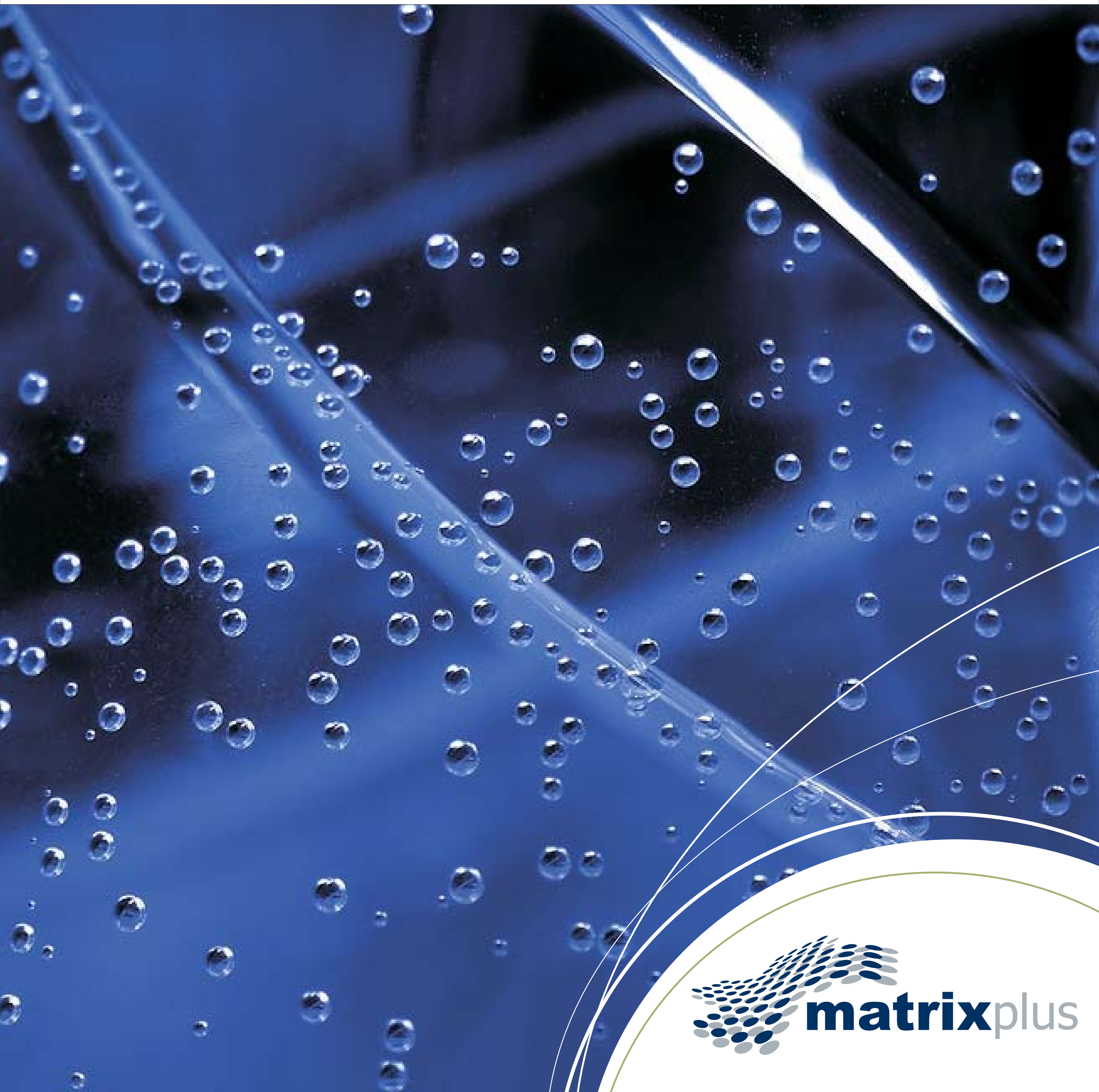
Groundwater (Deep Aquifer Modelling)

for

Santos GLNG Environmental Impact Statement

February 2009



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GLOSSARY OF TERMS

mAHD	Metres above Australian Height Datum (approximately Mean Sea Level).
Aquiclude	A saturated geologic unit that is incapable of transmitting significant quantities of water under ordinary hydraulic gradients.
Aquifer	A water bearing rock or sediment in a formation, group of formations, or part of a formation that is capable of yielding sufficient water to satisfy a particular demand.
Aquitard	A layer that is much less permeable than the aquifers themselves, but not impermeable.
BOM	Australian Bureau of Meteorology.
Bore	A bore is a hole drilled into the ground to enable the extraction of groundwater from an aquifer. The term 'well' is commonly used in the oil and gas industry and also in the water industry in some other countries to define the same type of facility. In Australia, the term 'well' normally applies to a large diameter bore. For the purposes of this report, the terms 'well' and 'bore' are synonymous.
Cone of depression	A depression in the groundwater table or potentiometric surface that has the shape of an inverted cone and develops around a bore, or any facility, from which groundwater is being withdrawn. The cone of depression defines the area of influence of a bore.
Darcy	A unit of intrinsic permeability. (Refer to Permeability (2)). It is not an SI unit, but is widely used in petroleum engineering and geology. A medium with a permeability of 1 Darcy permits a flow of 1 cm/sec of a fluid with a viscosity of 1 centipoise under a pressure gradient of 1 atmosphere/cm. To convert to equivalent values of hydraulic conductivity for water at normal atmospheric conditions, 1 millidarcy (mD) = 8.64 x 10^{-4} m/d.
Darcy's Law	Named after the Frenchman Henry Darcy, Darcy's law states that the rate '*Q*' (m^3/day) at which water flows through a cross-sectional area '*A*' (m^2) of a porous medium, such as sand, along a distance '*L*' (m) is directly proportional to the head loss (i.e. the change in water level) 'Δh' (m) over the distance '*L*' and inversely proportional to the distance travelled '*L*'. i.e. $Q = KA(\Delta h/L)$ where the constant of proportionality *K* is known as the hydraulic conductivity (also called the coefficient of permeability).
Drawdown	The distance that the water level in a bore is lowered from the standing water level when influenced by pumping.
DNRM	Queensland Department of Natural Resources and Mines. (Now DNRW.)
DNRW	Queensland Department of Natural Resources and Water.
Flow boundary	Any geologic, geomorphic or hydrologic feature which impedes the normal groundwater flow regime. An impermeable rock mass, such as bedrock, a feature which hinders flow across it, such as a fault, or drawdowns resulting from other pumping bores constitute impermeable boundaries and result in an increase in the rate of drawdown. A surface body of water, such as a lake or stream, which intersects the aquifer constitutes a recharge boundary and results in a reduction in the rate of drawdown.
GL/y	Gigalitre per year (1,000,000,000 L/y).

Groundwater	The water contained within the joints, vesicles, fractures or interconnected pores of an aquifer.
Groundwater flow	The movement of water through openings in sediment and rock; occurs in the zone of saturation.
Groundwater head	Refer 'hydraulic head'.
Hydraulic head	The sum of the elevation head, the pressure head and the velocity head at a given point in an aquifer (i.e. water level).
Hydraulic Conductivity	Hydraulic Conductivity (*K*) is an aquifer parameter. It is the rate at which water can be transmitted through a unit area of an aquifer, normal to the direction of flow, under a unit gradient. Units are length/time e.g. m/day.
Hydrograph	A graph that shows groundwater or surface water properties (such as water levels) as a function of time.
L/s	Litres per second.
L/d	Litres per day.
Megalitre (ML)	1,000,000 litres.
m/d	Metres per day
mbgl	Metres below groundwater level.
MODFLOW	Industry standard numerical groundwater modelling computer software. The numerical model allows groundwater flows within the aquifer to be predicted and described by numerical equations, with specified values for boundary conditions that are solved on a digital computer.
Monitoring bore	A non-pumping bore used to monitor water properties such as water levels or water quality. A monitoring bore is generally of small diameter and is typically screened or slotted throughout the thickness of the aquifer.
Permeability (1)	Coefficient of Permeability or Hydraulic Conductivity (*K*) is the rate at which water can be transmitted through a unit area of an aquifer, normal to the direction of flow, under a unit gradient. Units are length/time e.g. m/day.
Permeability (2)	Intrinsic Permeability (*k*) is a property of the aquifer matrix. It is a measure of the relative ease with which a porous medium can transmit a liquid under a specified gradient. It is related only to the matrix grain size and is independent of the fluid passing through it. Units are length^2 e.g. common unit is the millidarcy (9.87 x 10^{-12} cm^2).
Porosity	The ratio of the volume of voids to the total volume of soil mass.
Potentiometric level	An imaginary surface that represents the level to which water could rise in a bore. The water table is a particular potentiometric surface for an unconfined aquifer.
Recovery	A rise of the water level in a bore or an aquifer after the pumping rate has been reduced or the pump has been shut off or when mining has ceased.
Registered bores	Groundwater bores that have their details included within the DNRW database. Some of these bores may also be attached to Water Licences

Screen	A tubular device with slots, holes, gauze, or continuous-wire wrap; used at the end of a bore casing to allow entry of water while withholding aquifer material.
Specific Yield	The volume of water that will drain under gravity from a unit volume of aquifer; commonly referred to as the Storage Coefficient of an unconfined aquifer.
Standing water level	The depth from ground level (or other stated reference point) to the water level in a bore which is not influenced by pumping.
Storage Coefficient	Storage Coefficient (*S*) is an aquifer parameter. It is the volume of water that a saturated aquifer releases from or takes into storage per unit surface area per unit change of head. It is related to the elastic properties of the water and the soil matrix.
Surface catchment	The land area from which surface runoff drains into a stream system.
Transmissivity	Transmissivity (*T*) is an aquifer parameter. It refers to the ease with which a fluid can pass through an aquifer. It is defined as the rate of flow of fluid through a unit width of the aquifer, normal to the direction of flow, under a unit gradient. It is then simply the hydraulic conductivity (*K*) multiplied by the thickness of the aquifer. Its units are $m^3/d/m$ or simply m^2/d.

EXECUTIVE SUMMARY

Santos Limited (Santos) is planning to extract coal seam gas (CSG) from the coal seams located in the Surat Basin and Bowen Basin in southeast Queensland. These basins are two of a number of hydrogeologic basins which make up the Great Artesian Basin (GAB); a valuable source of water for town water supply, stock, domestic and industrial uses in the arid and semi-arid regions that overlie it.

Santos is confining its operations to the Fairview, Arcadia and Spring Gully fields (Comet Ridge fields) of the Bowen Basin and Roma field in the Surat Basin. Santos expects that its CSG fields will be capable of delivering approximately 4 trillion cubic feet (4,200 petajoules) necessary to operate the initial Gladstone LNG (GLNG) facility over a 20-year project life.

The production of CSG involves removal of methane from the coal seams after it has been desorbed from the coal by a reduction in the surrounding pressure. This pressure reduction is achieved by extracting groundwater from wells in the area and so reducing the hydrostatic head of the groundwater system.

There is a possibility that this dewatering will have impacts on existing groundwater users in the area. These impacts include: the drawdown of groundwater in the CSG aquifers and the overlying and underlying aquifer systems; the reduction of landholder bore yields; reduction in stream baseflow; contamination of shallow aquifers; and subsidence of the land surface overlying the well field.

In order to better understand the potential groundwater impacts on the surrounding area, mathematical flow models for the aquifers in the area of the CSG fields were constructed. The main objectives of the Comet Ridge and Roma CSG fields groundwater models include: the understanding of the hydrogeological environment; estimations on groundwater drawdowns in the CSG and surrounding aquifers; and the design of groundwater monitoring programmes.

Key Findings

- The maximum drawdown of groundwater levels within the coal seam aquifers in the CSG fields is expected to be in the order of 600 m with the drawdowns in some wells located in the extreme east of the Fairview CSG field ranging up to 1000 m;
- Landholder bores screened in affected aquifers which are located within the predicted radius of influence may experience a level of reduced groundwater heads;
- In the Arcadia Valley and Fairview CSG fields (which were modelled in conjunction with the neighbouring Spring Gully CSG field) the radius of influence of drawdown within the coal seam aquifer is expected to spread well outside the perimeter of the CSG fields;
- Groundwater drawdowns in the coal seam aquifer within the Arcadia Valley and Fairview CSG fields are expected to result in inter-aquifer transfer from the overlying Precipice Sandstone. Groundwater head loss within the Precipice Sandstone could range up to a maximum of 15 m at the end of 2013 and up to a maximum of 65 m at the end of 2028; (These impacts also include the effect of the Spring Gully CSG field);
- It is anticipated that 4 existing bores which are drilled into the Precipice Sandstone aquifer may be impacted by the groundwater drawdowns in the coal seam aquifer within the Arcadia Valley and Fairview CSG fields. One bore, (14988), is located inside the well field area, and 3 others, (16091, 14838 and 16785) are situated outside the well field area. It is anticipated that these bores will be impacted by a maximum 7 – 25 m of drawdown by 2028 depending on their locations within the area of influence.
- In the Roma CSG field, the radius of influence of drawdown within the coal seam aquifer is expected to be confined to an area proximal to the CSG field;
- Groundwater drawdowns within the Roma field are expected to result in minor inter-aquifer transfer from the underlying Hutton Sandstone. After 20 years of operation, as a result of inter-aquifer transfer, the groundwater levels within the Hutton Sandstone will decline by approximately 3 m at the edge of the CSG field and by lesser values further out from the CSG field;

- No landowner bores are expected to be impacted as a result of groundwater withdrawal from the Roma CSG field;
- No town water supply bores are likely to be impacted as a result of groundwater withdrawal from the Roma CSG field or from the Fairview and Arcadia Valley CSG fields;
- Drawdown of groundwater heads within the Precipice Sandstone as a result of groundwater extraction at Arcadia Valley and Fairview CSG fields is not expected to significantly alter the baseflow contributions to the perennial portion of the Dawson River and groundwater discharge volumes to springs located in the vicinity;
- Groundwater drawdown and associated inter-aquifer transfer is unlikely to have an adverse impact on the water quality of the CSG aquifer and the deep aquifers surrounding the CSG fields; and
- It is not expected that ground surface subsidence will occur as a result of groundwater withdrawal from the coal seam aquifers in the Roma CSG field or from the Fairview and Arcadia Valley CSG fields.

Recommendations / Mitigation Measures

Groundwater monitoring will be undertaken during and post-extraction. The aim of the monitoring will be to assess the impact CSG extraction has on the surrounding groundwater environment, both in radial extent and in the magnitude of the drawdown. Monitoring will provide early warning of any variation of the groundwater system from that predicted. This will enable the undertaking of mitigation measures to minimise impact on surrounding groundwater users.

Should groundwater users be assessed as being unduly impacted, proposed mitigation measures include:

- securing alternate groundwater supplies as under the make good obligation, through deepening existing bores, installation of pumps or lowering pump suction levels etc;
- injection of extracted water to reduce groundwater head losses within potentially impacted aquifers; and
- rehabilitation of proximal uncontrollable artesian wells thus reducing groundwater head losses within impacted aquifers.

1 INTRODUCTION

Santos Limited (Santos) has been involved with drilling in the Bowen and Surat Basins for coal seam gas (CSG) since the mid 1990s and commenced production in 2002. Santos' future CSG operation is focussed on increasing the size and productivity of its CSG fields to support an initial 3 – 4 million tonnes per annum LNG facility. Santos expects that its CSG fields will be capable of delivering approximately 4 trillion cubic feet (4,200 petajoules) necessary to operate the initial Gladstone LNG (GLNG) facility over a 20-year project life.

The production of CSG involves removal of methane from the coal seams after it has been desorbed from the coal by a reduction in the surrounding pressure. This pressure reduction is achieved by extracting groundwater from wells in the area, thereby reducing the hydrostatic head of the groundwater system.

The drawdown of groundwater heads within CSG aquifers is a necessary process and an unavoidable impact associated with the depressurisation of the target coal seam.

As part of its proposed CSG field development activities, Santos proposes to drill and complete approximately 540 development wells prior to 2015 and over 800 wells post 2015 (excluding exploration wells).

Santos' operations are located in southeast Queensland and will concentrate within the Comet Ridge fields (Fairview, Arcadia and Spring Gully) and Roma field, as shown in **Figure 1-1**.

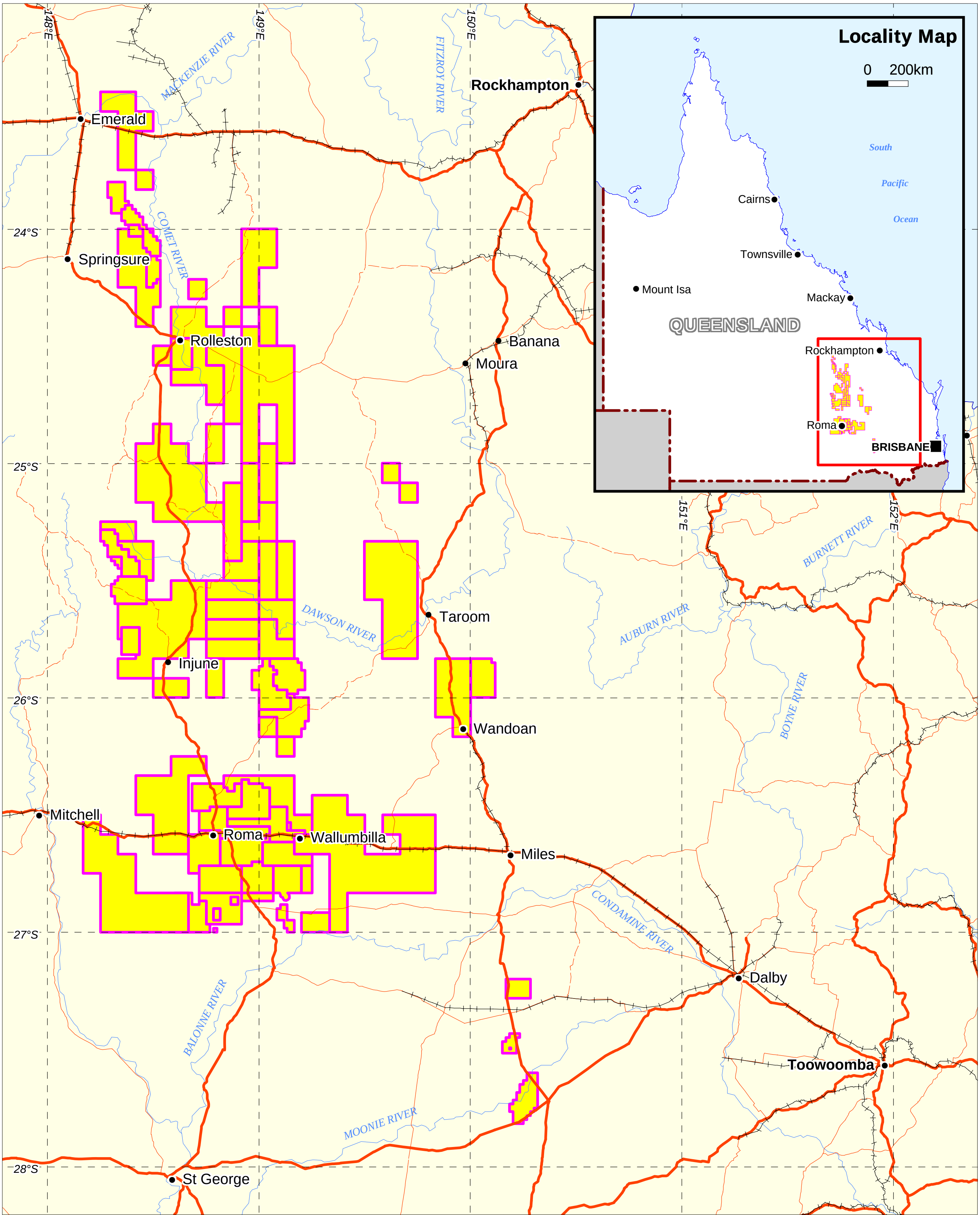
Matrixplus Consulting was commissioned to develop groundwater flow models capable of simulating existing conditions and thereby assessing the potential groundwater impacts of CSG production.

1.1 MODELLING OBJECTIVES

This groundwater assessment of Santos' CSG fields aims to characterise the existing deep groundwater environment and to assess potential groundwater related impacts caused by CSG extraction from the deep aquifers.

The main objectives of the Comet Ridge and Roma CSG fields groundwater models are the:

- understanding of the fields hydrogeological environment;
- predictive estimations of groundwater drawdown impacts within CSG aquifers;
- predictive estimations of groundwater drawdown impacts within overlying and underlying aquifers;
- predicted potential groundwater impacts on landholders bores;
- design of groundwater monitoring programmes to assess the potential drawdown in the CSG and overlying and underlying aquifers; and
- assess potential mitigation methods.



LEGEND

- Santos ATP & PL Tenement
- Highway
- Road
- Track
- Railway
- Watercourse
- City
- Town

Data Source:
Topography - Geoscience Australia. Tenement - URS.

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Santos GLNG EIS

Locality Plan
- Comet Ridge and Roma CSG Fields

0 50 100
Kilometres

Scale: 1:2,500,000 (A4)

Datum: WGS84
Projection: Long/Lats

FIGURE 1-1

2 EXISTING GROUNDWATER ENVIRONMENT

2.1 REGIONAL GEOLOGY

The Comet Ridge and Roma CSG fields are located within the Bowen and Surat geologic basins (**Figure 2-1**). The Bowen Basin is an Early Permian to Middle Triassic aged basin which contains shallow marine and continental clastics and volcanic rocks up to 10 km thick. The basin is comprised of two depocentres, the Denison and Taroom Troughs. The southern part of the Bowen Basin is unconformably overlain by the Surat Basin.

The Mesozoic-aged Surat Basin consists of alternating fluvial and lacustrine successions of sandstones, siltstones and coals, up to 1,500 m thick, followed by up to 1,200 m of shallow marine mudstones, sandstones and finally regressive sandy units in the Early Cretaceous.

2.2 REGIONAL HYDROGEOLOGY

The Bowen and Surat Basins are structurally separate depocentres, however, they are stratigraphically and hydraulically interconnected. The Bowen and Surat Basins are two of the seven basins which constitute the Great Artesian Basin (GAB) (**Figure 2-1**). When the basin is considered as a single entity the GAB is an asymmetrical basin tilted towards the south west. The GAB is one of the largest artesian groundwater basins in the world. It underlies approximately one-fifth of Australia and extends beneath arid and semi-arid regions of Queensland, New South Wales, South Australia and the Northern Territory.

The GAB was formed between 100 and 250 million years ago, and consists of a multi-layered confined aquifer system of alternating layers of water-bearing (permeable) sandstone and non-water-bearing (impermeable) siltstones and mudstones. The sandstone units store and transmit groundwater and are defined as aquifers, because these rocks are sufficiently permeable to conduct groundwater and to yield economically significant quantities of groundwater to water bores and springs.

The siltstone and mudstones are low permeability rocks referred to as confining beds that retard but do not prevent groundwater flow to or from adjacent aquifers. These confining beds do not readily yield groundwater to water bores and springs but may serve as a storage unit for groundwater (**Figure 2-2**) (Cox, 1998).

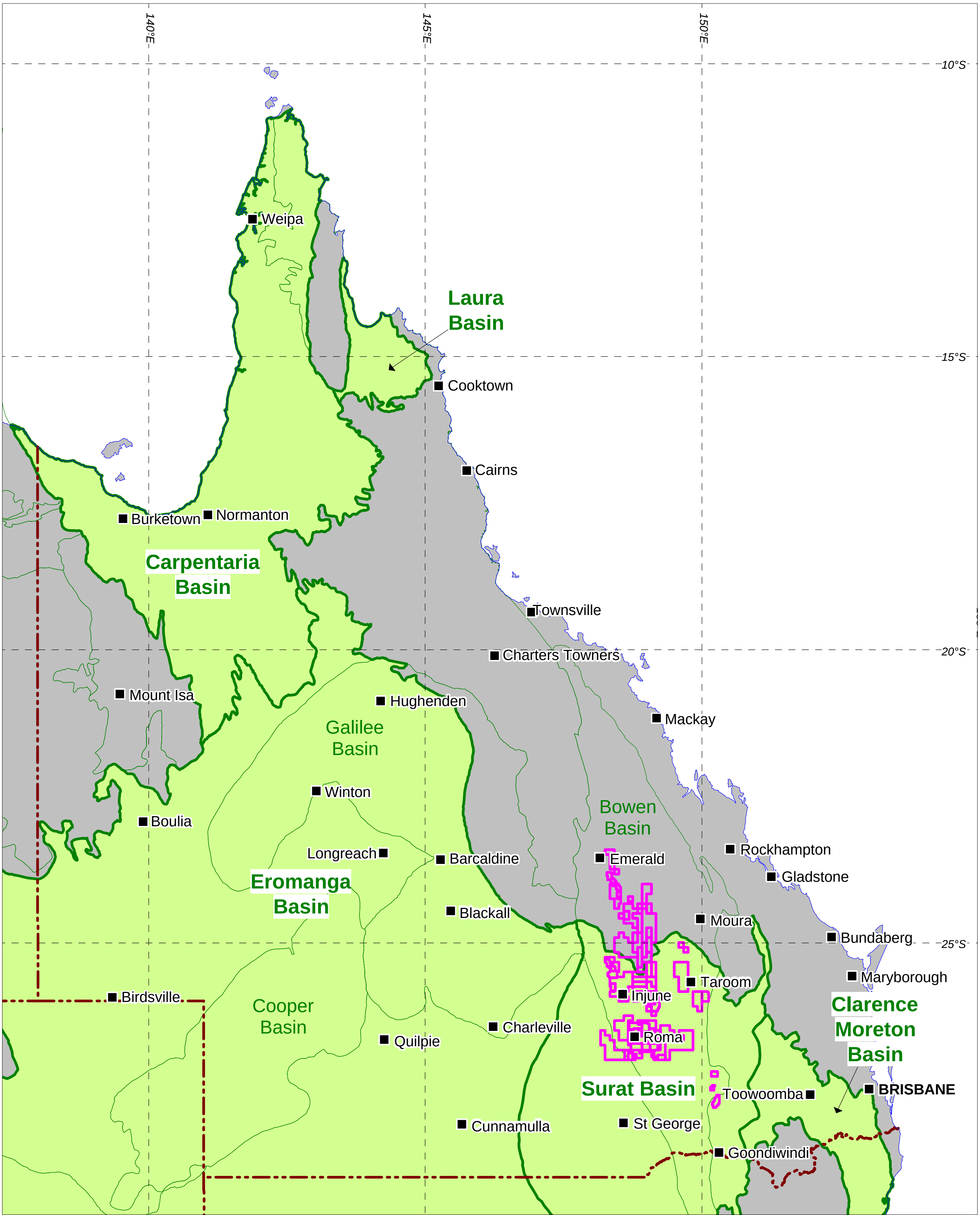
The GAB sequence thickness varies from less than 100 m on the Basin extremities to over 3,000 m in the deeper parts of the Basin. Most of the individual aquifers are relatively uniform in their hydrogeological characteristics, laterally continuous and hydraulically connected across the constituent geological basins. However, the aquifers thicknesses are variable and they may lens out or merge. The main GAB aquifers are shown diagrammatically in **Figure 2-2** and listed below:

- Cadna-owie Formation;
- Hooray Sandstone;
- Adori Sandstone;
- Hutton Sandstone;
- Precipice Sandstone; and
- Clematis Sandstone.

