonly combined with other terms to indicate some specific mode of recharge such as recharge well, recharge area, or artificial recharge.
Recharge Area	An area where permeable soil or rock allows water to seep into the ground to replenish an aquifer.
Recovery	The return of environmental conditions to the state before the project.
Rehabilitation	To restore to former condition or status
Remediation	Containment, treatment or removal of contaminated groundwater. May also include containment, treatment or removal of contaminated soil above the water table.
Reservoir	A subsurface, porous, permeable rock body in which oil and gas is stored.
Reservoir Pressure	The force exerted uniformly in all directions by a fluid (oil or gas) in the reservoir.
Residual Drawdown	The difference between the original standing water level measured prior to pumping, and the depth to groundwater at a given instant during the recovery period following the cessation of pumping.
Revegetation	The process of providing denuded land with a new cover of plants.
Runoff	The portion of precipitation (rain and snow) that ultimately reaches streams.
Safe Yield	The annual amount of water that can be taken from a source of supply over a period of years without depleting that source beyond its ability to be replenished naturally in "wet years."
Salinity	An accumulation of soluble salts in the soil root zone, at levels where plant growth or land use is adversely affected. Also used to indicate the amounts of various types of salt present in soil or water. (see Total Dissolved Solids).
Sandstone	A sedimentary rock composed of individual grains of sand cemented together.

Term	Description
Saturated Zone	The portion below the earth's surface that is saturated with water is called the zone of saturation. The upper surface of this zone, open to atmospheric pressure, is known as the water table.
Seep	Point where seepage occurs.
Seepage	(1) The slow movement of water into or out of a body of surface or subsurface water. (2) The loss of water by infiltration into the soil from a canal, ditch, lateral, watercourse, reservoir, storage facility, or other body of water, or from a field.
Seismic	Pertaining to shock waves, natural or artificial, within the Earth.
Shale	A sedimentary rock formed by the deposition of successive layers of clay.
Shear Stress	A condition in which the material on one side of a surface pushes another material on the other side of the surface with a force that is parallel to the surface.
Silt	Mud or clay or small rocks deposited by a river or lake.
Siltstone	A fine-grained sandstone of consolidated silt.
Soil Profile	A vertical section of the soil through all its horizons and extending into the parent material.
Sour Gas	A natural gas containing H_2S.
Specific storage	The volume of water released from a unit volume of porous aquifer when there is a unit decline of hydraulic head. Compare with storativity, which is the specific storage multiplied by the aquifer thickness.
Specific Yield (Sy)	The quantity of water which a unit volume of aquifer, after being saturated, will yield by gravity; it is expressed either as a ratio or as a percentage of the volume of the aquifer; specific yield is a measure of the water available to wells.
Mound Spring	Mound springs are geomorphic formations raised above the surrounding land surface formed by a deposit of minerals and sediment brought up from artesian aquifers or confining beds by water at certain natural discharge points in the Great Artesian Basin. Other spring systems not raised above the surrounding land surface also occur throughout the Basin.
Static Water Level	(1) Elevation or level of the water table in a well when the pump is not operating. (2) The level or elevation to which water would rise in a tube connected to an artesian aquifer or basin in a conduit under pressure.
Storativity	The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer, per unit change in head. It is equal to the product of specific storage and aquifer thickness. In an unconfined aquifer, the storativity is equal to the specific yield.
Stratigraphy	The study of the sequence of layered geologic deposits based on their spatial positions, depositional sequence in time, and correlations across different localities.
Subcrop	Bedrock unit occurring at the bedrock surface but covered by surficial deposits.
Subsidence	The gradual settling or sudden sinking of the land surface owing to natural or

Term	Description
	anthropogenic influences of materials in the subsurface.
Subsoil	The layer of weathered material that underlies the surface soil.
Surface Water	Water above the surface of the land, including lakes, rivers, streams, ponds, floodwater, and runoff.
Surficial Deposits	Uncompacted sediments and soil lying on bedrock or occurring on or near the earth's surface.
Sustainable Yield	See safe yield.
Stygofauna	Any fauna that live within groundwater systems, such as caves and aquifers, or more specifically small, aquatic groundwater invertebrates, though terrestrial air-breathing subterranean animals are also sometimes included
Tertiary	The first period of the Cainozoic Era, from about 65 to 2 million years ago.
Topography	The configuration of a surface including its relief and natural and artificial features.
Total Dissolved Solids (TDS)	Concentration of all substances dissolved in water (solids remaining after evaporation of a water sample).
Total Solids (TS)	The weight of all present solids per unit volume of water. It is usually determined by evaporation. The total weight concerns both dissolved and suspended organic and inorganic matter.
Transmissibility	The ease with which a fluid will flow through a porous medium. A low transmissibility indicates a high degree of difficulty in moving fluid through pore spaces at initial reservoir conditions.
Transmissivity	A measure of the capability of the entire thickness of an aquifer to transmit water. Also known as coefficient of transmissivity.
Treating	The act of subjecting a substance to a process or a chemical reagent to improve its quality or remove a contaminant.
Triassic	The Triassic encompasses a time frame between about 248 and 213 million years ago.
Unconfined Aquifer	A permeable bed only partly filled with water and overlying a layer of lower hydraulic conductivity. Its upper boundary is formed by a free water table where pore pressure is equal to atmospheric pressure. Water in a well penetrating an unconfined aquifer does not, in general, rise above the water surface.
Unsaturated Zone	The body of soil and rock separating the water table and the land surface.
Watercolumn	The height of water in a bore
Watertable	The upper surface of groundwater of the level below which the soil is saturated with water.
Watershed	An area bounded peripherally by a divide, draining ultimately to a particular watercourse or waterbody.
Well	An excavation or structure created in the ground by digging, driving, boring or

Term	Description
	drilling to access water in the subsurface
Wellbore	The physical hole that makes up the well, and can be cased, open or a combination of both
Unsaturated Zone	The body of soil and rock separating the water table and the land surface.
Yield	The quantity of water removed, or able to be removed from a well