The main confining beds of the GAB are the Rewan, Moolayember, Evergreen, Birkhead, Westbourne, Wallumbilla and Toolebuc Formations.

Individual bore depths vary up to 2,000 m with the average depth being 500 m. The GAB in Queensland is tapped by about 2,700 artesian bores and about 15,000 sub-artesian bores that vary in depth from less than 100 m to 2,000 m (DNRM, 2005).

Contained groundwater is predominately fresh (i.e. <1,500 mg/L TDS), and in many areas is under sufficient pressure to provide a naturally-flowing source when tapped by bores (Radke, 2000).



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LEGEND

- Santos ATP & PL Tenement
- City / Town
- Main GAB Sub-Basins
- Underlying Basins

Data Source:
Geology - Geoscience Australia. Tenement - URS.

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GAB and Underlying Sub-Basins

0 200 400

Kilometres

Scale: 1:10,000,000 (A4)

N

Datum: WGS84
Projection: Long/Lats

FIGURE 2-1

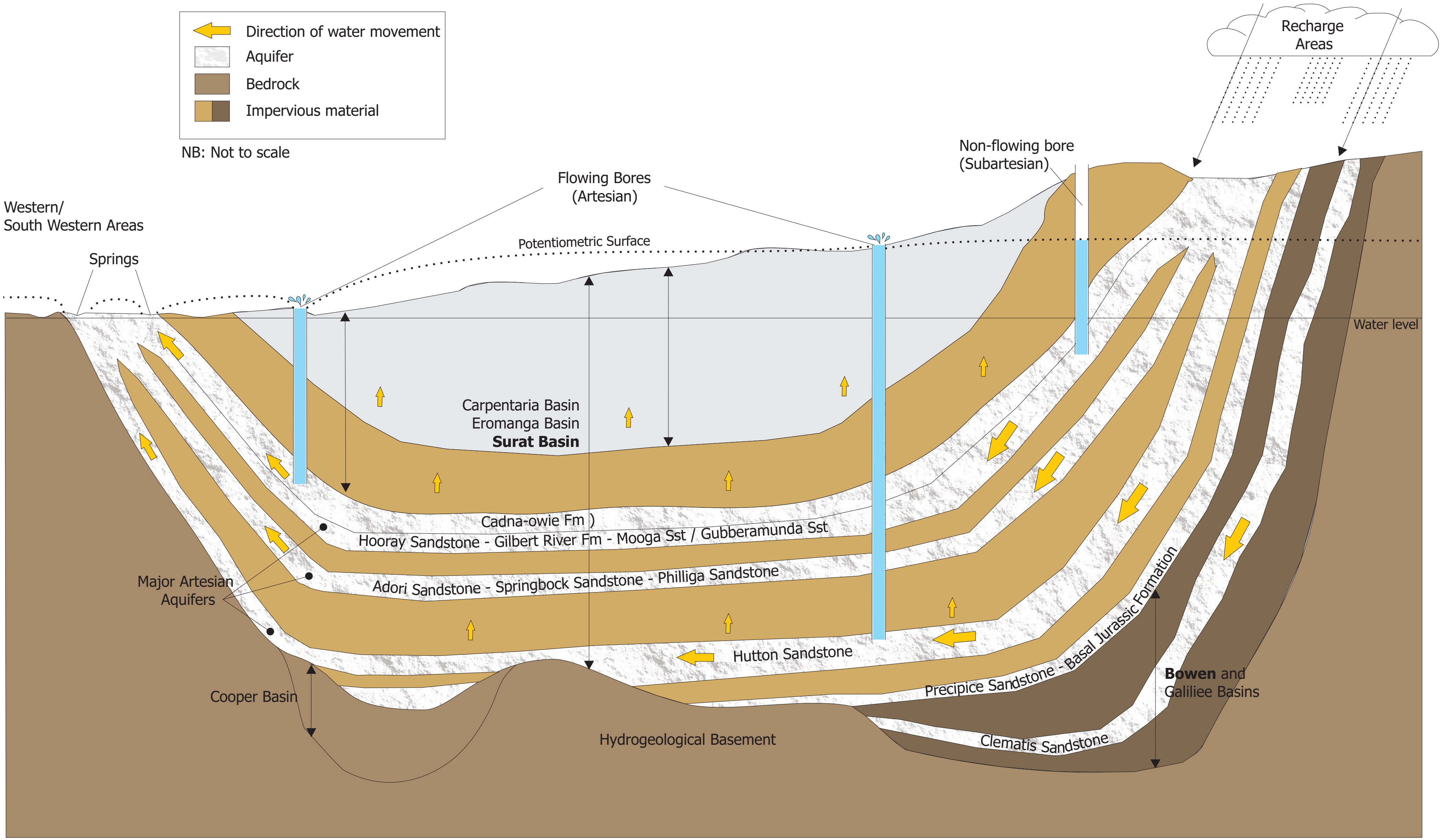

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Figure 2-2 KEY GAB Aquifer Units and Hydrogeological Features

GAB aquifers are recharged by infiltration of rainfall, and leakage from streams into outcropping sandstone mainly on the eastern margins of the Basin along the western slopes of the Great Dividing Range. Regional groundwater flow is from the topographically higher recharge areas around the basin margins towards the lowest parts of the basin in the southwest (**Figure 2-2**). Groundwater moves slowly, at about 1-5 m per year through the GAB.

The main area of recharge for the aquifers in the area covered by Santos' CSG fields is in the Great Dividing Range, in the area immediately to the north and northwest of the Comet Ridge fields, including the Carnarvon Gorge area.

The best source of groundwater data for Queensland is the DNRW Groundwater Database. However, this cannot always be considered a reliable source. The main reason for unreliability is the fact that the data have been collected from a variety of sources; mainly different drillers or landowners throughout the State. These sources, which may go back a hundred years or so, would have different interpretations for different strata or the bore may not have been drilled on the site which was initially recorded. However, one other reason for unreliability is that not all of the data recorded in the database has been validated. This means that some bore locations which were initially recorded as longitudes and latitudes have been converted to other projections incorrectly. This can result in some location records being very much in error and it is difficult to ascertain the true location. This problem arose when analysing the data for this study and DNRW was duly notified. The response from DNRW was that funds were not available to enable validation to be carried out. The study has been carried out on the assumption that the supplied database is accurate but with the full knowledge that it is not 100% reliable.

There are some 24,000 wells located in the search area used for the study. However, the study area was quite large, 600km north/south and 400 east/west, and many of the wells are drilled into surficial aquifers including shallow alluvial deposits. Nevertheless, there are still many wells taping the deeper aquifers in the vicinity of the CSG fields.

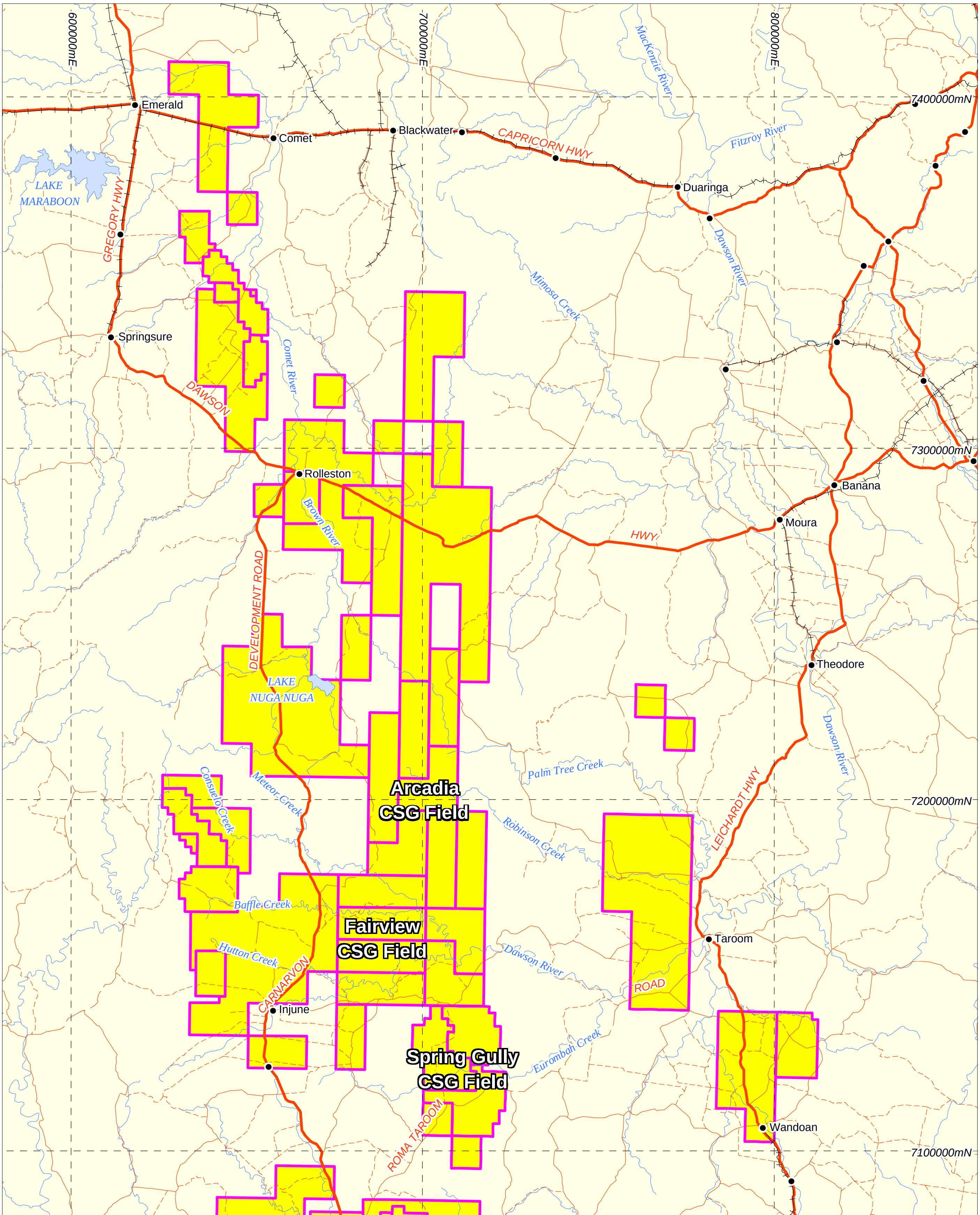
2.3 COMET RIDGE CSG FIELDS

The Comet Ridge Project Area consists of Fairview, Arcadia and Spring Gully tenements (**Figure 2-3**). Fairview has been operating since 1994. Gas production commenced at the Spring Gully Joint Venture in 2007, operated by Origin Energy. Gas production is intended to commence at the Arcadia CSG field in 2010.

2.3.1 Geology

The Comet Ridge CSG fields lie on the western margin of the Taroom Trough in the southern extent of the Bowen Basin. Gas in the Comet Ridge fields is extracted from coal seams of the Late Permian Bandanna Formation of the Bowen Basin at depths of 500 to 1,000 m from the surface. The Bandanna Formation typically ranges from 6 to 12 metres of thickness and has up to five separate seams in the Comet Ridge project area. The Bandanna Formation contains a bright to moderately dull black coal with a blocky, hackly to occasionally concoidal break. It is well-cleated, with little or no calcite vein filling. The coal seams are typically interbedded with fine-grained (and low-permeability) sediments, e.g. siltstones, shales and mudstones.

Analysis shows the Bandanna coal to be vitrinite-rich, thereby capable of storing significant quantities of gas. Vitrinite reflectance and BTU content indicates that the Bandanna is a high-volatile bituminous coal. Coal rank increases with depth to the east into the Taroom trough attaining a rank of medium-volatile bituminous – the peak rank of thermogenic methane generation (AHA, 2003).



LEGEND

- Santos ATP & PL Tenement
- Highway
- Road
- Track
- Railway
- Watercourse
- Town

30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS

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Layout
- Comet Ridge CSG Fields

0 25 50
Kilometres

Scale: 1:1,500,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 2-3

The Surat basin overlies the Comet Ridge fields; Surat Basin stratigraphy is absent north of Comet Ridge field due to erosion. Only the lowest three formations of the Surat sequence: the Precipice Sandstone; Evergreen Formation; and Hutton Sandstone are present in the northern part of the Comet Ridge fields (i.e. Fairview north and Arcadia). Down-dip in (Fairview south and Spring Gully) the Injune Creek Group overlies the Hutton Sandstone. Generalised stratigraphy for the north and south Comet Ridge fields is shown in **Table 2-1**.

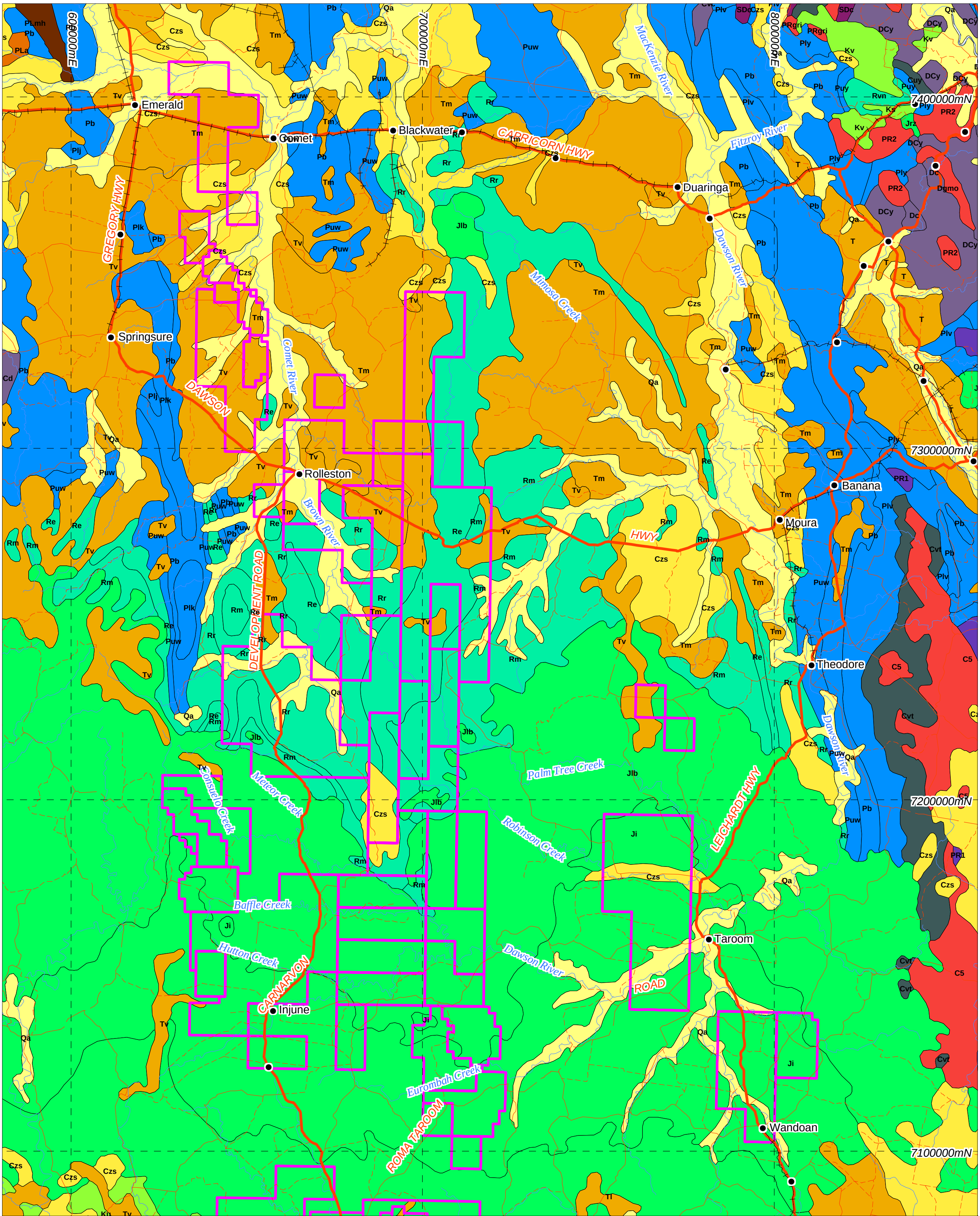
Table 2-1 Generalised Comet Ridge Field Stratigraphy.

Age	Group	Formation North Comet Ridge	Formation South Comet Ridge
Jurassic	Injune Creek Group	*not present at Fairview north and Arcadia*	Westbourne
			Springbok Sandstone
			Walloon Coal Measures
		Hutton Sandstone	Hutton Sandstone
		Evergreen Formation	Evergreen Formation
		Precipice Sandstone	Precipice Sandstone
Triassic	Rewan	Moolayember Formation	Moolayember Formation
		Clematis Sandstone	Clematis Sandstone
		Rewan Formation	Rewan Formation
Late Permian	Blackwater	Bandanna Formation	Bandanna Formation
		Black Alley Shale	Black Alley Shale

The lower Triassic age Rewan Group separates the overlying sandstones from the Bandanna Formation, the low-permeability lithology of the Rewan Group Moolayember and Formations suggests that it is a confining unit. Therefore, there is little likelihood of vertical leakage where this formation is present. However, the sandstone aquifers are susceptible to potential impacts from dewatering where the Rewan is absent. This is the case due to erosion of the Rewan southwest of the Fairview field. Where the Rewan is absent, in this area, the lowermost sandstone aquifer, the Precipice Sandstone, directly overlies the Bandanna Formation.

The Jurassic Hutton Sandstone, Evergreen Formation, Precipice Formation, and Boxvale Sandstone outcrop in the Fairview field area; Triassic rocks (Rewan Formation, Clematis Sandstone and Moolayember Formation) all outcrop in or near the Arcadia Valley area (**Figure 2-4**).

The Hutton Sandstone is pervasive in the southern and western parts resulting in a typical undulating topography, characterised by rounded hills. In the northern and central parts the Precipice and Boxvale Sandstones outcrop, resulting in raised plateaus with steep escarpments.



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LEGEND

- Santos ATP & PL Tenement
- Highway
- Road
- Track
- Railway
- Watercourse
- Town

30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS

Santos Ltd

Santos GLNG EIS

Surface Geology
- Comet Ridge CSG Fields

0 25 50
Kilometres

Scale: 1:1,500,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 2-4

2.3.2 Groundwater Occurrence

Regional and local groundwater systems exist within the Comet Ridge area. Most of the individual aquifers are continuous and relatively uniform in their hydrogeological characteristics across large areas, and hydraulically connected across GAB sub-basins (Habermehl, 2002). The main aquifers in the project area are the Hutton and Precipice Sandstones. **Table 2-2** shows the stratigraphic nomenclature for the Comet Ridge field and describes each unit's hydrogeological characteristics.

Table 2-2 Generalised Groundwater Occurrence Across the Comet Ridge CSG Fields

Age	Group	Formation	Hydrogeological Characteristics
Jurassic	Injune Creek Group	Westbourne Formation	Confining bed
		Springbok Sandstone	Aquifer
		Walloon Coal Measures	Water bearing
		Eurombah Formation	Aquifer
		Hutton Sandstone	Aquifer
		Evergreen Formation	Confining
		Precipice Sandstone	Aquifer
Triassic	Rewan	Moolayember Formation	Confining bed
		Clematis Sandstone	Aquifer
		Rewan Formation	Confining bed
Late Permian	Blackwater	Bandanna Formation	Water bearing
		Black Alley Shale	Confining bed

Aquifers within the Injune Creek Group occur in both outcrop and sub-crop in the southern part of the Comet Ridge field. The aquifers are usually targeted only for stock rather than potable (human) use, owing to poor quality and low yield. Typical yields range from 0.2 L/s to 3 L/s with quality ranging from 1,000 µS/cm in the Eurombah Formation and Springbok Sandstone to 10,000 µS/cm in the Walloon Coal Measures (DNRM, 2005).

The main aquifer in the Comet Ridge field is the Hutton Sandstone which outcrops in the northern part of the Comet Ridge fields and is associated with numerous spring complexes. This aquifer supports most of the stock and domestic use in the area because of the aquifer's shallow depth, its water quality and yield (> 10 L/s). Water quality is generally good in the range of 500-2000 µS/cm depending on the distance from the recharge zone (DNRM, 2005).

The Precipice Sandstone outcrops in the northern part of the Comet Ridge fields and provides significant stock and domestic supplies. Water quality in the Precipice Sandstone ranges from 100-600 µS/cm depending on the distance from recharge zones.

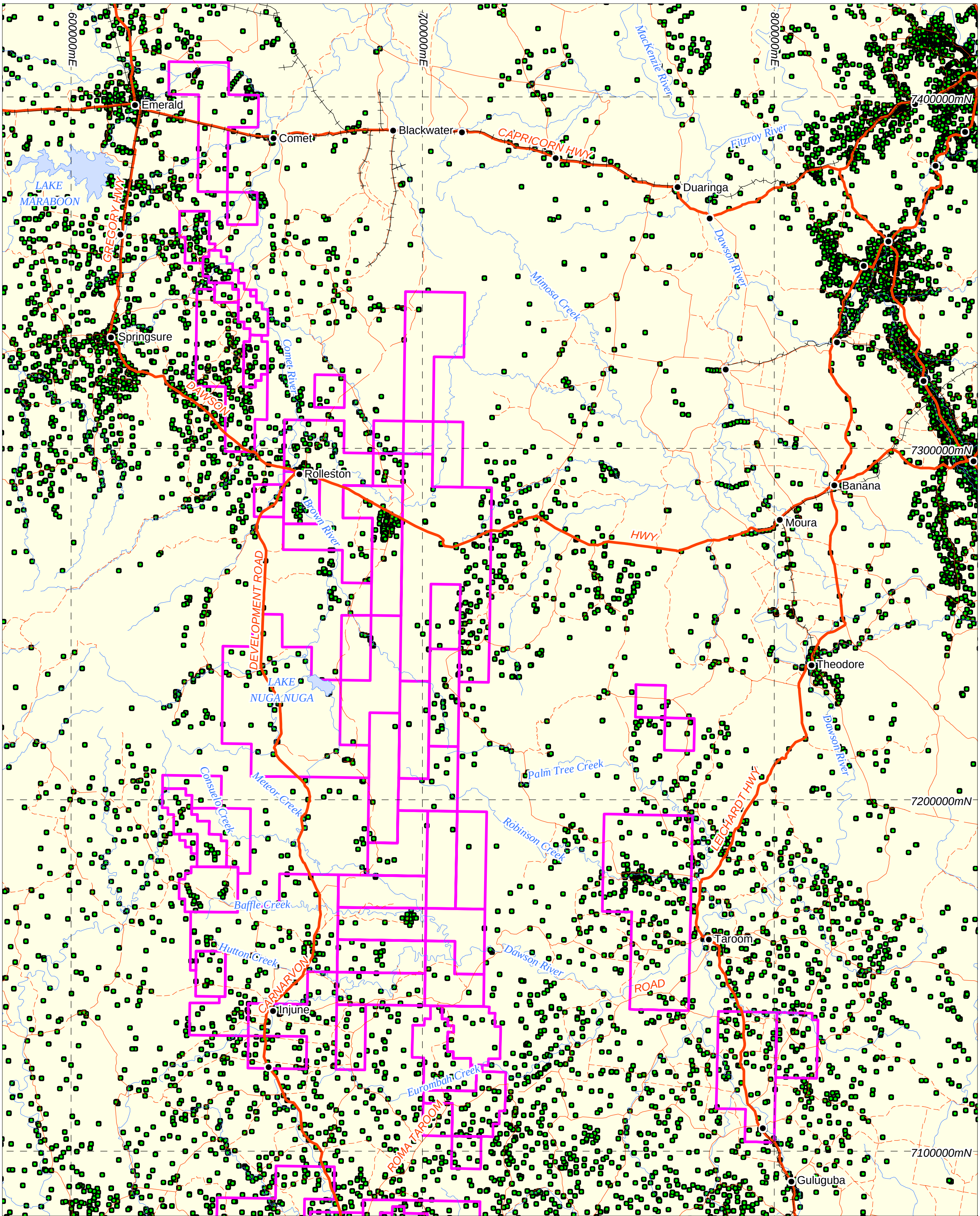
The deepest aquifer in the Comet Ridge field is the Triassic Clematis Sandstone, part of the underlying Bowen Basin sediments. Although the Clematis Sandstone is known to produce good supplies of potable water, it is generally too deep to be attractive as a stock and domestic source.

Large volumes of groundwater exist within the Bandanna Formation. However, the water is brackish to saline, at excessive depths >600 m and is therefore not an utilised resource.

2.3.3 Groundwater Use

A registered bore search of the DNRW database suggests groundwater for domestic consumption, irrigation use, and stock water is derived predominately from the Hutton and Precipice Sandstone aquifers in the Comet Ridge area. The location of registered bores is shown in **Figure 2-5**. Additional landholder bores, which have not been registered with the Department, may exist.

Santos and their JV partners and other CSG companies currently extract large quantities of groundwater in the Comet Ridge area under the authority of the *Petroleum and Gas (Production and Safety) Act 2004*.



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matrixplus

LEGEND

- Santos ATP & PL Tenement
- DNRW Registered Bore
- Highway
- Road
- Track
- Railway
- Watercourse
- Town

Santos Ltd

Santos GLNG EIS

DNRW Bore Locations
- Comet Ridge CSG Fields

0 25 50

Kilometres

Scale: 1:1,500,000 (A4)

Datum: GDA94
Projection: MGA55

30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS

FIGURE 2-5

2.3.4 Groundwater Levels

The groundwater levels in aquifers in the Comet Ridge and Roma areas, as recorded within DNRW registered bores, are summarised in **Table 2-3**.

Table 2-3 Summary of Groundwater Levels in Regional Aquifers in Comet Ridge and Roma

Formation	Number of wells	*n	Av. groundwater level (mAHD[1])	Range of groundwater levels (mAHD)
Wallumbilla Formation	42	43	307	135-375
Bungil Formation	232	239	327	221-541
Mooga Sandstone	333	1,320	315	195-453
Orallo Formation	58	67	319	162-505
Gubberamunda Sandstone	140	433	304	124-477
Walloon Coal Measures	16	423	298	148-341
Eurombah Formation	5	7	253	198-297
Hutton Sandstone	344	4,661	404	160-633
Precipice Sandstone	90	143	260	135-375
Rewan Group	10	33	212	129-488
Clematis Sandstone	15	16	262	157-439
Moolayember Formation	9	41	154	112-247
Triassic Combined	33	89	185	112-488

*n = total number of water level readings

1AHD = Australian Height Datum

Mostly, groundwater in the Comet Ridge and Roma areas is sub-artesian (with bore water levels above the top of the aquifer but below ground surface) although artesian conditions occur in some areas, particularly in down-dip parts of deeper aquifers (refer **Figure 2-2**). For example, in the Precipice Sandstone to the west of Taroom, wells are generally artesian and mound springs occur.

Multiple potentiometric level readings are available for relatively few bores. Owing to the limited potentiometric data, groundwater flow paths and the extent of flow between hydrogeologic units are not well defined.

2.3.5 Groundwater Quality

Water quality in the Comet Ridge and Roma target coal measures and in adjacent formations, as recorded in the DNRW registered bore database, is summarised in **Table 2-4**. As is the case for DNRW records of groundwater levels, there is uncertainty regarding the representativeness of water samples for particular aquifers. Furthermore, over the large areas and large time frames during which water samples have been collected, sample collection methods and sample integrity vary considerably. Notwithstanding these considerations, general trends in water quality are useful in developing a conceptual model of regional groundwater flow patterns in the Comet Ridge and Roma areas.

Table 2-4 Summary of Groundwater Chemistry in Regional Aquifers (all summarised concentrations are geometric means and are expressed in mg/L)

Formation	n*	pH	EC	Na	Ca	Mg	K	Cl	HCO3	CO3	SO4
Bungil Formation	88-166	8.0	2,525	527	17	6	1	448	469	43	98
Mooga Sandstone	98-499	8.3	1,789	453	5	2	2	205	594	51	25
Orallo Formation	41-59	8.2	1,812	428	9	3	2	235	533	34	37
Gubberamunda Sandstone	72-139	8.1	1,204	319	5	2	2	161	478	17	24
Walloon Coal Measures	56-119	8.2	4,438	886	14	8	5	766	566	30	14
Hutton Sandstone	155-305	8.0	1,015	196	8	3	2	156	265	9	13
Precipice Sandstone	112-260	7.5	291	57	5	1	3	24	98	1	6
Rewan Group	9-15	7.6	6,681	1,265	118	79	7	1,735	235	3	8
**Bandanna Formation	30	NA	9,101	2,014	14	4	19	2,154	1,634	70	1

**n* = number of samples. The number of samples varies between analytes.

EC (Electrical conductivity) is expressed in µS/cm at 25°C; pH is expressed in pH units.

Sources: DNRW groundwater database; **provided by Santos

2.3.6 Existing Groundwater Monitoring

Over many decades, extensive groundwater monitoring has been carried out by DNRW in private landholder bores and specific DNRW monitoring bores, resulting in a large groundwater database of bore-specific information. The database includes information on strata logs, bore construction, aquifer thickness, bore locations, water levels, and water chemistry. However, generally this data is not sufficiently detailed for the purpose of accurate assessment of local conditions. Also, due to input of data by many recorders over a long period of time, as such many inaccuracies exist.

Figure 2-6 shows the location of DNRW monitoring bores and monitoring bores installed by Santos within the Comet Ridge field areas.

2.3.7 Previous Groundwater Modelling

Two previous groundwater flow assessments of the Comet Ridge fields have been conducted on behalf of CSG companies (AHA, 2003; SKM, 2006).

The AHA report examined groundwater flow in the Fairview CSG field. It considered predicted rates of groundwater extraction and effects on adjacent aquifers of the GAB. Uncertainty regarding groundwater gradients and the effects of faults on groundwater flow were discussed. In 2003, with 57 CSG wells in operation at Fairview, underlying formations were hypothesised as a source of groundwater of higher salinity.

In a numerical model, groundwater extraction from CSG wells was simulated by the MODFLOW DRAIN function. Impacts on many aquifers, including the Hutton Sandstone, were simulated. The maximum drawdown within the coal measures was predicted to be more than 500 m. The maximum predicted drawdown within the Precipice Sandstone of 25 m occurred in 2027 near Hutton Creek. The maximum extent of drawdown occurred, at a later time, along the zero Triassic sub-crop (i.e. the contact between the Bandanna Formation and the Precipice Sandstone). Routine monitoring of Precipice water levels near the Bandanna-Precipice contact was recommended.

The SKM report followed the same modelling approach for a larger number of CSG wells in an extended area. While the extent of drawdown in the Bandanna Formation was consequently greater, predicted drawdowns in the Precipice Sandstone were similar to the AHA model results. Decline in baseflow to the Dawson River associated with CSG extraction was considered to be insignificant.

Both reports acknowledged the limitations of using the MODFLOW DRAIN function to simulate water extraction in CSG fields.

2.4 ROMA CSG FIELD

The Roma CSG field comprises of numerous ATPs and PLs. Current activities include exploration drilling and pilot well installations. **Figure 2-7** shows the layout of the Roma CSG field.

2.4.1 Geology

The Roma CSG field lies within the Surat Basin which consists of consolidated Jurassic, Cretaceous and Tertiary sediments and poorly consolidated Cainozoic colluvium and alluvium associated with local creeks (**Figure 2-8**). This section of the Surat Basin overlies the Upper Triassic sediments of the Bowen Basin.

Generalised stratigraphy of the Roma field is shown in **Table 2-5**.

The Jurassic aged Walloon Coal Measures is the CSG target unit within the Roma field. The Walloon Coal Measures in the Roma field comprise of (in stratigraphic order):

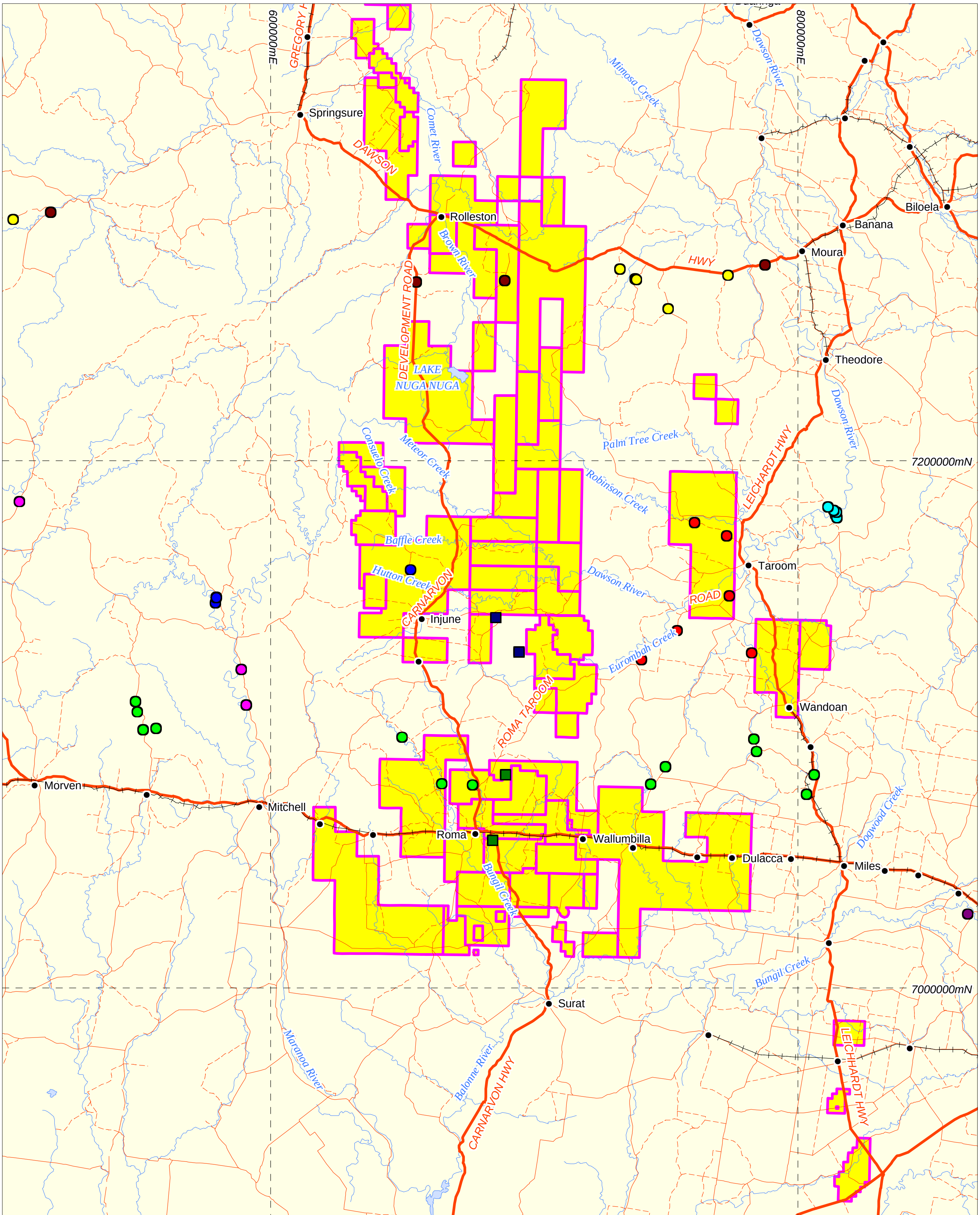
- Upper Juandah Coals;
- Proud Sandstone;
- Lower Juandah Coals;
- Tangalooma Sandstone;
- Taroom Coals; and
- Durabilla Formation.

The thickness of the Walloon Coal Measures in the Roma field ranges from 100-460 m and the depth to coal across the field varies from 170-933 m. Data from exploration logs provided by Santos indicate the coal seam may vary in thickness from 2 to 10 m and be separated by 30 to 80 m of predominantly silts and tight sands that restrict any vertical leakage between seams and overlying. Multiple seams may be encountered in a single well.

Unlike the strongly dipping and faulted geology in the Comet Ridge area, the geology of the main units i.e. the Walloon Coal Measures, the Hutton Sandstone, the Injune Creek Group and the overlying Gubberamunda Sandstone and Mooga Sandstone are relatively uniform over the Roma CSG field.

Table 2-5 Generalised Roma Field Stratigraphy

Age	Group	Formation
Cretaceous		Wallumbilla Formation
		Bungil Formation
		Mooga Sandstone
Jurassic		Orallo Formation
		Gubberamunda Sandstone
	Injune Creek Group	Westbourne Formation
		Springbok Sandstone
		Walloon Coal Measures
		Eurombah Formation
		Hutton Sandstone
		Evergreen Formation
		Precipice Sandstone
Triassic	Rewan	Moolayember Formation
		Clematis Sandstone
		Rewan Formation



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LEGEND

- Santos ATP & PL Tenement
- Highway
- Road
- Track
- Railway
- Watercourse
- Town

DNRW Registered Bore

- BIRKHEAD FORMATION
- HOORAY EQUIVALENTS
- HUTTON SANDSTONE
- INJUNE CREEK GROUP
- MOOLAYEMBER FORMATION
- PRECIPICE SANDSTONE
- REWAN FORMATION
- WALLOON COAL MEASURES

Monitoring Bore

- Santos Tensiometers
- Santos-Origin JV Precipice SS

Data Source:
Topography - Geoscience Australia. Tenement - URS

Santos Ltd

Santos GLNG EIS

Existing Groundwater Monitoring Bore Locations - Comet Ridge and Roma CSG Fields

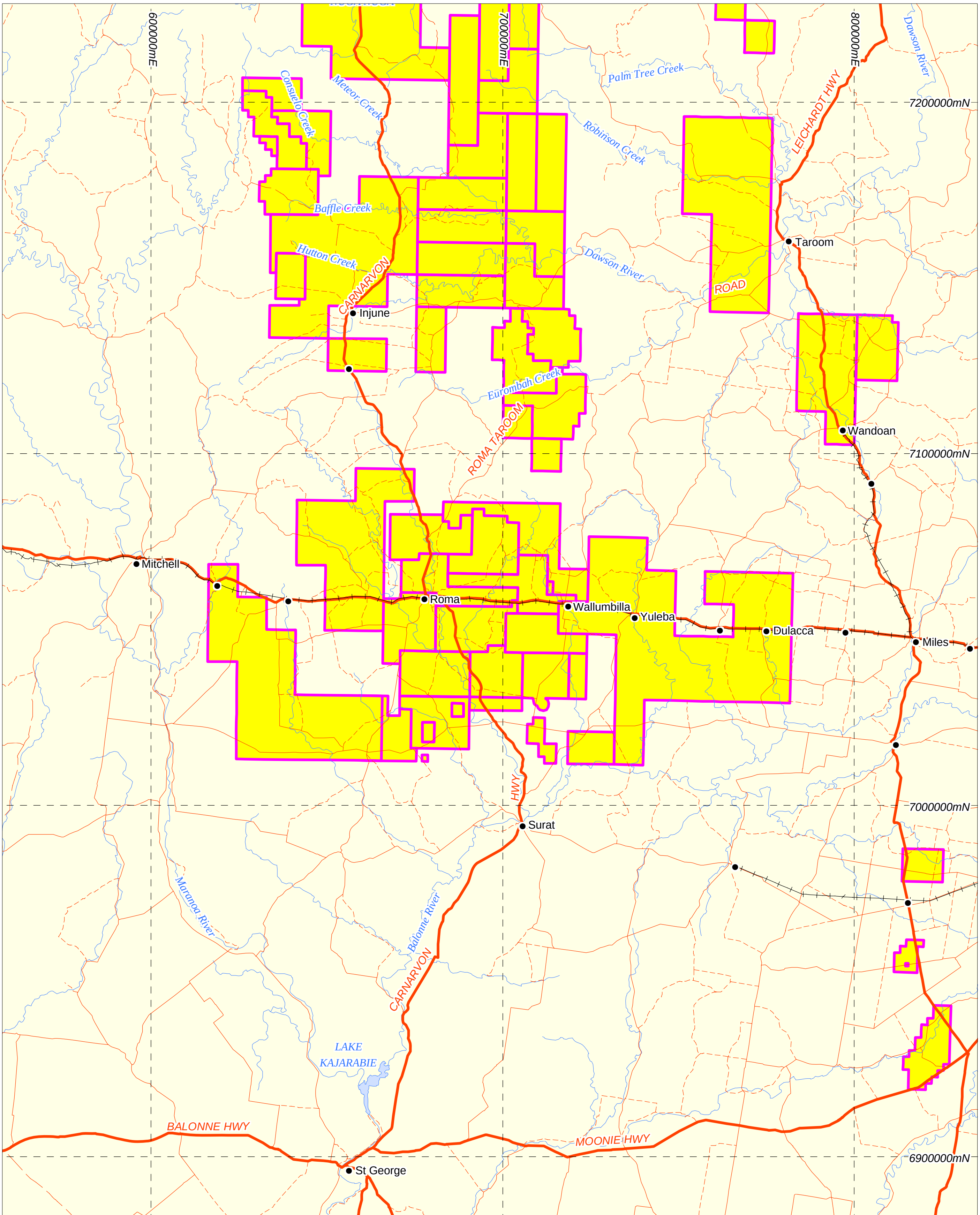
0 40 80

Kilometres

Scale: 1:2,000,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 2-6



LEGEND

- Santos ATP & PL Tenement
- Highway
- Road
- Track
- Railway
- Watercourse
- Town

Santos Ltd

Santos GLNG EIS

Layout
- Roma CSG Field

0 25 50
Kilometres

Scale: 1:1,500,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 2-7

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Data Source:
Topography - Geoscience Australia. Tenement - URS

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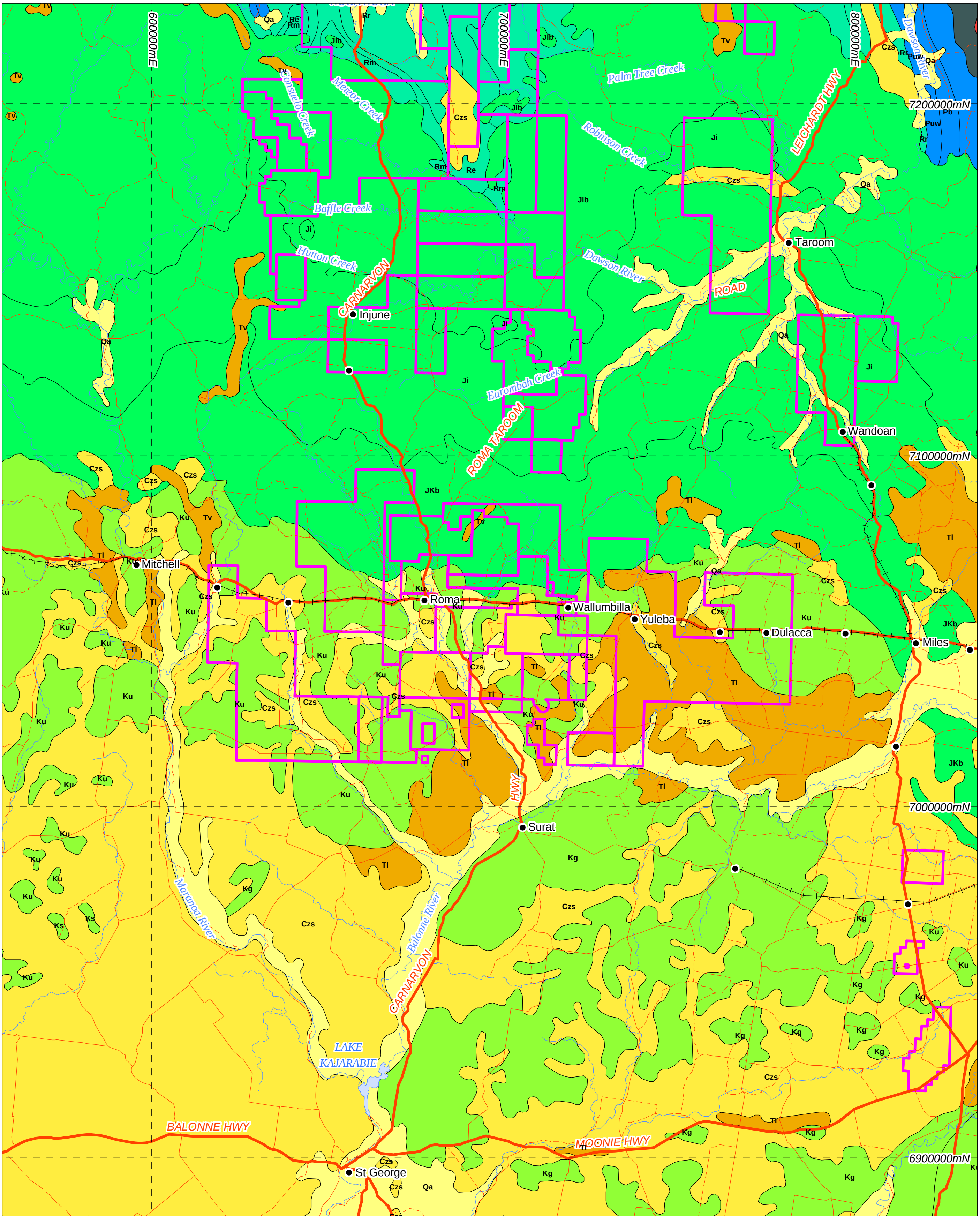

LEGEND

- Santos ATP & PL Tenement
- Highway
- Road
- Track
- Railway
- Watercourse
- Town

Data Source:
Topography - Geoscience Australia. Tenement - URS

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matrixplus

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Santos Ltd

Santos GLNG EIS

Surface Geology
- Roma CSG Field

0 25 50
Kilometres

Scale: 1:1,500,000 (A4)

N
Datum: GDA94
Projection: MGA55

FIGURE 2-8

2.4.2 Groundwater Occurrence

Within the Roma field aquifer, systems associated with both the Surat and Bowen Basins exist. **Table 2-6** shows the stratigraphic nomenclature for the Roma field and describes each unit's hydrogeological characteristics.

Table 2-6 Generalised Groundwater Occurrence Across the Roma CSG Field

Age	Group	Formation	Hydrogeological Characteristics
Cretaceous		Wallumbilla Formation	Aquifer
		Bungil Formation Unfifferentiated	Water bearing
		Mooga Sandstone	Aquifer
Jurassic		Orallo Formation	Confining bed
		Gubberamunda Sandstone	Aquifer
	Injune Creek Group	Westbourne Formation	Confining bed
		Springbok Sandstone	Water bearing
		Walloon Coal Measures	Water bearing
		Eurombah Formation	Water bearing
		Hutton Sandstone	Aquifer
		Evergreen Formation	Confining
		Precipice Sandstone	Aquifer
Triassic	Rewan	Moolayember Formation	Confining bed
		Clematis Sandstone	Aquifer
		Rewan Formation	Confining bed

The Wallumbilla Formation underlies most of the Roma field from the north of the field where it outcrops. Sandstone lenses within the Wallumbilla Formation provide sub-artesian water supplies, used predominately for stock and domestic purpose. Yields are low (<5 L/s), and water quality is variable due the marine deposition of this formation (DNRM, 2005).

The Bungil Formation is comprised of interbedded sandstone, siltstone and mudstone within three members; the Minmi, Nullawart Sandstone and Kingull Member. The Kingull Member is a confining bed while the Minmi and Nullawart Sandstone provide sub-artesian supplies, predominantly in the north of the Roma field, for stock and domestic purposes.

The Mooga Sandstone aquifer extends over the entire Roma field and outcrops in the north where it is recharged. This aquifer is used extensively for stock, domestic and feedlot purposes. It also provides significant urban water supply for surrounding towns including; Muckadilla, Roma, Wallumbilla and Yuleba. Water quality is good and yields are high (up to 35 L/s) (DNRM, 2005).

The Gubberamunda Sandstone is the major aquifer unit in the Roma CSG field and its surrounds. Extraction from this unit accounts for over 50% of stock and domestic use and approximately 70% of the water allocated for other purpose (DNRM, 2005). The Gubberamunda Sandstone aquifer provides significant feedlot, industrial and urban supplies, including the town of Roma.

The Injune Creek Group provides predominantly sub-artesian stock supplies, due to the poor water quality. The Walloon Coal Measures, in particular, contain highly saline water ranging from 1,500 to over 10,000 µS/cm (DNRM, 2005).

The Hutton Sandstone aquifer underlies most of the Roma CSG field. Even though its water quality is good this aquifer is not extensively developed in this area owing to its depth.

The Precipice Sandstone and the Triassic sediments (including the Clematis Sandstone) underlie the Roma CSG field. These aquifers are known to contain significant supplies of good quality water however they are relatively undeveloped due to their depth. Nonetheless, a number of bores are screened within these aquifers in close proximity to the Roma field and have been converted from conventional petroleum exploration wells.

2.4.3 Groundwater Use

A registered bore search of the DNRW database suggests groundwater for domestic consumption, and stock water, is derived predominantly from the Mooga and Gubberamunda Sandstone aquifers in the Roma area. The location of registered bores is shown in **Figure 2-9**, additional landholder bores many exist which have not been registered with the Department.

The Mooga and Gubberamunda Sandstone aquifers provide the only current source of groundwater supply for urban purposes for Roma. As a result of the current demands on the Mooga and Gubberamunda Sandstone aquifers, it is anticipated that additional extraction in the future will be required to be drawn from the deeper Hutton Sandstone.

The Walloon Coal Measures are not extensively utilised in the Roma area due to its depth and poor water quality. The Hutton Sandstone underlies the Walloon Coal Measures, and is relatively undeveloped in the Roma area due to its depth. Whilst the current entitlements and use are very small for the Hutton Sandstone proximal to the Roma field, future extraction needs to be monitored as this aquifer extends beyond the Roma field and it is used extensively in these locations.

2.4.4 Groundwater Levels

See section 2.3.4.

2.4.5 Groundwater Quality

See section 2.3.5.

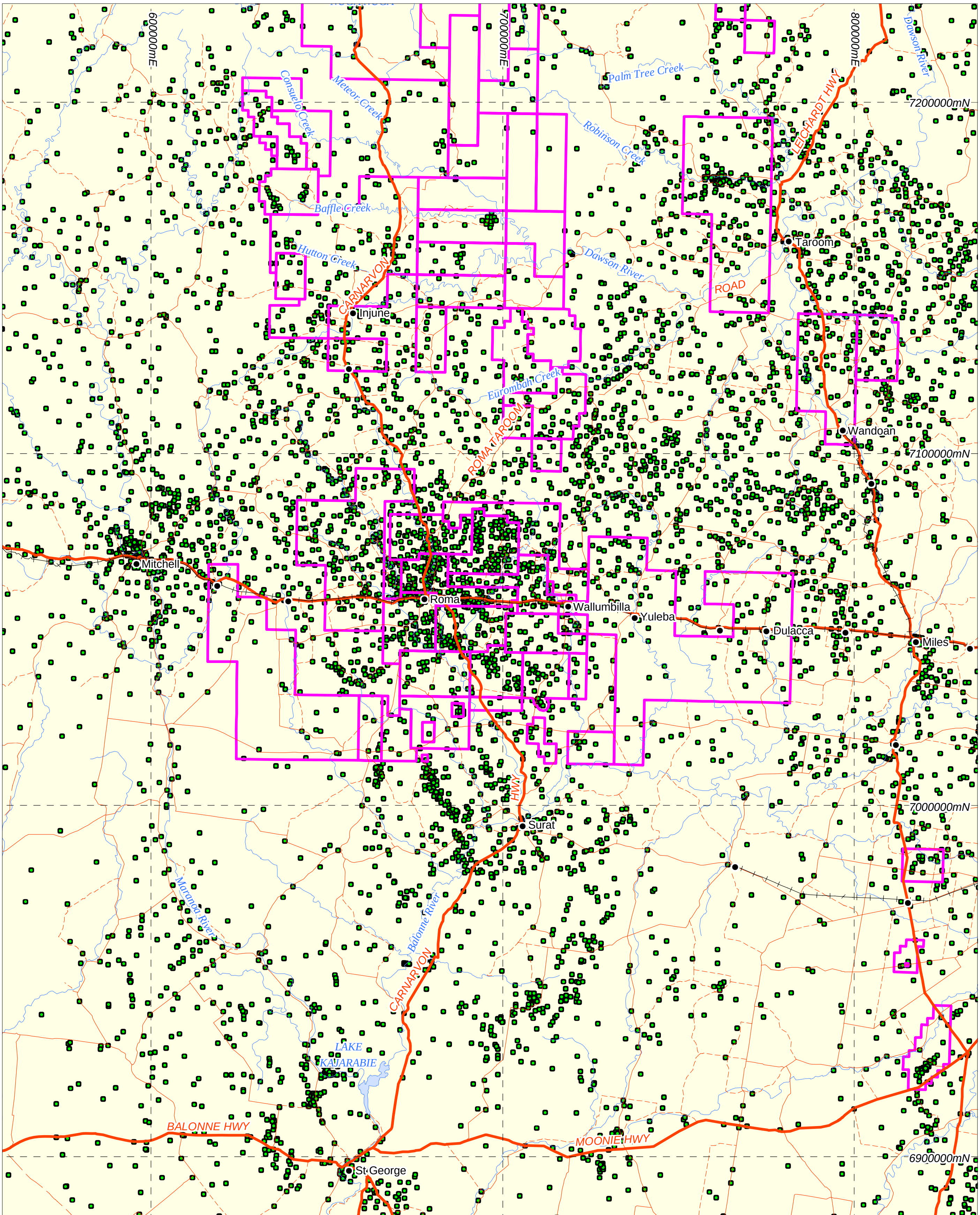
2.4.6 Existing Groundwater Monitoring

To date, Santos has installed nested vibrating wire tensiometers within two boreholes in the Roma CSG field to monitor pressures at various depths and adjacent to various aquifers. The boreholes are backfilled with cement/grout so that the tensiometers are encased in grout. After a short period of initial grout stabilisation following borehole conversion and equilibration of grout pore pressure, pressure readings correspond with the pressures determined within particular aquifers during drill stem testing. The installation of further nested vibrating wire tensiometers, as well as a number of conventional monitoring wells is planned.

2.5 GROUNDWATER LEGISLATION RELEVANT TO CSG EXTRACTION

CSG exploration and production is carried out under the *Petroleum and Gas (Production and Safety) Act 2004*. Impacts on groundwater resources associated with CSG projects must be mitigated through compliance with legislation requirements to ensure environmental responsibility.

The Queensland CSG industry has an unlimited right to take water as part of petroleum production as stated under section 185 (1) *Petroleum and Gas (Production and Safety) Act 2004*. However, the legislation requires for a petroleum tenure holder to assess and monitor potential impacts of petroleum production on existing groundwater users, by stipulating numerous mitigation measures which are to be emplaced by the tenure holder. **Table 2-7** summarises mandatory mitigation measures under the *Petroleum and Gas (Production and Safety) Act 2004*.



LEGEND

- Santos ATP & PL Tenement
- DNRW Registered Bore
- Highway
- Road
- Track
- Railway
- Watercourse
- Town

Data Source:
Topography - Geoscience Australia. Tenement - URS

30/01/2009

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Santos Ltd

Santos GLNG EIS

DNRW Bore Locations
- Roma CSG Field

0 25 50
Kilometres

Scale: 1:1,500,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 2-9

Table 2-7 Petroleum Tenure Holder – Legislative Requirements

Section	*Petroleum and Gas (Production and Safety) Act 2004* Conditions
Water monitoring activities	
187	(1) A petroleum tenure holder may carry out any of the following activities in the area of the tenure to comply with, or assess the need to comply with, the make good obligation for the tenure— (a) gathering information about, or auditing, an existing Water Act bore; (b) gathering information for an underground water impact report, pre-closure report, monitoring report or review report; (c) monitoring the effect of the exercise of the underground water rights for the tenure; (d) constructing or plugging and abandoning a water observation bore; (e) carrying out restoration measures in relation to an existing Water Act bore for which the make good obligation applies.
Obligation to make good for existing Water Act bores	
250	(1) 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 restoration measures to restore the supply of water to the owner of the bore; or (b) compensate the owner for the bore being unduly affected.
Request for trigger thresholds	
253	(1) The petroleum tenure holder may ask the chief executive what the trigger threshold is for the aquifers. (2) The chief executive must— (a) if no trigger threshold already applies for the aquifers—fix a trigger threshold for the aquifers and tell the tenure holder what that trigger threshold is; or (b) if, under section 255, a trigger threshold already applies for the aquifers—tell the tenure holder what that trigger threshold is.
Underground water impact report	
257	(1) Subject to section 258, an underground water impact report must include each of the following— (a) the trigger threshold for aquifers in the area affected by the exercise of underground water rights for the petroleum tenure; (b) details of an underground water flow model prepared by the holder to predict the drop in the water level, because of the exercise of the rights, in aquifers predicted by the holder to be affected by the exercise of the rights; (c) the area and aquifers predicted by the holder to be affected by the rights; (d) details of the existing Water Act bores predicted by the holder to be unduly affected by the exercise of the rights, either alone or in combination with the exercise of underground water rights of another petroleum tenure holder; (e) an estimate of when each of the bores will become unduly affected; (f) details of a monitoring program proposed to be carried out by the holder to monitor the impact of the exercise of the rights; (g) other information or matters prescribed under a regulation.
Pre-closure report	
262	The pre-closure report must state each of the following— (a) the existing Water Act bores that, after the petroleum tenure ends, the tenure holder predicts may become unduly affected by the exercise of the underground water rights for the tenure during its term; (b) an estimate of when each of the bores will become unduly affected; (c) what steps have been taken to comply with the make good obligation in relation to the bores; (d) the information or matters prescribed under a regulation.
Monitoring and review reports	
265	(1) This division requires the tenure holder to lodge monitoring reports and review reports. (2) The purpose of a monitoring report is to monitor the effect of the exercise of a petroleum tenure holder's underground water rights. (3) The purposes of a review report are to— (a) compare the effect of the exercise of the rights with the predicted effect in the holder's relevant underground water impact report to show whether the report continues to be appropriate; and (b) amend the underground water impact report to reflect the results of the comparison.

3 POTENTIAL GROUNDWATER IMPACTS

The drawdown of groundwater heads within CSG aquifers is a necessary process and an unavoidable impact associated with the depressurisation of the target coal seam.

The rate at which water is pumped from wells during depressurisation varies not only between different fields and different parts of the same field but also during the lifespan of individual producing wells. The rate of groundwater extraction will exceed the rate of replenishment of the resource through recharge, thus reducing the volume of water stored within the aquifer. The extent of drawdown (i.e. radius and magnitude of influence) within coal seams is site-specific and is dependent on the intensity of production, style of wellfield configuration, aquifer hydraulic parameters, duration of pumping and geological conditions. The extent of drawdown is important when determining the potential impact on other groundwater users.

During the construction of CSG production wells, the overlying aquifers are sealed off and the open section of the production well is located only within the target coal seams. Hence, the pumping well is unlikely to extract water directly from these overlying aquifers. However, pressure differentials between the waters in the coal seam and the waters in other aquifers above or below the coal seam aquifer may result in indirect access by inter-aquifer transfer and a subsequent reduction in water levels in those aquifers. Such inter-aquifer transfer could occur either vertically through the low-permeability confining beds between the aquifers or vertically through fault zones if they exist.

As part of its proposed CSG field development activities, Santos proposes to drill and complete approximately 540 development wells prior to 2015 and over 800 wells post 2015 (excluding exploration wells).

Santos' operations will concentrate within the Comet Ridge fields (Fairview, Arcadia and Spring Gully) and Roma field, as illustrated in **Figure 1-1**.

During the CSG project development and operation, potential impacts which could be related to the withdrawal of groundwater from the coal seams are:

- drawdown of groundwater head levels within CSG aquifers (i.e. coal seams);
- drawdown of groundwater head levels within overlying and underlying aquifers;
- reduction of bore yields from town water supply bores and landowner bores in the area surrounding CSG projects (due to lower groundwater heads) where the bore owner extracts groundwater from impacted aquifers;
- reduction in spring flow and baseflow of streams by reducing the groundwater discharge to those features;
- contamination of shallow aquifers and surface waters surrounding CSG projects via leakage of by-product water storages; and
- subsidence of the land surface overlying the wellfield.

3.1 GROUNDWATER MODEL DEVELOPMENT

In order to test the likely impact of significant depressurisation of coal measures within the Comet Ridge and Roma CSG fields, conceptual and mathematical models of groundwater flow were developed following accepted guidelines for the modelling of groundwater flow (ASTM, 1994; Middlemis, 2000).

Conceptual models for both areas were developed by considering geologic frameworks (e.g. aquifer types, aquifer geometry, aquifer parameters), hydrologic frameworks (e.g. recharge and discharge zones, recharge rates, groundwater level and groundwater chemistry records), current groundwater users (including environmental use) for all fields and hypothetical future rates of use.

Different approaches were adopted in constructing mathematical models for the Roma and Comet Ridge CSG fields. In the case of Roma, analytical models were considered suitable, largely due to the paucity of the CSG field data and the comparatively simple geologic geometry.

The methodology used to assess the impact of gas extraction from the coal measures was based on the application of Darcy's Law and the normal theory of groundwater flow through porous media. While the coal measures could be classified more correctly as fractured media, it has been found in practice that, on a macro scale, the equations for flow through porous medium can be used satisfactorily in fractured media to predict aquifer responses to applied stresses such as groundwater extraction or groundwater recharge.

The application of these flow equations involves the use of a number of aquifer parameters. These parameters are listed below and the equations used are referred to in section **3.1.2**.

3.1.1 Aquifer Parameters

The main aquifer parameters that are relevant to this study are;

a) Hydraulic Conductivity (K)

b) Transmissivity (T)

c) Intrinsic Permeability (k)

d) Porosity (θ) and Specific Yield (S_y)

e) Storativity (or Storage Coefficient) (S)

f) Hydraulic Resistance (c) and

g) Leakage Coefficient or Vertical Leakage (V_L).

These parameters are described in detail in **Appendix A**.

3.1.2 Theory of Groundwater Flow and Drawdown Impacts

The wellfields used to extract gas from the coal seams are comprised of a number of individual wells, each extracting water from the aquifer at varying rates. The rate at which water can be extracted by an individual well depends on the aquifer parameters of the aquifer supplying the water; the pressure differential between the initial standing water level in the aquifer and the pumped water level in the well (the drawdown); the duration of pumping and the efficiency of the well, which is related to construction techniques.

The equations to groundwater flow were used to develop analytical models for the Roma field and the aquifer parameters and Darcy's Law were used to develop a numerical model for the Comet Ridge fields. These equations are discussed briefly in **Appendix B**.

While the groundwater flow equations have been developed for flow in porous media, it has been found that they can be applied with reasonable accuracy for flow through fractured rock aquifers on a macro scale. On the micro scale, the fractures and crevices in fractured rocks put a strong directional component into the flow that is not accounted for in the porous media equations but this is of no consequence in the analysis of these fields. The use of the flow equations for porous media is considered to be appropriate for the analysis of the CSG wellfields.

From discussions with Santos staff and an analysis of the available production test data from the Roma field, it was assumed that the turbulent head loss (the CQ^2 term in the equation to drawdown), (**Appendix B**) for the wells in all fields is zero i.e. the potentiometric water level in the well is taken to be the same as the water level in the aquifer immediately outside the well casing.

In addition, because of the large distances between some of the interacting wells, the value of u (**Appendix B**) was very large and it was not appropriate to use the Jacob's modification to the non-steady state flow equations. The Theis equation was used with the series extending to the u^{15} term.

Since one of the assumptions made in developing the non-steady state flow equations is that the aquifer is infinite in areal extent, the existence of an hydrologic boundary, either source or sink, will have an impact on the magnitude of the drawdown experienced. The effect of such a boundary can be simulated by imposing an 'image well' equidistant from but on the opposite side of the boundary from the pumping well. The image well is a discharging well if the boundary is an impermeable boundary and is a recharging well if the boundary is a fully-penetrating recharge boundary with a constant head.

Likewise cessation of pumping can be simulated by the introduction of a hypothetical recharge pump superimposed on the (continuing) discharging well but starting at the actual time of cessation of pumping.

Owing to the comparatively greater complexity of the geometry of the Comet Ridge CSG field and the greater availability of field data, a numerical model of groundwater flow was constructed based on the MODFLOW groundwater flow simulation programme (McDonald and Harbaugh, 1984).

The following section describes how each model was developed.

3.2 COMET RIDGE GROUNDWATER MODEL

3.2.1 Conceptual Model

3.2.1.1 Model Complexity

The model was designed specifically to study the impacts that large scale extraction of water from the Bandanna Formation would have on (a) the water resources of the Bandanna Formation itself, (b) the interaction between the waters in the Precipice Sandstone aquifer and the Bandanna Formation and (c) potentiometric levels in adjacent aquifers. The model also considers impacts on baseflow in the Dawson River, tributaries and springs. The complexity of the numerical model was deemed to be sufficient for an impact assessment study. Owing to data limitations (e.g. current and future water productions rates, Precipice Sandstone water levels and hydraulic gradients), construction of a highly-detailed model was not warranted. With future data acquisition, it will be possible to modify the model to include refined parameter estimates and additional geologic layers.

3.2.1.2 Data Collation and Initial Interpretation

3.2.1.2.1 Data Collation

In developing conceptual and mathematic models of groundwater flow, extensive use was made of hydrogeological data, regional geological maps and site-specific geological and operational data made available to Matrixplus by Santos.

The DNRW database was searched within a search rectangle of dimensions 400 km east-west x 600 km north-south centred on the CSG fields. The database information included stratigraphy, lithology, aquifers, historical water levels and water quality data.

In order to increase confidence in estimates of aquifer parameters for the various aquifers in the area, an additional request was made of the DNRW for private landowner well tests. This information was able to be made available because the CSG projects were deemed to be of State significance.

Neither groundwater allocation nor water use data were available for the DNRW-registered wells in the area. The historical CSG extraction rates were made available to Matrixplus by Santos.

Streamflow data for the Utopia Downs stream gauging station 130324A were collected. Monthly rainfall records for Injune and Roma were collected for comparison with streamflow records.

The aquifer parameters assessed included transmissivity, storage coefficient and vertical leakage. The methodology used to determine these parameters is described fully in **Appendix C**.

3.2.1.2.2 Initial Interpretation

With respect to local groundwater movement, the significant elements of geology are:

- The Bandanna Formation, comprised of sandstone, coal, siltstone, mudstone, tuff and conglomerate is approximately 100 m thick in the CSG area. This formation dips steeply to the east and is kilometres deep in the centre of the Mimosa Syncline;
- Based on the effectiveness of the Evergreen Formation as an effective confining unit, the Hutton Sandstone is unlikely to be impacted by CSG groundwater extraction;
- While the Hutton Sandstone is more heavily utilised in the area, the Precipice Sandstone is the aquifer most likely to be affected by CSG extraction. Furthermore, it is assumed contact between the Clematis Sandstone and the Precipice Sandstone is sufficiently remote from the Precipice-Bandanna contact to be discounted;
- The Rewan Group is very thick and impermeable over most of the areal extent of the CSG fields however it does thin out to the west and in some areas is completely eroded away as it and the Bandanna Formation drape over the Comet Ridge. This allows easier access between the Bandanna Formation and the Precipice Sandstone;
- Permian formations underlying the Bandanna Formation are not significant aquifers and are considered to be aquicludes; and
- Based on geophysical evidence, the Hutton-Wallumbilla Fault (HWF) is a physical barrier to horizontal groundwater flow for at least some areas within the Bandanna Formation. In the southwest of the Fairview field, the throw of the Hutton/Wallumbilla Fault is such that it effectively makes the Bandanna Formation discontinuous and allows a much closer contact between the Bandanna Formation and the Precipice Sandstone. The type of contact is shown diagrammatically in **Figure 3-1**. The Precipice Sandstone is particularly vulnerable in one section, approximately 40 km long, where the Rewan Group has eroded away completely and the Bandanna Formation sub-crops under the Precipice. However, the interface between the two formations will not be clean and it has been assumed that a 50 m layer of undifferentiated (weathered) material exists between the two formations. The effect of minor faults within coal measures is less certain and may be less important than spatial *T* variations (see section **3.2.2.5** Model Assumptions).

Groundwater recharge rates in the Precipice Sandstone are not certain, however, based on recharge estimates for the Hutton Sandstone (Kellett *et al.*, 2003) and a comparison of groundwater salinity between aquifers, a recharge rate of between 7 and 15 mm/year was estimated. Based on hydraulic heads in existing Precipice Sandstone wells, estimates of groundwater recharge rates were numerically-calibrated based on a uniform *T* estimate of 50 m/day.

The high groundwater salinity within the Rewan Group and also the Bandanna Formation indicates that recharge is minimal within these formations. Within the Bandanna Formation, groundwater is progressively more saline down-dip and groundwater is fresher toward Comet Ridge. While this indicates contact with fresher formations, active groundwater flow in the coal measures is not likely under non-pumping conditions. Processes such as diffusion and compaction-driven flow over geologic time may be more significant in controlling groundwater movement in the coal measures.

For the Bandanna Formation, values of *T* were determined by the methods described in **Appendix C**. *T* varies significantly within the Bandanna Formation (**Figure 3-2**). The spatial distribution does not change uniformly across the CSG field. However, the following general trends are evident:

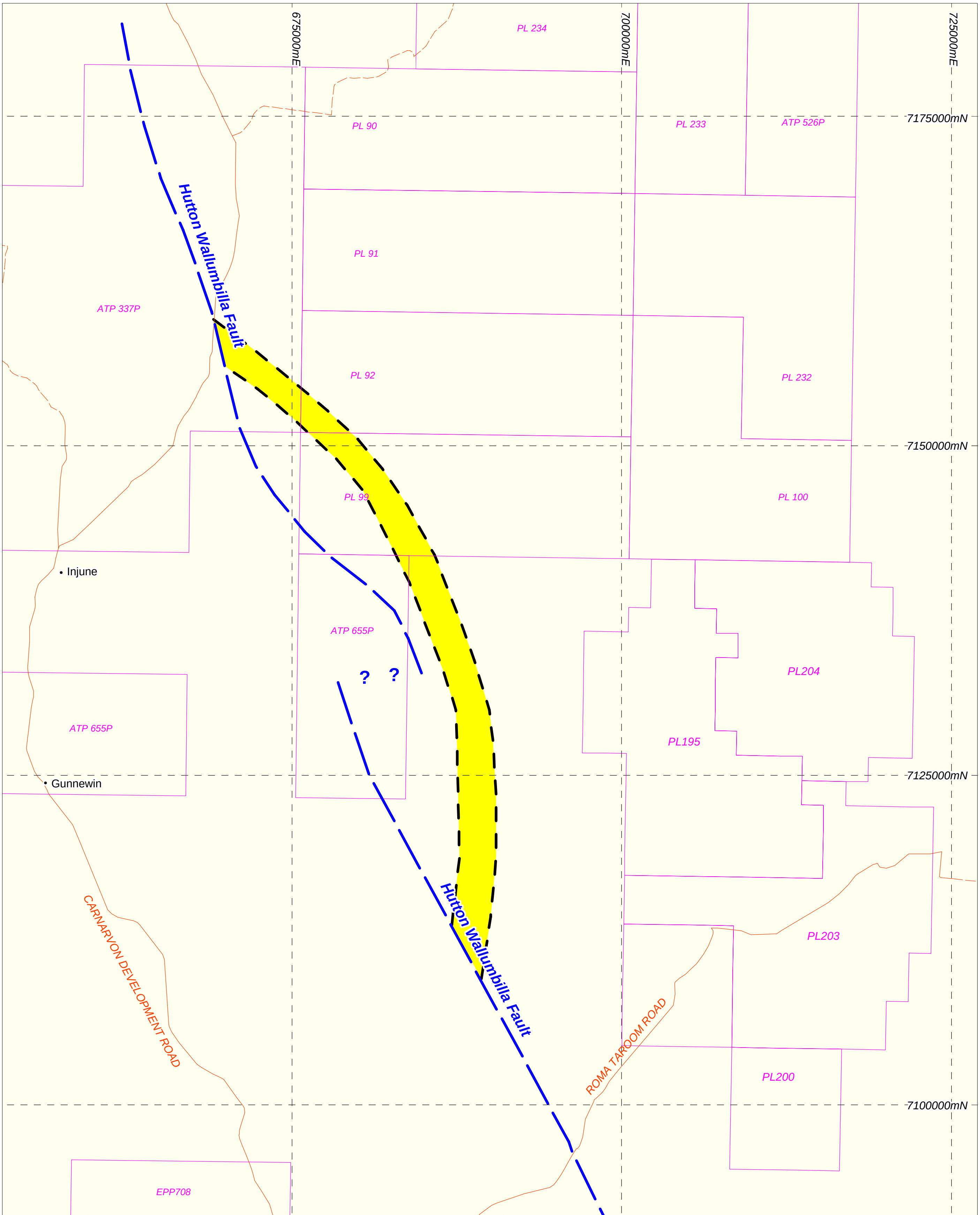
- associated with increased coal seam depth to the east of the CSG fields, *T* in the coal measures is markedly reduced. However, at a smaller scale (within the Comet Ridge CSG fields), the relationship between seam depth and transmissivity is less clear;
- *T* is generally less at Spring Gully than at Fairview. *T* estimates for Arcadia are not available but are known to be lower than for both other fields;

- in addition, *T* values for surrounding aquifers were determined based on analysis of private bore flow tests (**Appendix D**). Estimates of vertical hydraulic conductivity (and vertical leakage) are derived from these *T* values;
- initially, a storage coefficient of 1 x 10^{-4} was assumed for coal measures (later refined to 1.3 x 10^{-4}) and 1 x 10^{-4} for other consolidated rocks; and
- in the Comet Ridge area, the main productive aquifers are the Hutton Sandstone, Precipice Sandstone and Clematis Sandstone which all overlie the Bandanna Formation. There are no high groundwater users other than extraction associated with coal seam gas production which draws water from the Bandanna Formation.

3.2.1.3 Develop Conceptual Model

The following are key features of the conceptual model:

- due to the large number of hypothetical extraction wells, it is assumed inferred internal flow boundaries (i.e. faults within the CSG field) will not greatly affect the shape of the final drawdown volume;
- the interpretation of the contouring is that an average T value of 5 m^2/d can be applied for most of the field but zones of higher and lower *T* values occur within the fields;
- the extent of the contact between the Precipice Sandstone and the Bandanna Formation is only approximately known based mainly on geophysical surveys by CSG companies. While previous conceptual models of the contact considered isolated zones of erosion, this is conjecture and a contiguous zone was assigned in this model (**Figure 3-3**). This zone is partly within the southwest corner of the Fairview field;
- in the calibration model, bottom hole pressures for many low-yield bores are omitted. Also, due to uncertainty in production rates in the Spring Gully area, pressure observations for many wells in the south of the Fairview area were omitted from the calibration;
- groundwater heads are gradually drawn down over 10 years to a threshold operating pressure that is 70 m (approximately 100 psi) above the top of the Bandanna Formation; and
- while the Clematis Sandstone occurs within the Triassic sequence and in places directly underlies the Precipice Sandstone (to the west, north and east of the CSG area), the contact between these aquifers is distant enough from the CSG area that inclusion of the Clematis Sandstone in a model of preliminary groundwater impacts is not warranted.



matrixplus

LEGEND

- Santos ATP & PL Tenement
- Road
- Track
- Railway
- Town
- Contact Zone

30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS

Santos Ltd

Santos GLNG EIS

Contact Zone Between the Bandanna Formation and the Precipice Sandstone - Comet Ridge CSG Fields

0 5 10
Kilometres

Scale: 1:400,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 3-1

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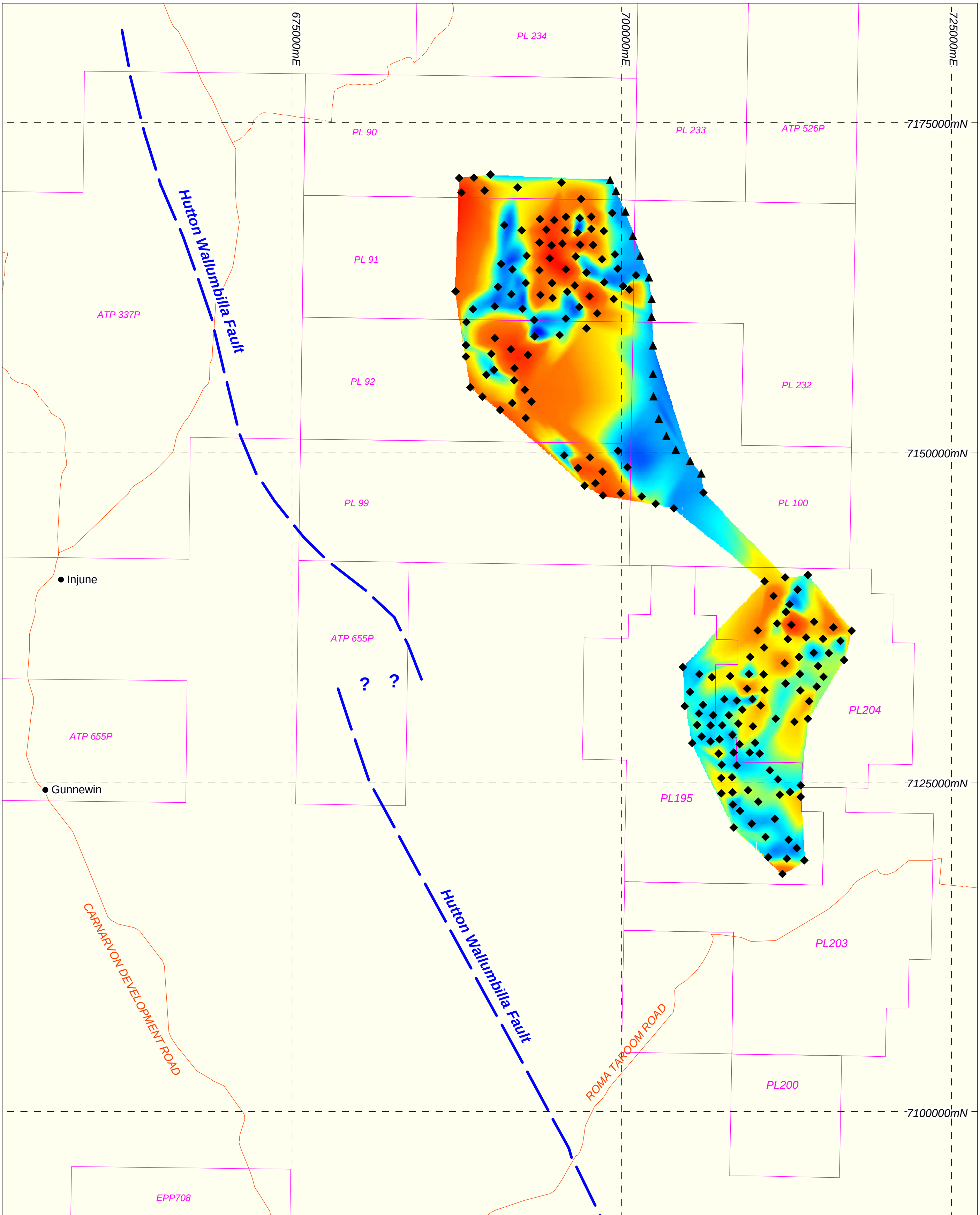

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matrixplus

LEGEND

- Santos ATP & PL Tenement
- Road
- Track
- Railway
- Town
- CSG Well
- Assumed Value

Transmissivity

20
5
2
1
0 (m2/d)

Santos Ltd

Santos GLNG EIS

Transmissivity Contours - Comet Ridge CSG Fields

0 5 10
Kilometres

Scale: 1:400,000 (A4)

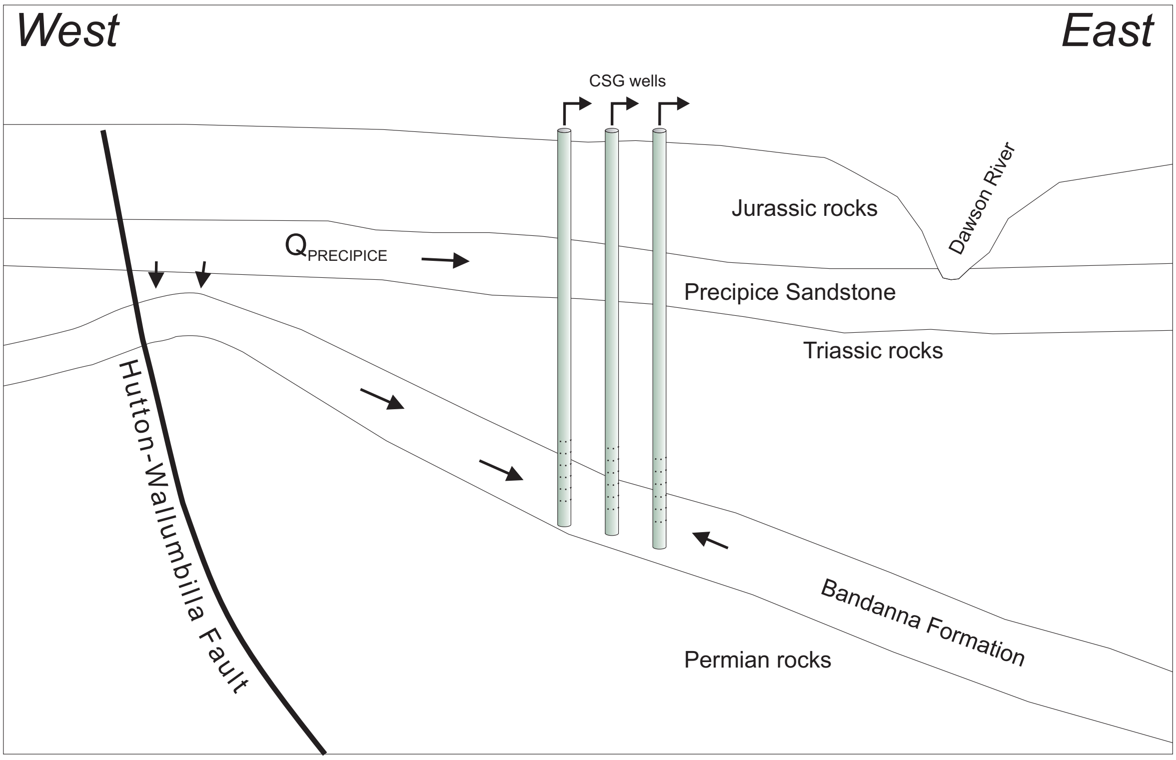
Datum: GDA94
Projection: MGA55

FIGURE 3-2

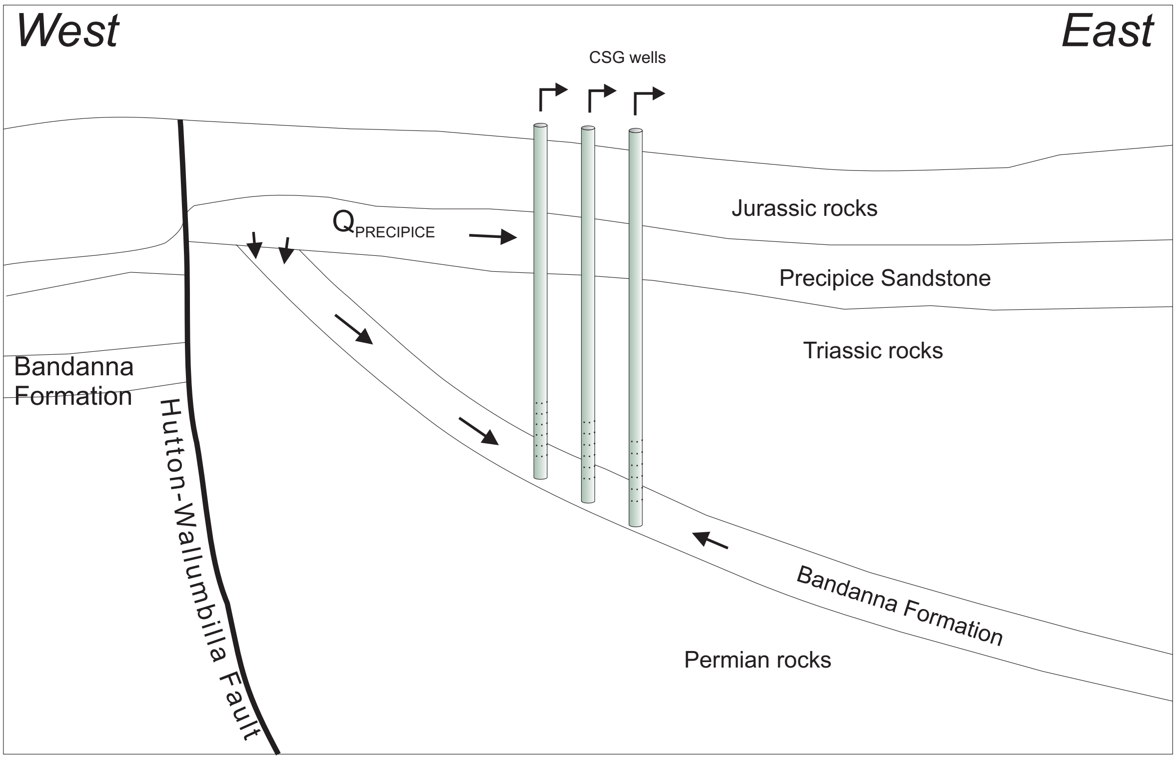
30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS

Northern Fairview Transect



Southern Fairview Transect



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Santos GLNG EIS
Conceptual Model – Comet Ridge CSG Fields
Figure 3-3

3.2.1.4 Model Code Selection

A numerical model based on the MODFLOW groundwater flow simulation programme (McDonald and Harbaugh, 1984) was selected to assess the impact of the CSG fields in the Comet Ridge area. A numerical model was used because sufficient hydrodynamic and aquifer parameter data were available and the aquifer geometry is complex.

Importantly, the MODFLOW software package is capable of simulating groundwater flow in fully-saturated conditions. Potential model instability due to the development of unsaturated flow conditions was considered to be unlikely in this setting. Subsequently, few model stability problems were encountered.

3.2.1.4.1 Feasibility of Mathematical Modelling

A number of limitations on the usefulness of mathematical modelling of groundwater flow in CSG fields are recognised.

Large drawdowns are predicted to occur in the Bandanna Formation, thereby creating large hydraulic gradients between the wellfield and other formations. There is necessarily great uncertainty in model predictions due to the marked departure from existing conditions. In particular, parameters estimating the vertical movement of groundwater are not as well constrained as for horizontal flow. Each geologic setting has unique characteristics and, therefore, improved aquifer parameter estimates can only be achieved following future monitoring and model refinement.

As noted in previous modelling, by not considering gas flow during depressurisation, rates of water removal are overestimated. However, pressure effects remote from the wellfield and in adjacent aquifers are still adequately simulated by conventional groundwater modelling.

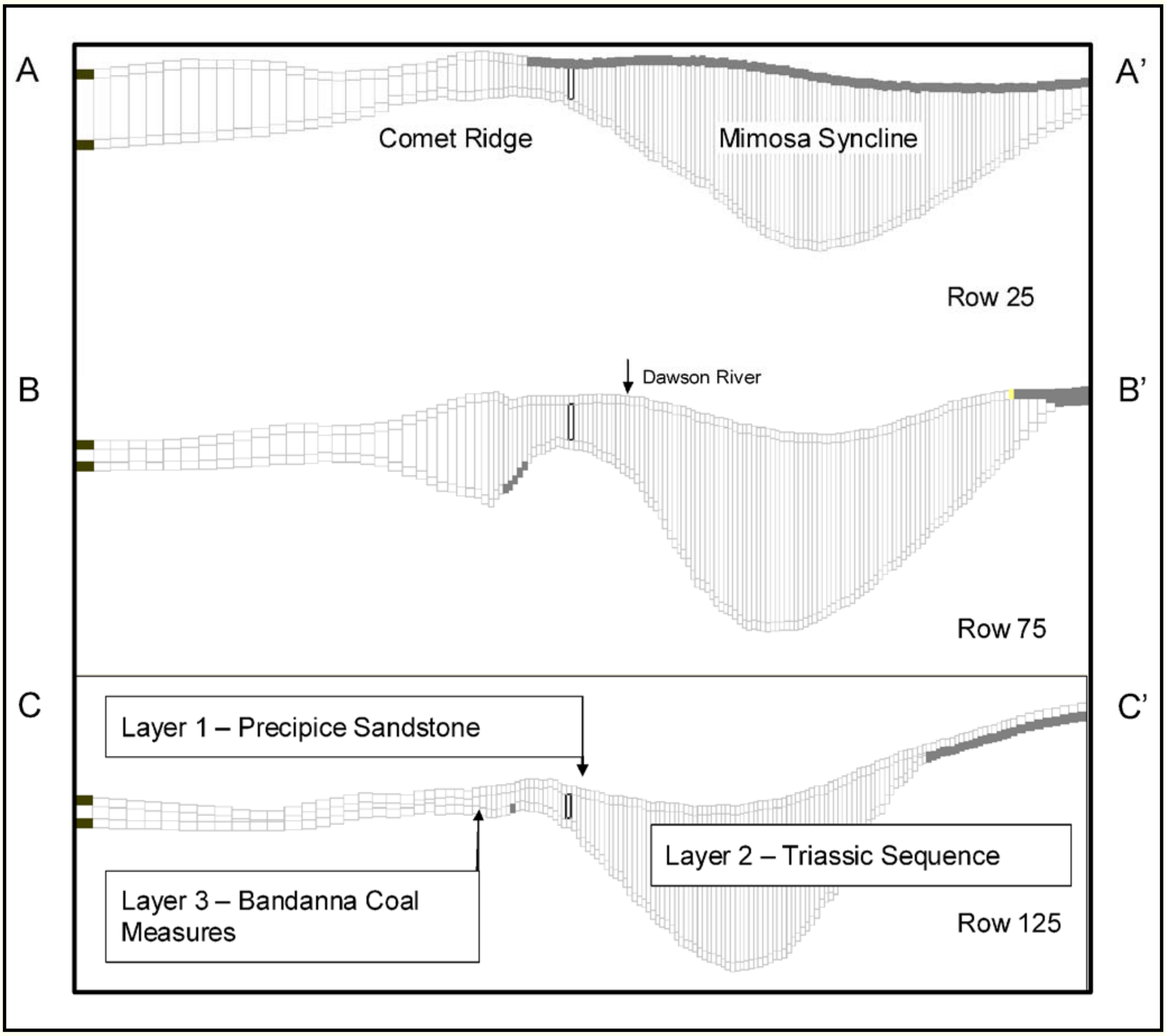
There are many aquifers with varying degrees of confinement and interconnection. However, by considering the Precipice Sandstone, Rewan Group and Bandanna Formation in isolation, a fit-for-purpose model of the impact of coal seam depressurisation can be assessed.

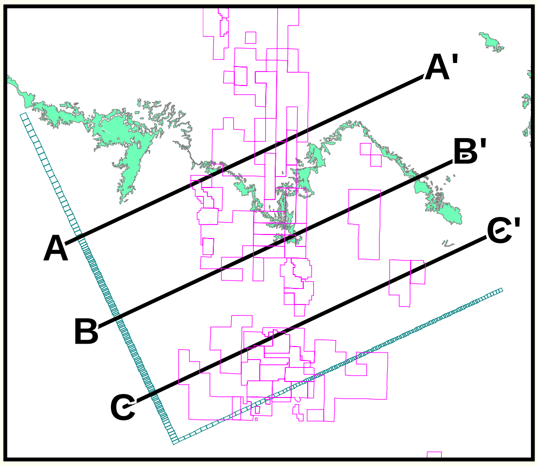
3.2.2 Mathematical Modelling

3.2.2.1 Model Construction

3.2.2.1.1 Model Geometry

The geometry of the model comprises three horizontal layers: an upper layer representing the Precipice Sandstone (Layer 1), an intermediate layer representing Triassic formations (Layer 2), and a layer representing the Bandanna Formation (Layer 3) (**Figure 3-4** and **Appendix E**). Layer 1 and Layer 3 are both assumed to be 100 m thick while the thickness of Layer 2 varies considerably. However, due to the assignment of user-specified T, S and V_L values, layer thickness is not a critical parameter in the model and chiefly aids in model visualisation. Minimum cell widths are approximately 1,350 m giving a total model extent of 289 km x 289 km. The model grid is aligned with the Hutton-Wallumbilla Fault (HWF) (22 degrees west of north).





matrixplus

LEGEND

- Santos ATP & PL Tenement
- Model GHB Cells
- Precipice Sandstone Outcrop

Santos Ltd

Santos GLNG EIS

Model Geometry
- Comet Ridge CSG Fields

0 100 200
Kilometres

Scale: 1:6,000,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 3-4

30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS

3.2.2.1.2 Time Steps

A calibration model was developed in order to inversely calibrate distributed *T* values within zones and also a non-distributed value of *S*. This model progressed from 1995 (incorporating late 1994) to 2008 with yearly stress periods for a total of 14 stress periods. Each year was subdivided into 5 time steps.

In the calibration model, it was assumed the V_L of the contact area was very low (10^{-8} d^{-1}). Drawdowns in the Bandanna formation at this contact area were not significant at the end of the calibration model.

Based on the results of the calibration model, a separate prediction model was developed. This model used the calibrated parameters from the calibration model and the Layer 3 hydraulic heads output of the calibration model as initial hydraulic heads. This model progressed in yearly stress periods from 2009 to 2028 for a total of 20 stress periods. Each year was subdivided into 5 time steps.

3.2.2.1.3 Boundary Conditions

Five types of boundary conditions were applied in the Comet Ridge numerical model:

- no-flow boundaries were applied where particular rock formations were absent and to simulate the HWF (in Layer 3 only). In Layer 1, the area to the north of the Precipice Sandstone outcrop is a no-flow area. In Layers 2 and 3, small areas in the north and east of the model grid are designated as no-flow boundaries to represent the absence of Triassic and Permian rocks;
- in order to ensure model stability, MODFLOW drain cells (head-dependent outflow boundaries) were assigned along the northern boundary of several Precipice Sandstone outcrop areas representing seepage areas. This condition has physical justification since intermittent and perennial releases of groundwater occur from the Precipice Sandstone to watercourses to the north (e.g. the Comet River). This feature of the model controls maximum groundwater heads in the recharge area;
- general Head Boundaries (GHB) (head-dependent bi-directional flow boundaries) were applied to the west and south boundaries of Layer 1 and to the west boundary of Layer 3; and
- river cells (head-dependent and head-conditional bi-directional flow boundaries) were applied to the area to the east of the CSG fields where the confluence of the Dawson River and Hutton Creek incises the Precipice Sandstone. A streambed conductance of 200 m^2/day was assumed. Streambed elevations of 235 mAHD were applied and river depth was assumed to be 2 m, i.e. a water surface elevation of 237 mAHD. For the reasons outlined below, rates of baseflow were not sensitive to these parameters.

Time-variant constant head cells representing the wellfield were used in the predictive model but not in the calibration model. The number of constant head cells was increased over time as field hypothetical development progressed. Because constant head boundaries were not used elsewhere in the model, the constant head component of the whole-of-model water budget predicted the progressive extraction of groundwater due to the wellfield.

3.2.2.1.4 Aquifer Parameters

Values of aquifer parameters used within the model are tabulated in **Table 3-1**.

Table 3-1 Aquifer Parameters Used in the Comet Ridge Mathematical Model

CSG Field	Transmissivity (T) (m2/d)	Storativity (S)
Fairview	Distributed (0.1- 18)	1.3×10^{-4}
Arcadia	0.5	1.3×10^{-4}
Spring Gully	Distributed (0.1- 15)	1.3×10^{-4}
Precipice Sandstone	50	10^{-4}

Constant *T* values were applied to Layer 1 and 2 of the numerical model.

The observed variation in well production rates (yields) warrants the assignment of spatially-variant (distributed) *T* values within the Bandanna Formation. Using these *T* estimates for individual wells and also using assumed low *T* values for points along the eastern edge of the CSG fields, *T* values for Layer 3 were distributed using the MODFLOW Field Interpolator routine.

For consolidated rocks (Layers 1 and 2), an *S* estimate of 1×10^{-4} was assigned uniformly. This is a minimum value based on the compressibility of water alone, a Precipice Sandstone bed thickness of 100 m and a porosity of 20%. However, this estimate is considered to be very close to the true value. An initial *S* estimate of 1×10^{-4} was made for Layer 3 (coal measures) that was later refined through calibration to be 1.3×10^{-4}. A specific yield (S_y) of 0.15 was assumed throughout; model results are not sensitive to this parameter.

User-specified vertical leakage (V_L) in Layer 1 and 3 was assigned as 10^{-8} d^{-1}. In the calibration model, it was assumed the V_L of the contact area within Layer 2 was very low (10^{-10} d^{-1}). In all models, the V_L value in the remainder of Layer 2 was set very low. Since Layer 3 is the lowest layer, the Layer 3 V_L value had no influence on model results. Drawdowns in the Bandanna formation at this area were not significant at the end of the calibration model.

3.2.2.1.5 Model Inputs

The primary input to both models was recharge to the main areas of Precipice Sandstone outcrop. For the two main areas of Precipice Sandstone outcrop furthest to the northwest of the Comet Ridge CSG fields, a recharge rate of 15 mm/y was applied. For other areas of Precipice Sandstone outcrop, a lower recharge rate of 7 mm/yr was assumed.

In the calibration model, the MODFLOW well function was used to simulate individual wells with averaged annual recorded water production rates assigned to each.

In the predictive model, existing CSG wells and all other wells were simulated by the MODFLOW Time-Variant Constant Head function. Field development was simulated by the introduction of batches of wells in each year until field areas were fully utilised. Available drawdown in each active time-variant head cell was reduced by 10 % each year to simulate progressive wellfield development.

No groundwater extraction by wells other than CSG wells was simulated.

3.2.2.2 Model Calibration

Model parameters were automatically calibrated against hydraulic heads recorded within the Fairview wellfield using the PEST parameter optimisation software (**Appendix F**) (Doherty, 2004). In the calibration model, bottom hole pressures for many low-yield bores are omitted from the calibration set. Also, due to uncertainty in production rates in the Spring Gully area, pressure observation for many wells in the southern part of the Fairview CSG field were omitted from the calibration.

For 50 water level observations in 39 wells, calibration was acceptable with a correlation coefficient (r^2) of 0.96 achieved between observed and simulated hydraulic heads.

3.2.2.3 Prediction Scenarios

A predictive model used Time-Variant Constant Heads to simulate the development of the three CSG areas (Arcadia Valley, Fairview and Spring Gully). The model was used to predict drawdowns in the Bandanna Formation and the Precipice Sandstone over a 20-year period (2009-2028). For the predictive model, outputs (drawdowns and mass balances) for 5-year intervals are presented (**Appendix G**). Baseflow and vertical leakage rates are important components of mass balance results. This is based on a particular scenario of wellfield development and operation but can be adapted to investigate different configurations in the future.

In order to isolate the relative contribution to drawdown by gas extraction wells at Spring Gully, an additional scenario considered the effects of pumping at Arcadia Valley and Fairview with no gas extraction at Spring Gully.

3.2.2.4 Sensitivity Analysis

The sensitivity of predictive model results to various estimates of aquifer parameters (e.g. V_L at the contact zone, recharge rates, T in the Precipice Sandstone) was tested. Drawdowns at specific points were compared in order to assess impacts on the Precipice Sandstone aquifer for different parameter values (**Table 3-2**). The specific points were the hypothetical observation points on the longitudinal and transverse axes of the predicted cone of depression in the Precipice Sandstone aquifer.

In Case 1b, T was reduced by one half (25 m/d) from the base case; in Case 1c, all recharge amounts were reduced by one-half. In Cases 2 and 3, V_L values were varied from Case 1. Only the value of V_L for Layer 1 is presented in **Table 3-2**, however both the values for Layers 1 and 2 are changed and are similar. The average relative changes between magnitudes of drawdown were averaged over four time periods (5, 10, 15, and 20 years).

Table 3-2 Sensitivity Analysis – Comet Ridge CSG Fields

Cases	VL (d-1)	Parameter Change (Magnitude)	T in Precipice Sandstone (m3/d)	Recharge (mm/y)	Ave. Relative Change from Base Case*
Case 1 (Base Case)	3.8 x 10-6	-	50	7 – 15	-
Case 1b	3.8 x 10-6	x0.5 (2)	25	7 – 15	+32%
Case 1c	3.8 x 10-6	x0.5 (2)	50	3.5 – 7	0.02%
Case 2	4 x 10-5	x~10 (10)	50	7 – 15	+2.1%
Case 3	3.85 x 10-7	x~0.1 (10)	50	7 – 15	-5.9%

*Average relative change (%) = ((Case result / Base case result) -1) / Magnitude of change

The analysis demonstrates that predicted drawdowns in the Precipice Sandstone are relatively sensitive to T in the Precipice Sandstone and relatively insensitive to the estimated rates of recharge. The recharge areas are remote from the Bandanna-Precipice contact area; recharge variations cause more water level variation within in the unconfined recharge areas.

Since estimates of V_L are not based on field information, a comparatively larger range of V_L values are tested. The sensitivity of drawdowns to variations in V_L varies with the magnitude of V_L because the maximum drawdown in the precipice Sandstone is limited. At lower values of V_L, relative changes in drawdown are more marked but the magnitude of the relative sensitivity is smaller than for T (6% cf. 32%).

3.2.2.5 Model Assumptions

The assumptions for the numerical model of the Comet Ridge CSG fields are summarised below:

- groundwater flow is considered in isolation. The inclusion of gas flow is not considered to significantly affect the validity of flow equations used within the model;
- due to proximity of the CSG fields, the Arcadia, Fairview and Spring Gully CSG fields were included in one groundwater flow model and the effect of their combined groundwater extraction was examined;
- three numerical model layers are sufficient to model groundwater movement between the Precipice Sandstone, Triassic rocks and the Bandanna Formation. It is assumed that groundwater flow from underlying aquifers to the Bandanna Formation is not significant;
- aquifer thickness and storativity is sufficiently uniform across the CSG fields to warrant the assignment of a constant layer thickness of 100 m and a constant storativity;
- the observed variation in well production rates (yields) warrants the assignment of spatially-variant (distributed) *T* values within the Bandanna Formation. Non-distributed *T* values are assigned to the Precipice Sandstone and to the Rewan Group;
- due to the large number of hypothetical extraction wells, it is assumed inferred internal flow boundaries (i.e. faults within the CSG field) will not greatly affect the shape of the final drawdown volume. Since the coal seams may be more compartmentalised than has been simulated, the model is conservatively large with respect to extent of drawdown;
- the extent of the contact between the Precipice Sandstone and the Bandanna Formation is only approximately known based mainly on geophysical surveys by CSG companies. While previous conceptual models of the contact considered isolated zones of erosion, this is conjecture and a contiguous zone was assigned in this model. This zone is partly within the southwest corner of the Fairview field; and
- groundwater heads are gradually drawn down over 10 years to a threshold operating pressure that is 70 m (approximately 100 psi) above the top of the Bandanna Formation.

3.3 ROMA GROUNDWATER MODEL

3.3.1 Conceptual Model

3.3.1.1 Model Complexity

The model was designed to specifically study drawdown within the Walloon Coal Measures as a result of depressurisation associated with CSG operations and impacts on adjacent aquifers. The complexity of the model was deemed to be sufficient for an impact assessment study.

3.3.1.2 Data Collation and Initial Interpretation

The values of the aquifer parameters for the coal seams used in the mathematical models are, wherever possible, values determined using field test data. However, some of the wellfields are in the early stages of development and data are not available and in other cases the testing procedures used are not amenable to accurate determination of aquifer parameters. In these cases, values used in the model have been determined by more approximate methods or are best estimates. However, these can be altered at a later stage when more reliable data become available.

3.3.1.3 Develop Conceptual Model

Bottom hole pressures within the coal seams were converted to hydraulic heads. Due to the small differences in hydraulic heads across the area and with depth, it was concluded that interpreted faults did not have a significant control over groundwater flow.

Therefore, a uniform head of 355mAHD was assumed to be the initial head across the Roma CSG area. Furthermore, existing hydraulic head differences within and between aquifers in the Roma area are significantly less than the hydraulic head differences likely to be generated as a result of CSG operations. Predicted drawdowns at CSG wells are many hundreds of metres in magnitude.

Due to the number and extent of CSG wells, the final combined drawdown in the coal measures will constitute an exceedingly large depressurised volume.

Figure 3-5 schematically illustrates the comparative effects in the coal measures and in underlying and overlying aquifers of large drawdowns in the coal measures.

Due to the phenomenon of flow refraction, all flow within the lower-permeability units between aquifers (aquifers and aquitards) will be normal to the direction of flow within aquifers. As shown in the schematic diagram, the velocity of flow within aquitards will be a function of hydraulic head differences between aquifers.

While various strata occur within the coal measures with various aquifer parameters, flow refraction effects within the coal measures were not considered; the coal measures were conceptualised as a single porous layer.

3.3.1.4 Model Code Selection

In the case of Roma, an analytical model was considered suitable, largely due to the paucity of the CSG field data and the simple geologic geometry.

Matrixplus Consulting has developed an in-house analytical groundwater model which is capable of analysing potential groundwater impacts due to CSG production. This type of model is applicable where aquifer geometry is simple and the application of non-distributed aquifer parameters is justified and was used to analyse the performance of the Roma CSG field.

By using a fully-explicit spreadsheet-based model, drawdown of threshold levels is better controlled than in proprietary numerical models where water is withdrawn at fixed rates (WELL function) or at head-dependent rates (DRAIN function). Furthermore, well efficiency factors can be accurately applied to individual wells. In total, the model consisted of a spreadsheet analysis of a wellfield comprised of 501 interacting wells with different start times and declining pumping rates.

Once threshold depressurisation is achieved at individual wells, water levels are kept constant by incrementally superimposing recharge rates with maximum rates equal to the maximum discharge rate for individual well, wells effectively operate ‘intelligently’.

Due to the predicted low rates of groundwater transfer between aquifers, this was treated as a separate exercise but was based on the predicted outputs from the analytical model.

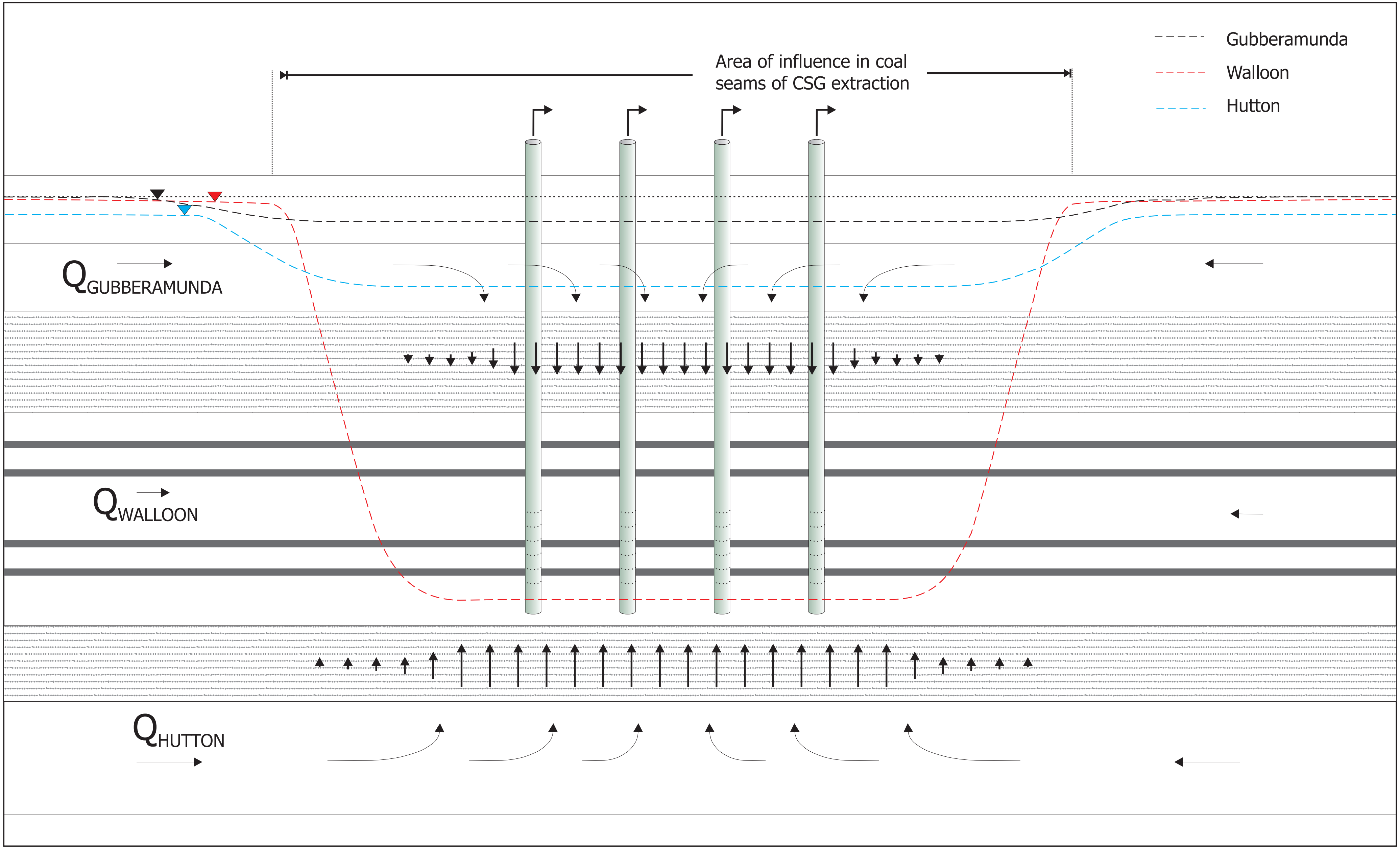
A complete coverage of the methodology and calculated results are included as **Appendix H**.

3.3.2 Mathematical Modelling

3.3.2.1 Model Construction

3.3.2.1.1 Model Geometry

While the analytical model models groundwater extraction from a single layer, threshold groundwater levels are based on 30 m above the base of the Walloon Coal Measures. Since the elevation of base of the Walloon Coal Measures varies across the CSG field, threshold pressures and available drawdowns vary across the CSG field. With uniform initial hydraulic heads, minimum available drawdowns range between 280 m and 840 m.



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Conceptual Model – Roma CSG Field
Figure 3-5

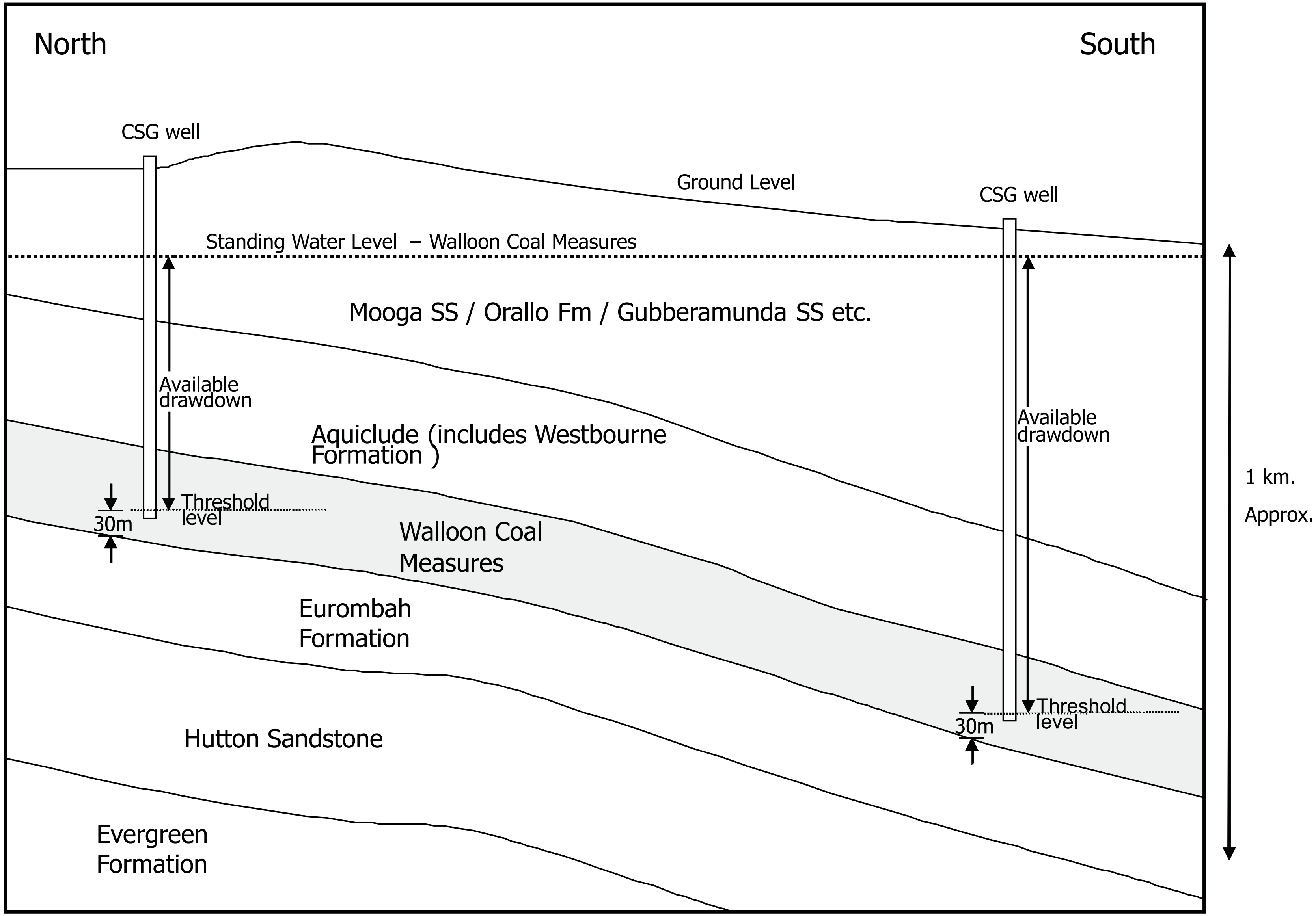

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Figure 3-6 Model Geometry - Roma CSG Field

3.3.2.1.2 Time Steps

The first 20 years of field operation was simulated, during which time no hypothetical wells were decommissioned. Being an explicit model, the model progressed in set time increments, e.g. 10 days, sufficiently short to allow model stability.

3.3.2.1.3 Boundary Conditions

The predicted drawdown within the CSG wellfield is based on superposition of the analytical groundwater flow equation for point drawdown resulting from all wells. Therefore, theoretically the field is of infinite extent. The validity of this assumption with regard to up-dip and down-dip boundaries is appraised on the basis of model output.

The recharge area for the Walloon Coal Measures lies within the sub-crop of the Injune Creek Group but is not well-defined. Overlying the recharge area of the Walloon Coal Measures is a sub-crop of weathered regolith which effectively reduces recharge.

It is likely that hydraulic conductivity in the coal seams becomes reduced down-dip as is the case for the Comet Ridge fields.

3.3.2.1.4 Aquifer Parameters

Hydraulic Conductivity (Coefficient of Permeability)

In the absence of relevant production test data, the hydraulic conductivity (*K*), for the Roma field, was calculated from field determination of *k* from drill stem tests where such information was available. These *k* values were expressed in millidarcys (mD). In order to insert the data into the equations used in the model values were converted to consistent units. The conversion used to convert *k* (mD) values into *K* values (m/d) (assuming water as the fluid) was:

$$1 \text{ mD} = 8.64 \times 10^{-4} \text{ m/day.}$$

These *k* and *K* values are listed in **Appendix I** together with the name of the formation being tested and the computed values of *T*. The *k* value varies quite significantly from formation to formation within a particular well and even within the same formation from well to well.

The variation is summarised in **Table 3-3** for the various seams in the Roma field.

Table 3-3 Permeability and Transmissivity of the Coal Seams in the Roma Field

Formation	Aquifer Thickness (net pay) (m)	*k* (mD)	*T* (m^2/d)
Upper Juandah	1.3 – 6.36	4 – 1200	0.01 – 1.81
Upper Juandah (Lower)	1.2 – 3.8	0.05 – 11.0	0.00005 – 0.04
Lower Juandah (Lower)	1.4 – 3.5	2 – 130	0.0027 – 0.38
Lower Juandah (Sand)	2.1	26	0.047
Lower Juandah (Upper)	1.05 – 2.9	0.6 - 260	0.0005 – 0.33
Taroom (Upper)	1.3 – 2.9	13.7 - 1140	0.03 – 2.07
Taroom (Lower)	0.86 – 3.0	0.1 - 790	0.00007 – 2.05

Transmissivity

T values determined from production tests are preferable to data obtained from drill stem *k* tests. The production test data give a far better indication of what is happening in the aquifer remote from the well whereas the estimates from drill stem tests represent a very small area of the aquifer around the well. For this reason the *T* values, wherever possible, have been determined from production test data.

Sections of the production test data (21 June to 7 November 2007) for Coxon Creek 2 and (26 June to 21 July 2007) for Coxon Creek 4 wells were analysed and provided *T* estimates. The analyses of these wells are presented in **Appendix I**. These analyses give a value of *T* which is an average of the effects of all of the aquifers contributing to the well. Some seams have a high value of hydraulic conductivity and others low; but the data obtained from the test well average all of those to give a value of *T* for the producing well.

However, there are very few instances where these data are detailed enough to allow an accurate determination of *T*. Where production well test data were not available, the *T* values were determined from *k* data and bed thickness. Because each well draws water and gas from all beds simultaneously, *T* was determined for each well as the summation of the individual *T* values of the individual formations encountered by that well. These values were calculated and are listed in **Appendix J**.

In addition, because of the possibility that the Roma area is crossed by a number of faults (information transmitted by Santos staff), it was thought that *T* values within the zones between faults may have similar characteristics. The wells are grouped within these zones in **Appendix J** together with their *T* estimates. The locations of the possible faults and the zones adopted are shown in **Figure 3-7**.

Even though the values of permeability varied quite significantly from bed to bed, the values of *T* obtained in this manner for each wellfield were reasonably consistent; mostly within 10% of each other and no more than an order of magnitude different. They also agreed very closely with the *T* values obtained from the limited production test data.

Storativity (Storage Coefficient)

Storativity (*S*) is not an easy parameter to determine. It is best determined by analysing the drawdown effects of a pumping well at an observation well remote from the pumping well. However, this cannot always be arranged. In the absence of drawdown data at an observation well, *S* was calculated using the equation:

$$S = b\rho g(\beta\theta + \alpha(1-\theta))$$

where

S = storativity (or storage coefficient)

b = aquifer thickness (net pay) (m)

ρ = density of fluid (kg/m^3)

g = acceleration of gravity (length/time^2)

β = compressibility of fluid (for water 4.8 x 10^{-7} (kPa)$^{-1}$)

α = compressibility of matrix

θ = porosity

The minimum value of *S* can be determined solely from the compressibility of water, i.e. the first term in the right hand side of the equation given above. It is expressed approximately as:

$$S_{min} = 5 \times 10^{-6}\, b\theta$$

The true value of *S* will be somewhat larger than this minimum value as the coal matrix is far more compressible than the water within it.

This relationship has been used to estimate *S* for the equations used in the model. In addition, another estimate attempting to take into account the compressibility of the matrix has been used. These two values are then used as part of a sensitivity analysis for the model outputs. The smaller value of *S* will result in a larger radius of influence of the pumping wells than will occur in practice and will then be conservative.

Using field determinations of porosity values of *S* were calculated. The values of *S* determined in this manner are listed in **Appendix K**.

The *S* values for the Roma field ranged from 2.2 x 10^{-5} to 3.1 x 10^{-4} with most of the values in the 10^{-4} range.

The drawdown effects resulting from the minimum *S* estimate will be conservatively large. The value of *S* can be changed in the model as more reliable data become available or to carry out a sensitivity analysis.

The parameters used in the analytical model are given in **Table 3-4**.

Table 3-4 Aquifer Parameters Used in the Roma Mathematical Model

CSG Field	*T* (m^2/d)	*S*
Roma	0.36	10^{-4}

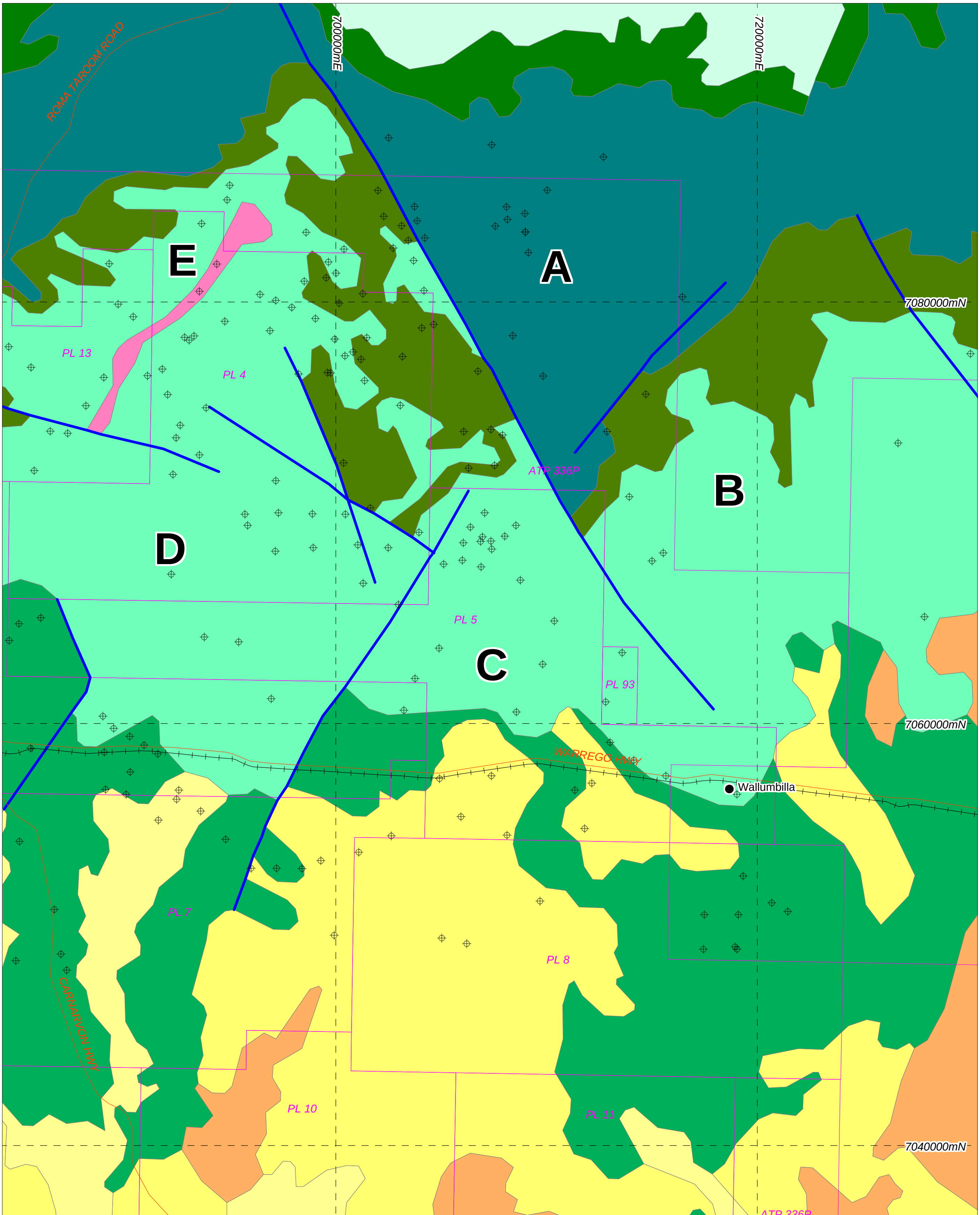
3.3.2.2 Model Calibration

Because there were no long-term field observations for the Roma CSG field, whole–of-field calibration was not possible.

3.3.2.3 Prediction Scenarios

A prediction of progressive drawdowns in the Walloon Coal Measures was developed based on one hypothetical wellfield development plan for the Roma CSG field (**Figure 3-8**).

As a separate exercise, the extent of CSG-related drawdowns in the Hutton Sandstone was calculated based on the predicted drawdowns in the Walloon Coal Measures. Three scenarios of inter-aquifer transfer were considered.



LEGEND

- Santos ATP & PL Tenement
- Road
- Track
- Railway
- Town
- Exploration Well
- A Transmissivity Zones

Geology

- Alluvium
- Sand Plain
- Sediments
- Tertiary Volcanics
- Wallumbilla Formation
- Bungil Formation
- Mooga Sandstone
- Orallo Formation
- Gubberamunda Sandstone
- Injune Creek Group
- Fault

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Data Source:
Geology - Geoscience Australia. Tenement - URS.

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Santos GLNG EIS

Possible Fault Zones - Roma Area

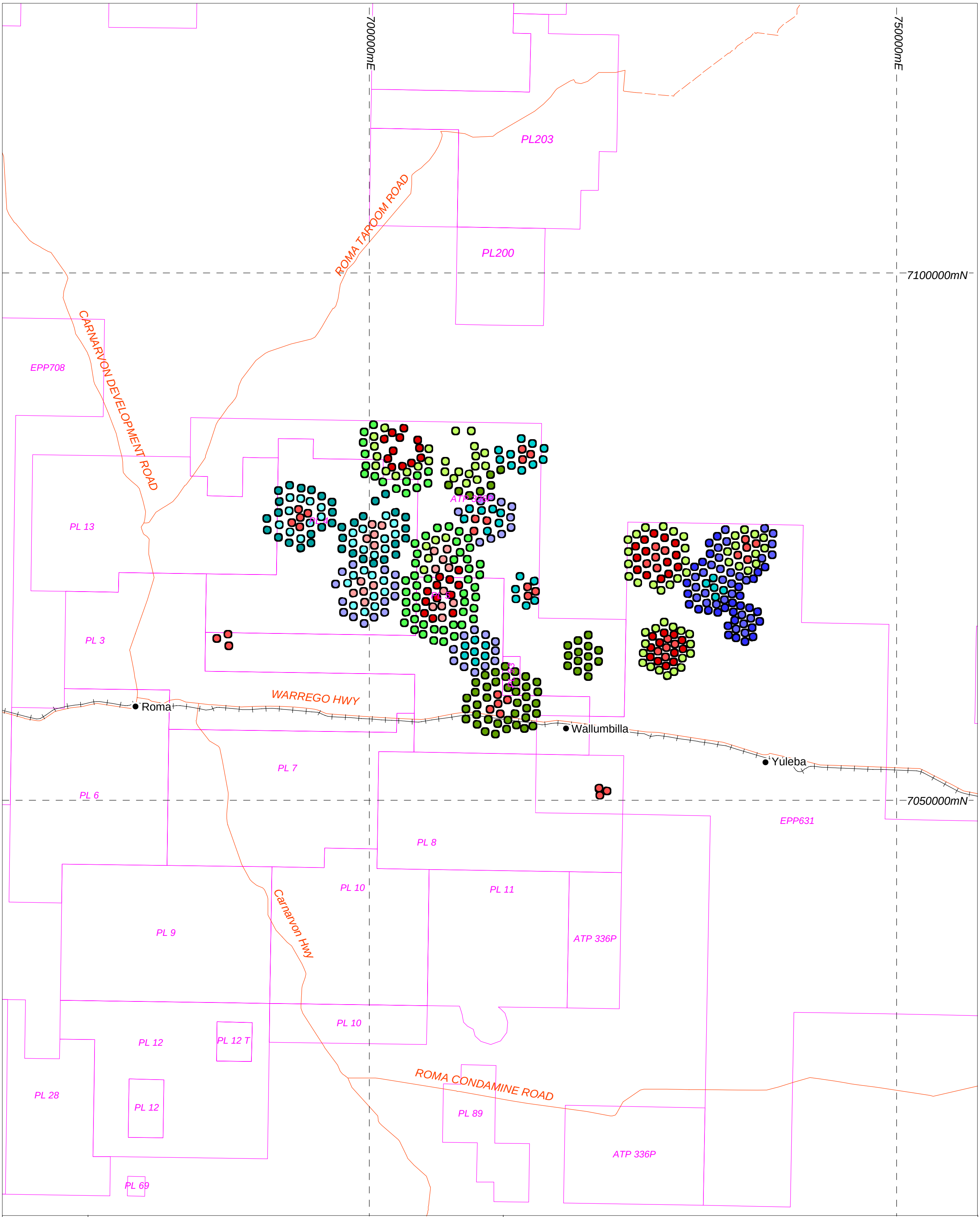
0 5 10

Kilometres

Scale: 1:250,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 3-7



matrixplus

LEGEND

- Santos Atp & PL Tenement
- Road
- Track
- Railway
- Town

Projected Start Years

2008
2009
2010
2011
2012
2013
2015
2016
2017
2018
2019
2020

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Hypothetical Wellfield Development - Roma CSG Field

0 10 20

Kilometres

Scale: 1:500,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 3-8

30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS

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3.3.2.4 Sensitivity Analysis

Storativity was assessed *a priori* as being a critical aquifer parameter. Furthermore, there are no field results suitable for determination of this parameter. Therefore, sensitivity analysis specifically addressed this parameter (refer **Table 3-5**).

While it is common for there to be no field results for the estimation of *S*, values are expected to lie within a certain range. Storage coefficients values in confined aquifers (i.e. storativities) can be many orders of magnitude less than storage coefficients in unconfined aquifers (i.e. specific yields). Minimum storativity is limited by the compressibility of water; for an aquifer of 10 m thickness and a porosity of 10%, the minimum likely storativity is 5×10^{-6}.

In order to assess the confidence in predictions from the analytical model, the expected dewatered volumes and volumes of water extracted from the coal measures at 20 years were compared for various storativity estimates.

Table 3-5 Sensitivity Analysis – Roma CSG Field

Storativity (-)	Volume of Aquifer Dewatered After 20 Years (m3)	Water Volume Extracted After 20 Years (ML)	Average Daily Water Volume Extraction (ML/d)
5×10^{-5}	1.24×10^{-12}	61,900	8.5
7.5×10^{-5}	9.73×10^{-11}	73,000	10.0
1×10^{-4}	7.59×10^{-11}	75,900	10.4
1.5×10^{-4}	6.25×10^{-11}	93,700	12.8
2×10^{-4}	5.89×10^{-11}	117,800	16.1

The sensitivity analysis shows that a four-fold increase in the storativity estimate produces a two-fold difference in predicted aquifer dewatering and in water extraction rates. Sensitivity of model results is approximately linear across the range of storativities. The sensitivity analysis demonstrates a greater storativity estimate results in a greater water extraction rate however this is counter-balanced, to some extent, by a reduced extent of dewatered aquifer.

3.3.2.5 Model Assumptions

The model assumptions for the Roma CSG field are summarised below:

- groundwater flow is considered in isolation. The inclusion of gas flow is not considered to significantly affect the validity of flow equations used within the model;
- aquifer parameters (thickness, storativity and transmissivity) are sufficiently uniform across the CSG field to warrant the use of non-distributed parameters in the model;
- the coal seam aquifer is essentially hydrostatic prior to depressurisation with a uniform initial head within the aquifer. Moreover, variations in initial head are insignificant compared with the magnitude of predicted drawdowns;
- due to the large number of hypothetical extraction wells, it is assumed inferred internal flow boundaries (i.e. faults within the CSG field) will not greatly affect the shape of the final drawdown volume because there are many wells located on each side of the boundaries; and
- it is assumed all wells will pump at an initial maximum rate of 100 m^3/d. However, pumping commencement and threshold are variable between wells.

3.4 POTENTIAL GROUNDWATER RELATED IMPACTS DURING CSG PRODUCTION

During the production of CSG, the rate of groundwater extracted from the target coal seam will exceed the rate that these aquifers can be recharged. This will lead to a depression or 'drawdown' of the potentiometric surface within the coal seams and a dewatering within the area of influence of the wellfield. The influence of CSG related groundwater extraction on the CSG aquifer and surrounding aquifers has been simulated with a numerical model for the Comet Ridge fields and an analytical Model for the Roma field.

Based on the outputs from the models the impacts on the groundwater resources of the areas covered by the wellfields were assessed. These are differentiated into the impacts on the coal seam aquifers themselves, the impacts on other aquifers and on the users reliant on groundwater from those aquifers.

3.4.1 Drawdown of Groundwater Head Levels within CSG Aquifers

3.4.1.1 Comet Ridge Fields

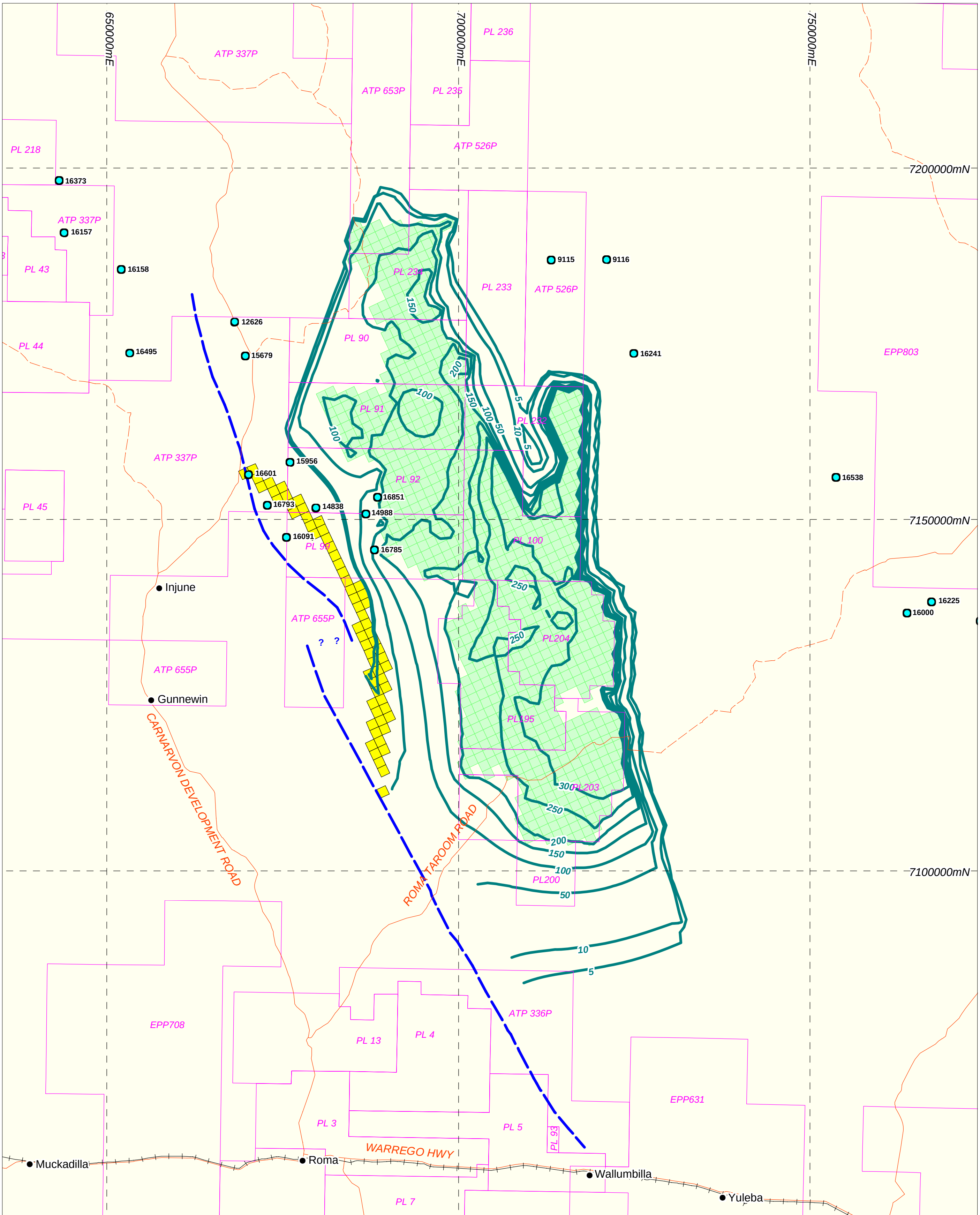
The model predicts significant drawdown of groundwater levels within the Bandanna Formation as a result of CSG extraction. Depressurisation associated with CSG extraction at Fairview, Arcadia and Spring Gully is predicted to create an amalgamated drawdown cone; up to 600 m in places. **Figures 3-9** to **Figure 3-12** show contours of drawdowns at time intervals 5, 10, 15 and 20 years (between 2009 and 2028). These drawdowns also include the effects of pumping prior to 2009.

Because the model includes extraction from the Spring Gully CSG field as well as the Fairview and Arcadia Valley CSG fields the contours of drawdown also include the drawdown effects from the Spring Gully CSG field. Based on the comparison of inter-layer flow rates between the base case scenario and the scenario without Spring Gully CSG field included, the relative contribution of Spring Gully to drawdown was calculated. At 5 years (2013), 24% of the inflow from the Precipice Sandstone is due to extraction from the Spring Gully CSG field rising to 36% after 20 years (2028). Consequently, the contribution of the extraction from the Spring Gully CSG field to drawdown in the Precipice Sandstone has the same percentages.

3.4.1.2 Roma Field

The predicted drawdown of groundwater levels within the Walloon Coal Measures aquifers is also significant; up to 600 m in places. **Figures 3-13** to **Figure 3-16** show contours of drawdowns at time intervals 5, 10, 15 and 20 years after the start of production. This large vertical drawdown is confined to the gas producing aquifers, and as the transmissivity of the Walloon Coal Measures is very small, the radial extent of the cone of depression does not extend much beyond the extremity of the wellfield.

It must be stressed that these drawdowns are related solely to the extraction of gas from the Santos operated Roma CSG field. There are other GSG fields in the general area which are not operated by Santos and details of which were not known to Matrixplus when this report was prepared. The impacts resulting from the operation of these fields, while being similar to that resulting from the Santos operated field, will vary in magnitude and extent depending on the configuration of the wellfields, the aquifer parameters of transmissivity and storativity and the threshold drawdown required to extract the gas. If the drawdown impacts caused by individual wellfields overlap then the total impact will be the sum of the impacts of the individual wellfields.



LEGEND

- Santos ATP & PL Tenement
- Road
- Track
- Railway
- Town
- Active CSG Field
- Vertical Leakage Cell
- Drawdown Contour (m)
- Hutton Wallumbilla Fault
- DNRW Reg. Bore (Precipice)

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5 Year Model Simulated Head Drawdown in the Bandanna Formation at 2013 - Comet Ridge CSG Fields

0 10 20
Kilometres

Scale: 1:750,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 3-9

30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS

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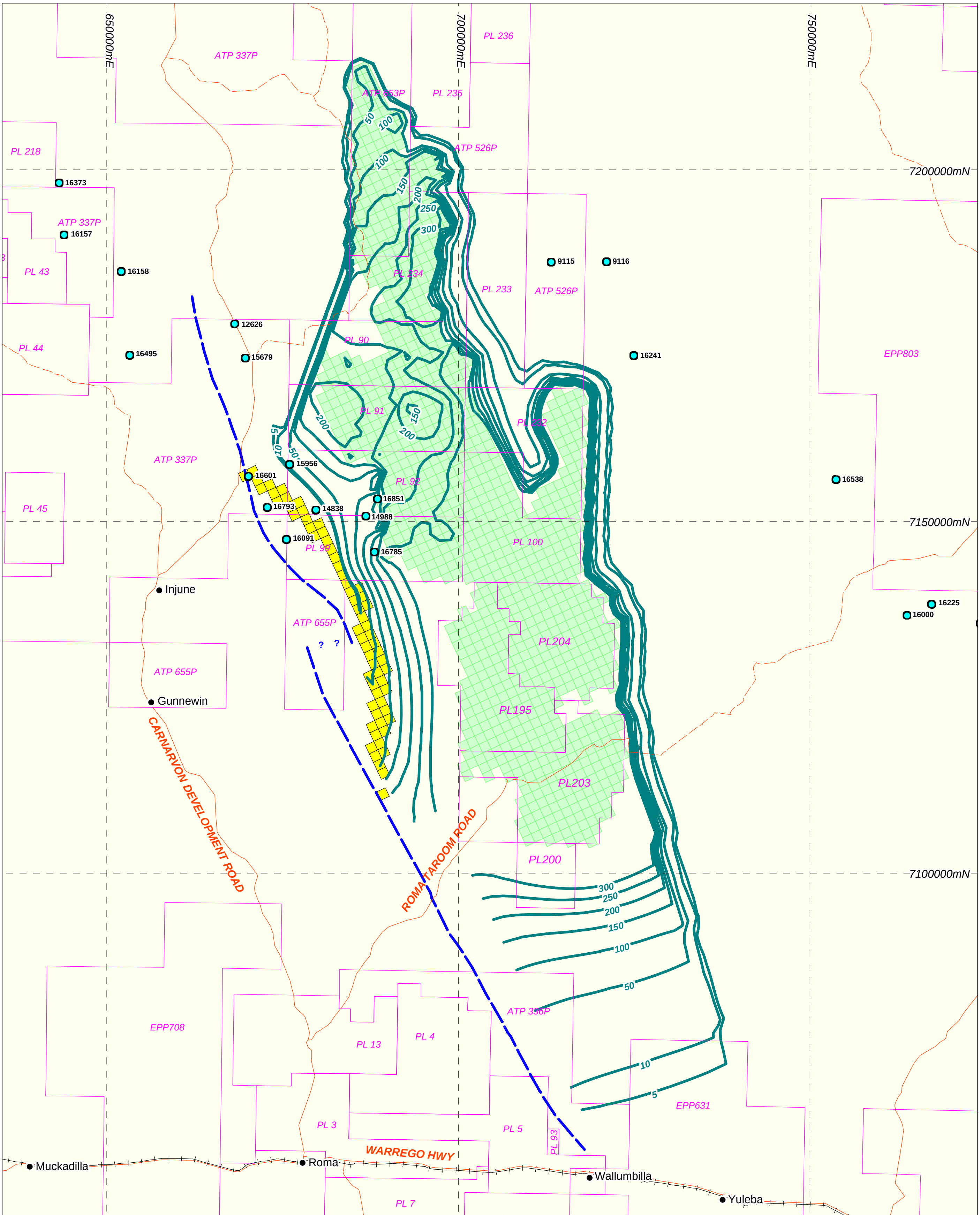

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matrixplus

LEGEND

- Santos ATP & PL Tenement
- Road
- Track
- Railway
- Town
- Active CSG Field
- Vertical Leakage Cell
- Drawdown Contour (m)
- Hutton Wallumbilla Fault
- DNRW Reg. Bore (Precipice)

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10 Year Model Simulated Head Drawdown in the Bandanna Formation at 2018 - Comet Ridge CSG Fields

0 10 20
Kilometres

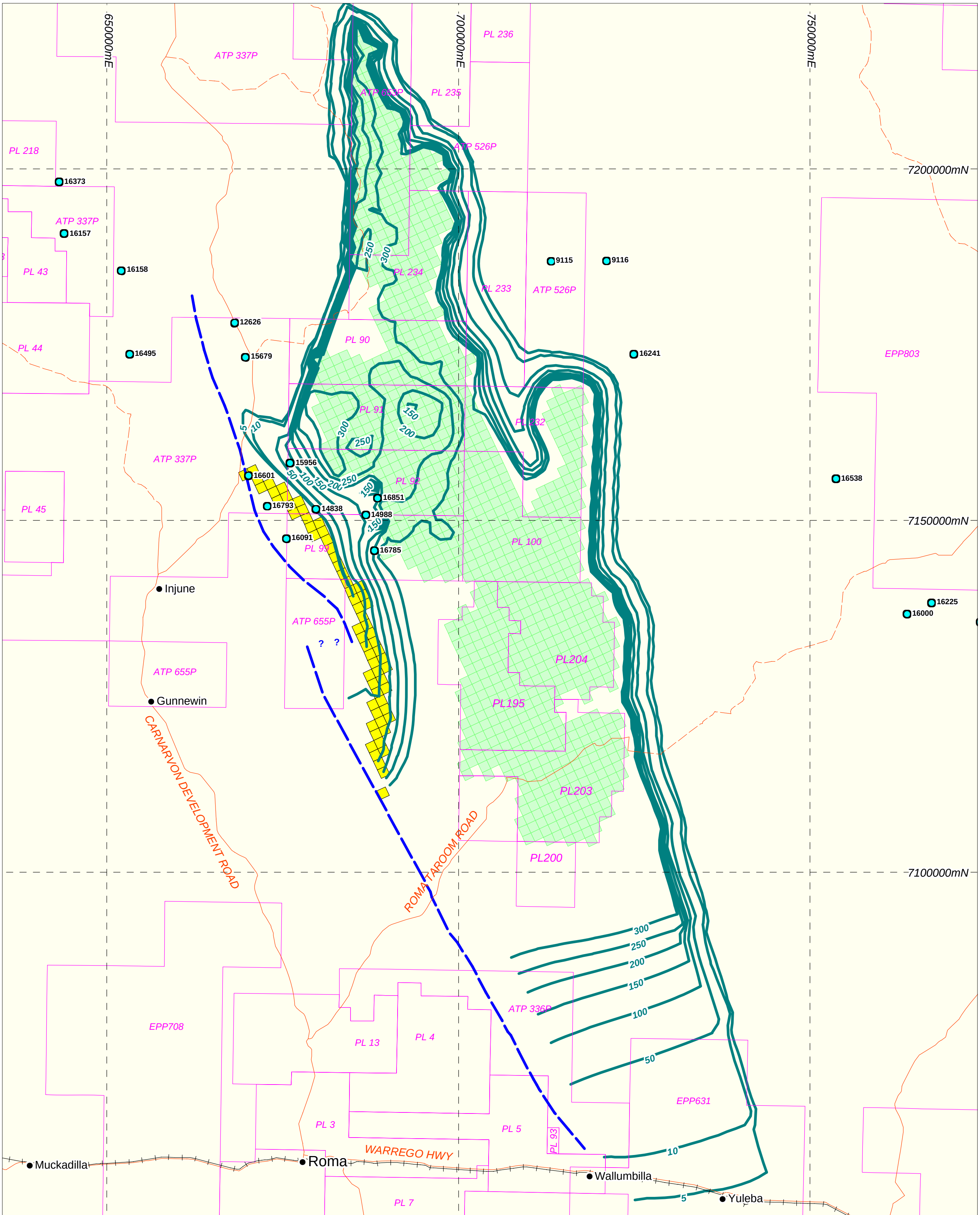
Scale: 1:750,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 3-10

30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS



LEGEND

Santos ATP & PL Tenement	Active CSG Field
Road	Vertical Leakage Cell
Track	Drawdown Contour (m)
Railway	Hutton Wallumbilla Fault
Town	DNRW Reg. Bore (Precipice)

Santos Ltd

Santos GLNG EIS

15 Year Model Simulated Head Drawdown in the Bandanna Formation at 2023 - Comet Ridge CSG Fields

0 10 20

Kilometres

Scale: 1:750,000 (A4)

Datum: GDA94

Projection: MGA55

FIGURE 3-11

30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS

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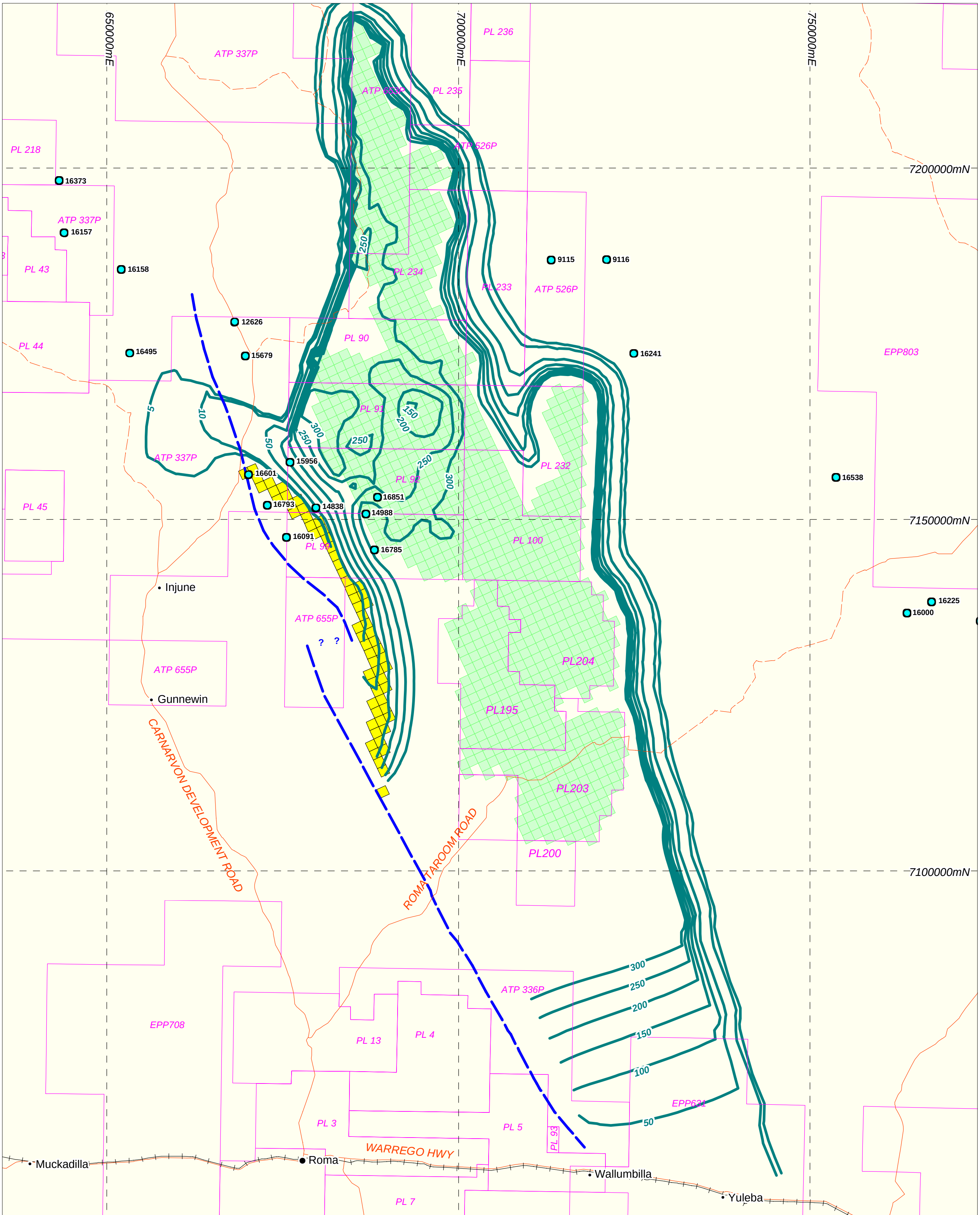

LEGEND

- Santos ATP & PL Tenement
- Road
- Track
- Railway
- Town
- Active CSG Field
- Vertical Leakage Cell
- Drawdown Contour (m)
- Hutton Wallumbilla Fault
- DNRW Reg. Bore (Precipice)

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Santos GLNG EIS

20 Year Model Simulated Head Drawdown in the Bandanna Formation at 2028 - Comet Ridge CSG Fields

0 10 20
Kilometres

Scale: 1:750,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 3-12

matrixplus

30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS

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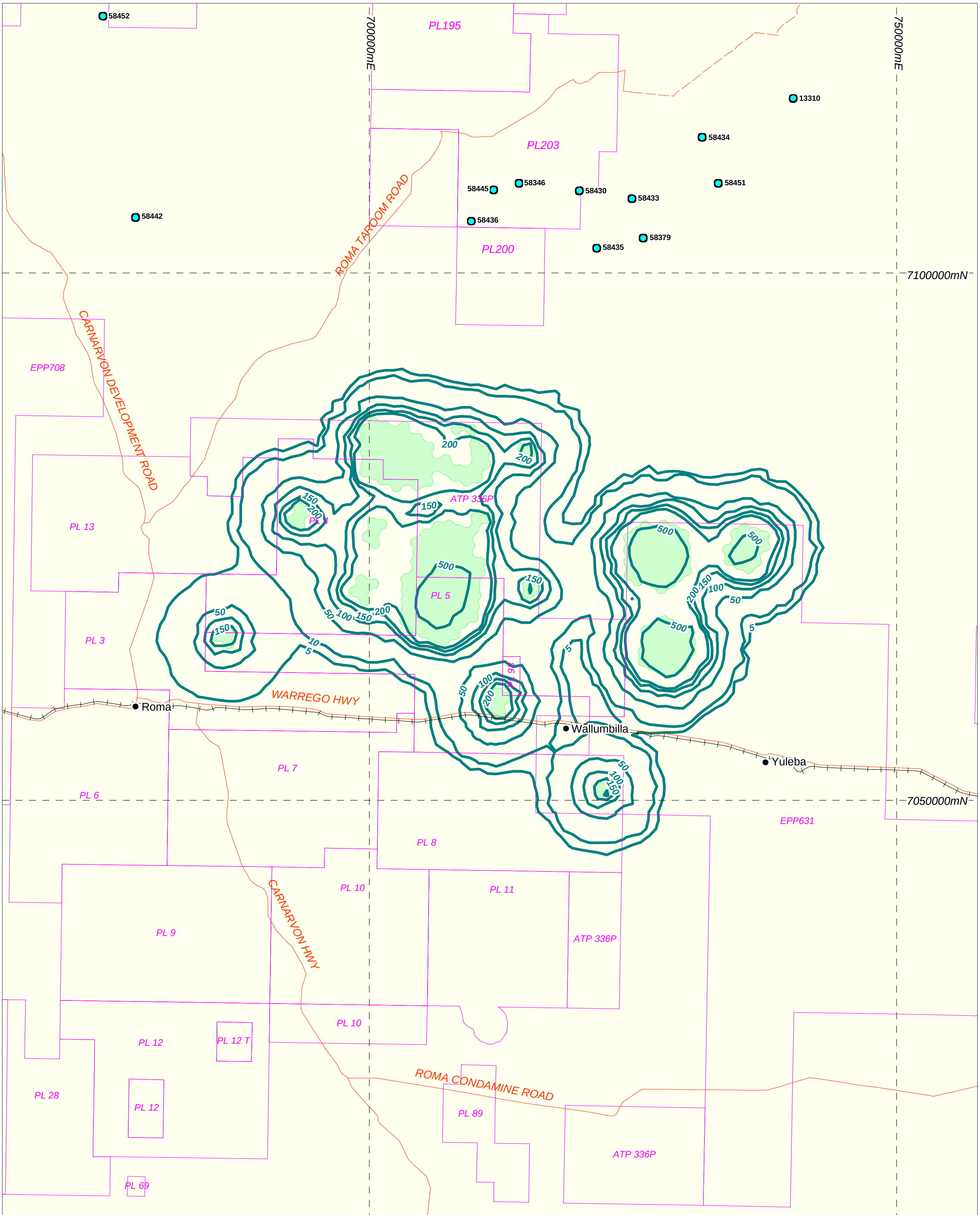

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matrixplus

30/01/2009

LEGEND

- Santos ATP & PL Tenement
- Road
- Track
- Railway
- Town
- Proposed CSG Field
- Drawdown Contour (m)
- DNRW Reg. Bore (Walloon)

Data Source:
Topography - Geoscience Australia. Tenement - URS

Santos Ltd

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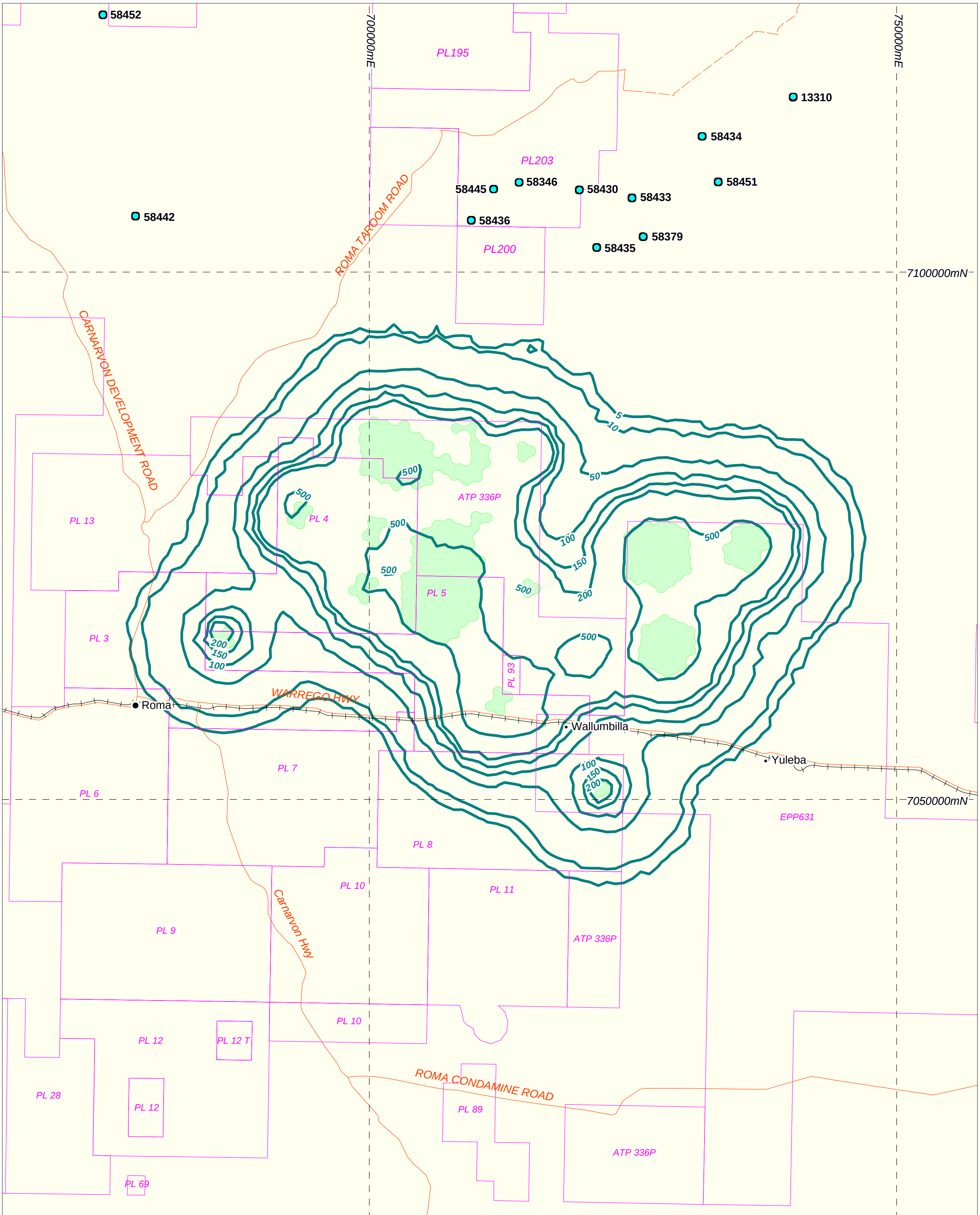
5 Year Model Simulated Head Drawdown in the Walloon Coal Measures at 2013 - Roma CSG Field

0 10 20
Kilometres

Scale: 1:500,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 3-13



LEGEND

- Santos ATP & PL Tenement
- Road
- Track
- Railway
- Town
- Proposed CSG Field
- Drawdown Contour (m)
- DNRW Reg. Bore (Walloon)

Santos Ltd

Santos GLNG EIS

10 Year Model Simulated Head Drawdown in the Walloon Coal Measures at 2018 - Roma CSG Field

0 10 20
Kilometres

Scale: 1:500,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 3-14

30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS

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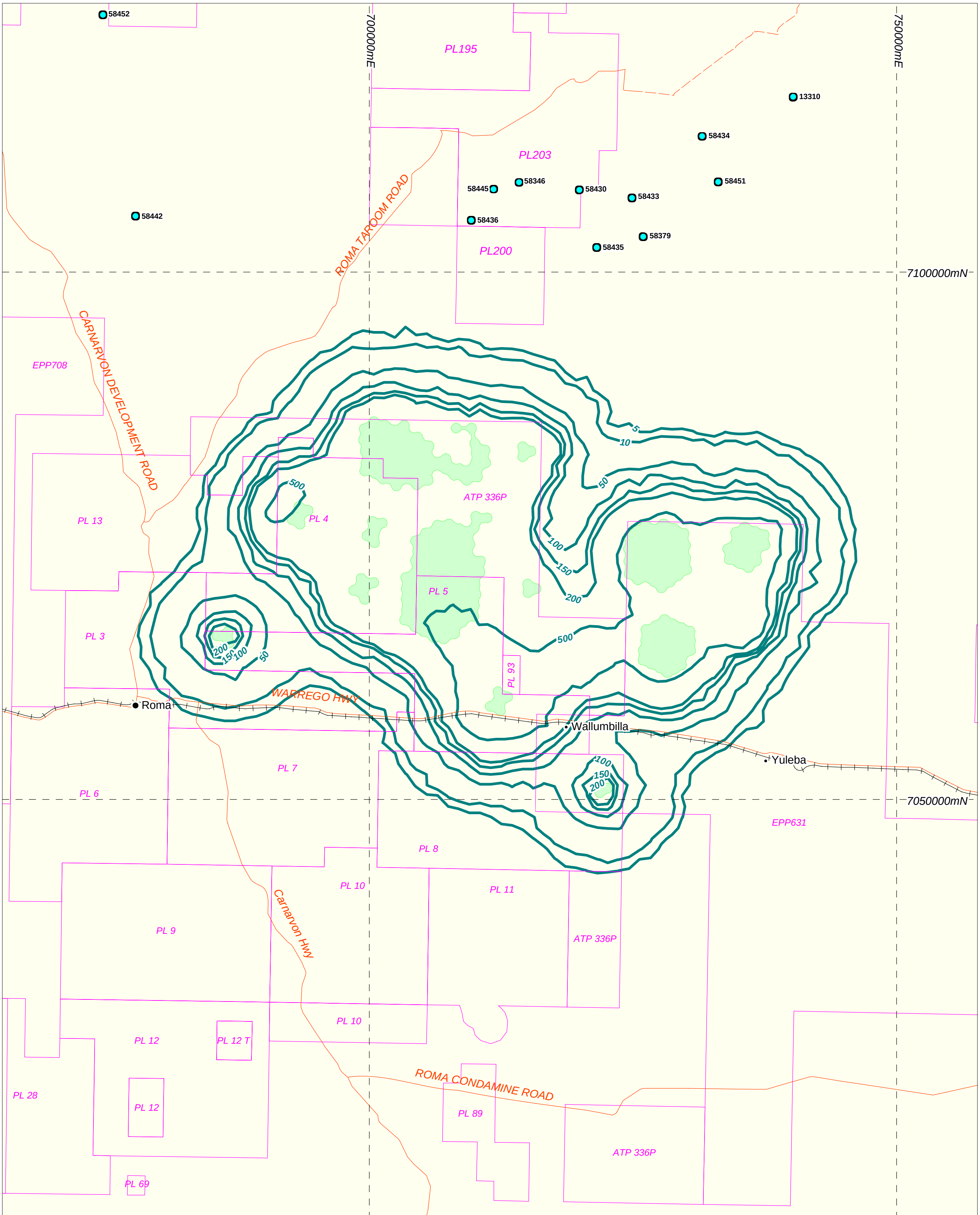

LEGEND

- Santos ATP & PL Tenement
- Road
- Track
- Railway
- Town
- Proposed CSG Field
- Drawdown Contour (m)
- DNRW Reg. Bore (Walloon)

Santos Ltd

Santos GLNG EIS

15 Year Model Simulated Head Drawdown in the Walloon Coal Measures at 2023 - Roma CSG Field

0 10 20

Kilometres

Scale: 1:500,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 3-15

30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS

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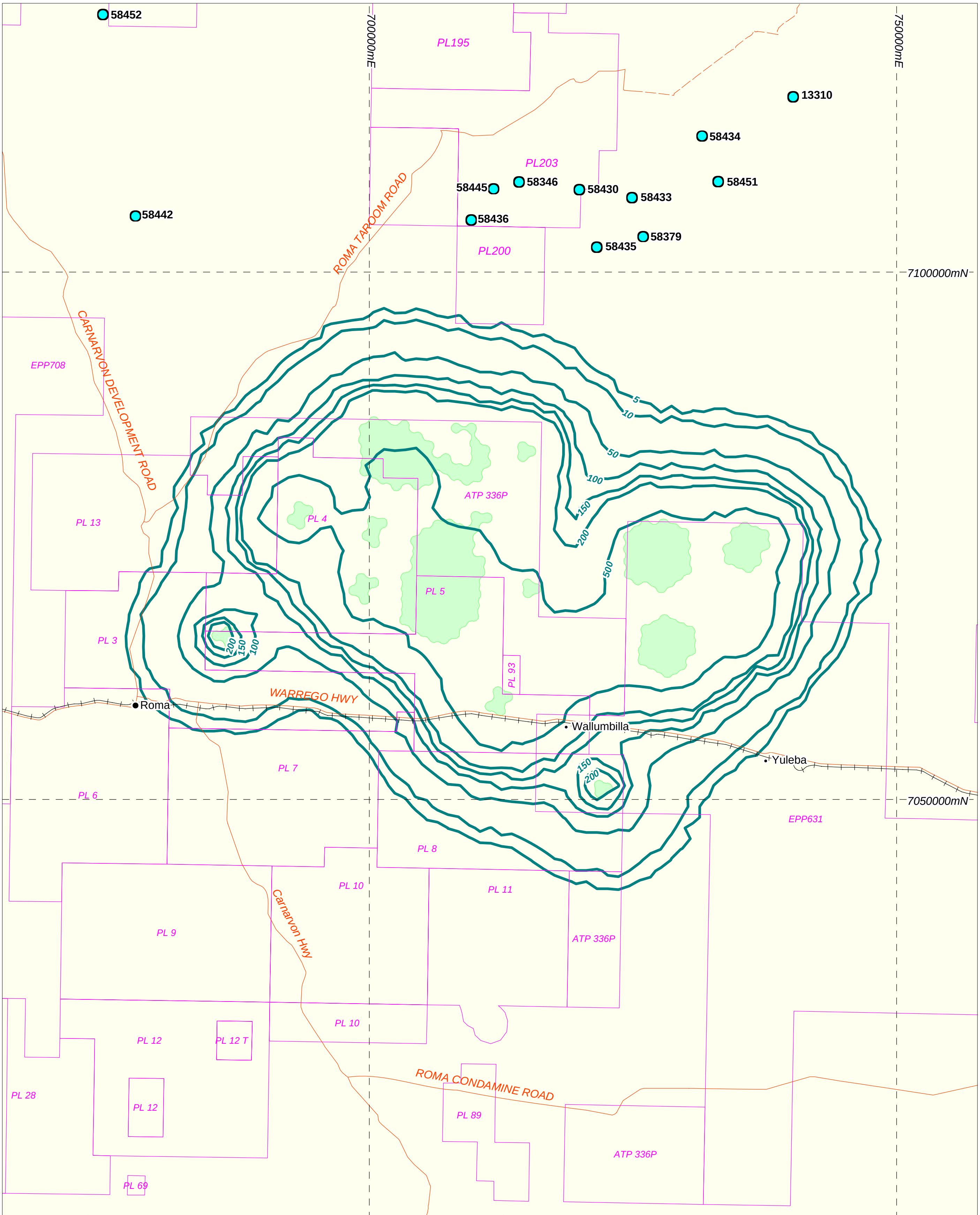

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30/01/2009

LEGEND

- Santos ATP & PL Tenement
- Road
- Track
- Railway
- Town
- Proposed CSG Field
- Drawdown Contour (m)
- DNRW Reg. Bore (Walloon)

Data Source:
Topography - Geoscience Australia. Tenement - URS

Santos Ltd

Santos GLNG EIS

20 Year Model Simulated Head Drawdown in the Walloon Coal Measures at 2028 - Roma CSG Field

0 10 20

Kilometres

Scale: 1:500,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 3-16

3.4.2 Drawdown of Groundwater Head Levels within Overlying and Underlying Aquifers

In all fields there is potential for water to move vertically from aquifers above and below the wellfield into the coal seams as a result of the huge pressure differential caused by the drawdown of groundwater heads.

The coal seams in the Bandanna Formation of the Fairview, Spring Gully and Arcadia fields have quite different hydraulic parameters from those in the Walloon Coal Measures of the Roma field and the mode of inter-aquifer transfer is also quite different.

The methods of analysing these different situations are set out below.

3.4.2.1 Comet Ridge Fields

The impact of the withdrawal of water from the Bandanna Formation has been assessed by modelling the water level response in the Bandanna Formation and the corresponding pressure differential between the water level in the Bandanna Formation and in the overlying formations.

The Rewan Group acts as an effective barrier to flow in all areas except where it is absent due to erosion.

The magnitude of the drawdown is such that it produces a pressure differential between the Bandanna Formation and the overlying Precipice Sandstone sufficiently large to result in a transfer of water from this water-producing aquifer to the Bandanna Formation.

In the Comet Ridge fields, the Bandanna Formation dips to the east and the overlying Rewan Formation which separates the Bandanna Formation from the overlying Clematis Sandstone is also very thick and impermeable in the eastern part of fields and forms an effective impermeable boundary over most of the areal extent of the fields.

However, the Rewan Group thins out towards the west, as it and the Bandanna Formation drape over the Comet Ridge, and in some areas is completely eroded away. In the southern part of this western area the throw of the Hutton/Wallumbilla Fault is such that it effectively makes the Bandanna Formation discontiguous and allows a much closer contact between the Bandanna Formation and the Precipice Sandstone. In these areas, depending on the thickness of the Rewan Group and the differential in water pressure, water may move down through the Triassic rocks from the Precipice Sandstone and into the Bandanna Formation. The Precipice Sandstone is particularly vulnerable in one section, approximately 40 km long, where the Rewan Group has eroded away completely and the Bandanna Formation sub-crops under the Precipice. However, the interface between the two formations will not be clean and it has been assumed that a 50 m layer of undifferentiated (weathered) material exists between the two formations. Based on geophysical evidence, the extent of contact between the Bandanna Formation and the Precipice Sandstone varies along the length of the Hutton/Wallumbilla Fault. The type of contact is shown diagrammatically in **Figure 3-1**.

The transfer of water from the Precipice Sandstone to the Bandanna Formation can be manifested not only as a drop in water levels in surrounding bores but may on occasions result in a reduction in flow from natural springs and in the base flow of the streams in the area.

In order to quantify this inter-aquifer transfer, vertical hydraulic conductivities (K_z) have been assigned to the Precipice Sandstone, to the Bandanna Formation and to the intervening weathered layer and leakage coefficients were assigned to the interfaces between each of the three layers i.e. the Precipice Sandstone, the Bandanna Formation and the intervening weathered layer.

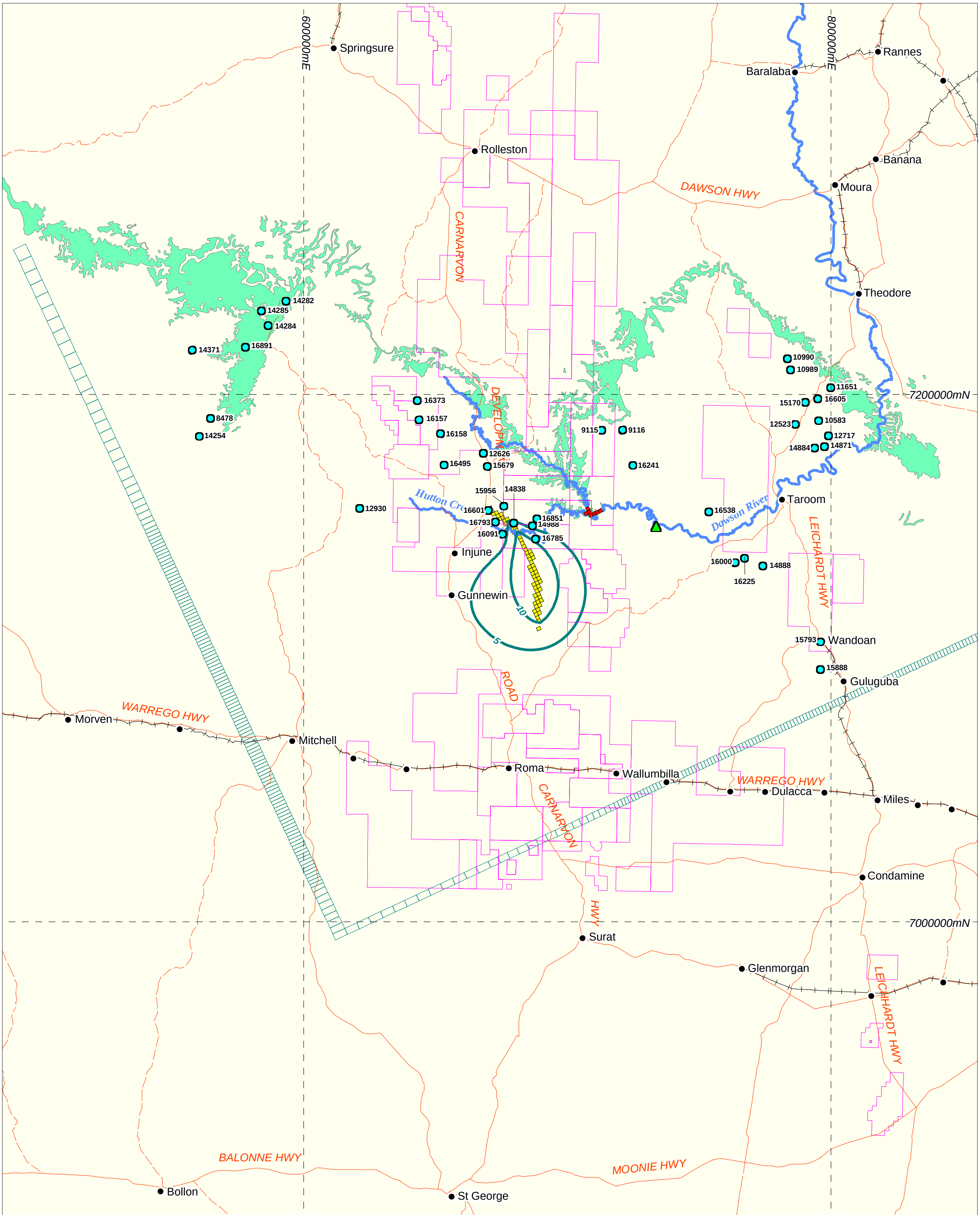
These leakage coefficients were then put into the model and the drawdowns in the Precipice Sandstone for various time steps were determined. These were output as contours of drawdown (**Figures 3-17** to **Figure 3-20**) and as drawdown profiles (**Figure 3-21**) for time periods 5, 10, 15 and 20 years after 2009. These drawdowns also include the effects of extraction prior to 2009.

DNRW Bore 14988 bore drilled in the Precipice Sandstone within the wellfield will experience a maximum drawdowns of some 9 m by 2028. Bores 16091, 14838 and 16785.are located in the area surrounding the wellfield. With the extraction programme used in the model they are expected to experience drawdowns ranging from 7 m to 25 m as at 2028. The expected drawdowns in these bores are set out in **Table 3-6** below.

The DNRW database does not have details of bores within this area which have been drilled into the Bandana Formation.

Table 3-6 Impacted DNRW Bores (Precipice Sandstone) in the Comet Ridge CSG

DNRW Bore	Easting	Northing	Drawdown m (2028)
14988 (Inside wellfield)	686841	7151020	9
14838	679773	7151888	14
16091	675564	7147697	7
16785	688079	7145955	25



LEGEND

- Santos ATP & PL Tenement
- Road
- Track
- Railway
- Watercourse
- Town
- Precipice Sandstone Outcrop
- River Model Cell
- Vertical Leakage Cell
- Model GHB Cells
- Drawdown Contour (m)
- DNRW Stream Gauging Station
- DNRW Reg. Bore (Precipice SS)

Santos Ltd

Santos GLNG EIS

5 Year Model Simulated Head Drawdown in the Precipice Sandstone at 2013 - Comet Ridge CSG Fields

0 40 80

Kilometres

Scale: 1:2,000,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 3-17

matrixplus

30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS

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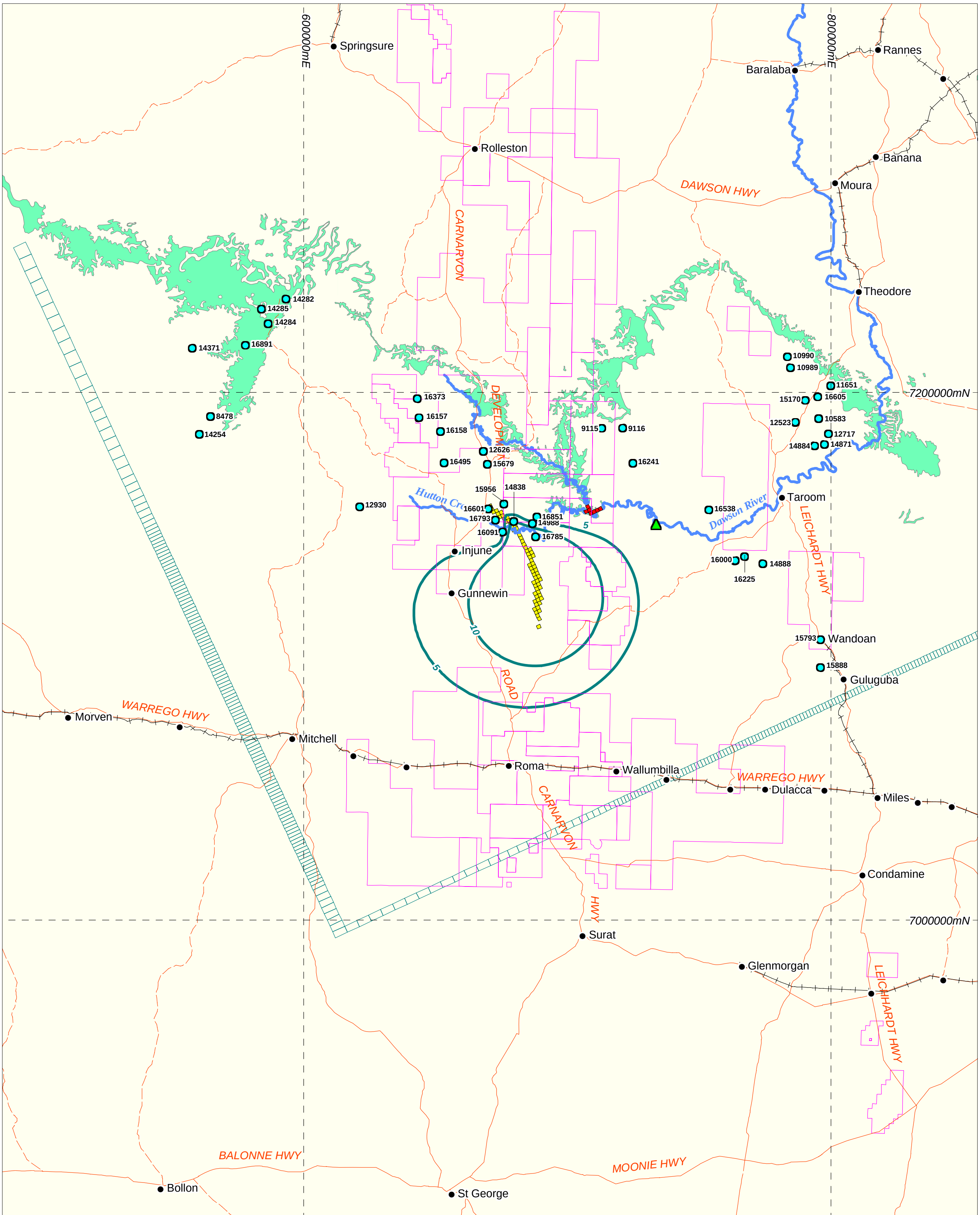

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matrixplus

LEGEND

- Santos ATP & PL Tenement
- Road
- Track
- Railway
- Watercourse
- Town
- Precipice Sandstone Outcrop
- River Model Cell
- Vertical Leakage Cell
- Model GHB Cells
- Drawdown Contour (m)
- DNRW Stream Gauging Station
- DNRW Reg. Bore (Precipice SS)

30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS

Santos Ltd

Santos GLNG EIS

10 Year Model Simulated Head Drawdown in the Precipice Sandstone at 2018 - Comet Ridge CSG Fields

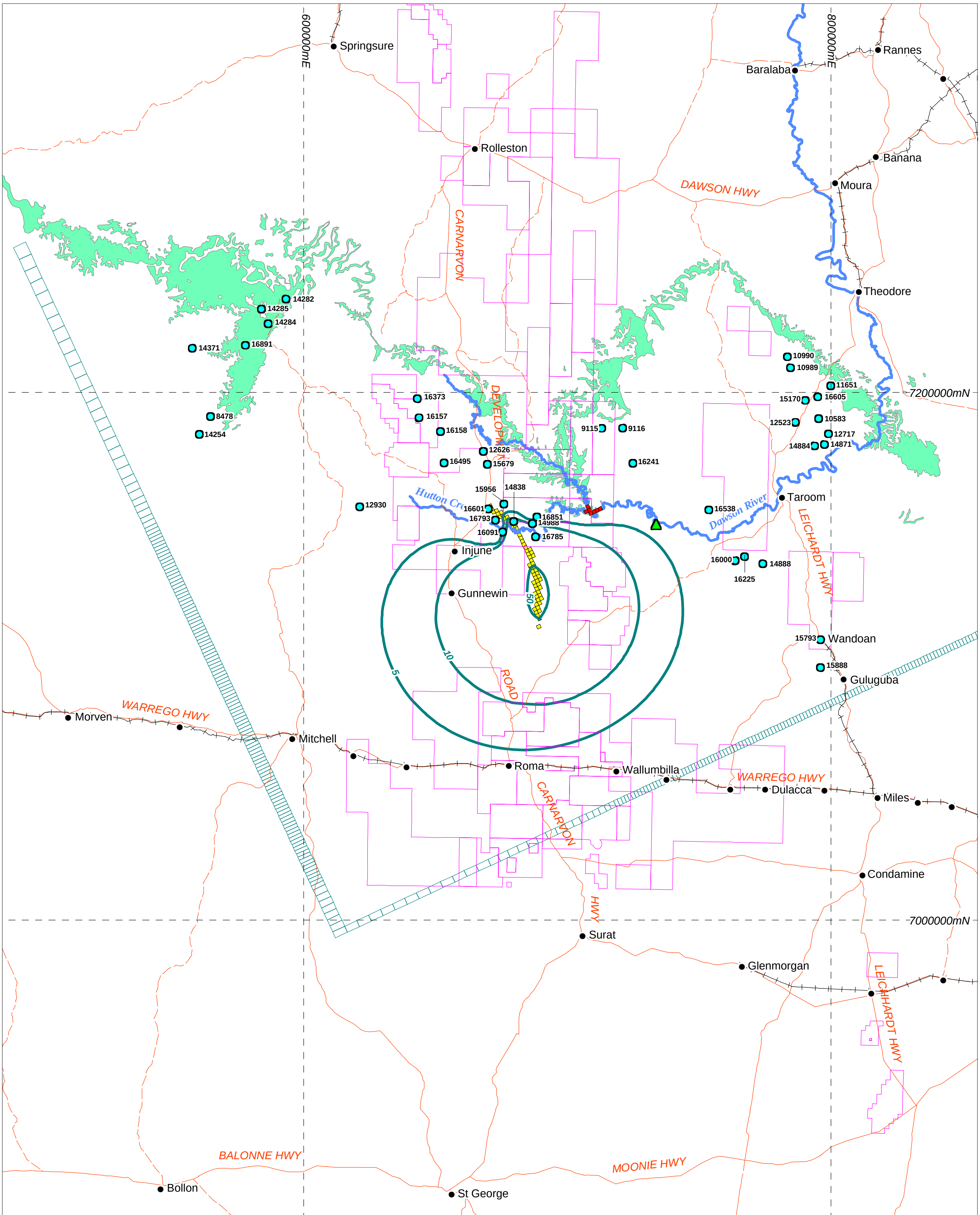
0 40 80

Kilometres

Scale: 1:2,000,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 3-18



LEGEND

Santos ATP & PL Tenement
Road
Track
Railway
Watercourse
Town
Precipice Sandstone Outcrop
River Model Cell
Vertical Leakage Cell
Model GHB Cells
Drawdown Contour (m)
DNRW Stream Gauging Station
DNRW Reg. Bore (Precipice SS)

matrixplus

30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS

Santos Ltd

Santos GLNG EIS

15 Year Model Simulated Head Drawdown in the Precipice Sandstone at 2023 - Comet Ridge CSG Fields

0 40 80
Kilometres

Scale: 1:2,000,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 3-19

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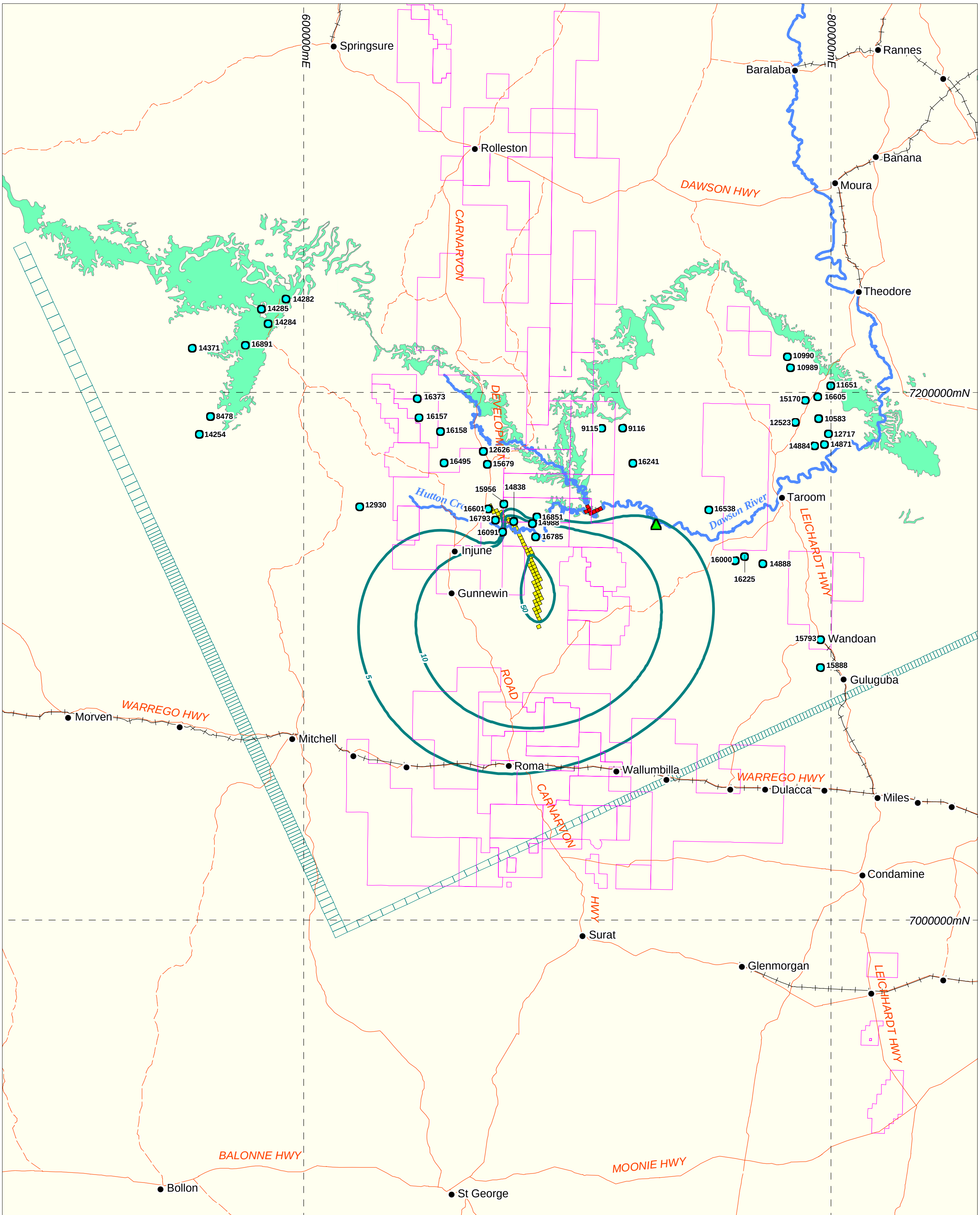

LEGEND

- Santos ATP & PL Tenement
- Road
- Track
- Railway
- Watercourse
- Town
- Precipice Sandstone Outcrop
- River Model Cell
- Vertical Leakage Cell
- Model GHB Cells
- Drawdown Contour (m)
- DNRW Stream Gauging Station
- DNRW Reg. Bore (Precipice SS)

matrixplus

30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS

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Santos Ltd

Santos GLNG EIS

20 Year Model Simulated Head Drawdown in the Precipice Sandstone at 2028 - Comet Ridge CSG Fields

0 40 80

Kilometres

Scale: 1:2,000,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 3-20

3.4.2.2 Roma Field

In the Roma CSG field, gas is extracted from the Walloon Coal Measures which are overlain by a number of aquifers including the Springbok Sandstone, Gubberamunda Sandstone, Mooga Sandstone and the Orallo Formation and are underlain by the Hutton Sandstone which are sources of water supply for local landowners, towns and local industries. In addition there are many coal seams within the Walloon Coal Measures that are supplying the gas. All of these formations are separated by beds of relatively impermeable material.

Extraction of water from each coal seam is accompanied by a reduction of hydrostatic pressure within that seam and a subsequent differential in pressure between the water within it and other formations above and below it. This pressure differential has the potential to transfer water vertically from one aquifer to another through the intervening material. The magnitude of this transfer is limited by the pressure differential which exists and on the ability of the intervening layer to transmit the water vertically through it.

The transfer mechanism is illustrated in **Figure 3-5**. Even though the beds dip in a southerly direction and bed thicknesses vary spatially, the various layers can be considered to be reasonably uniform throughout the field and the potential to move vertically is also reasonably uniform throughout the field.

In the Roma CSG field, the process of transfer from the bounding aquifers to the depressurised layer is the same over the whole field. Thus the total rate of transfer from the underlying and overlying aquifers is the sum of the incremental discharges multiplied by the area through which those incremental discharges occur. The methodology and calculations are given in full in **Appendix H**.

3.4.2.2.1 Volume Transferred

In assessing the potential volume transferred from the overlying and underlying aquifers to the Walloon Coal Measures, three possible cases were considered:

Case 1. Water was being contributed from both the Gubberamunda and Hutton aquifers and was moving across the total thickness of the Hutton Sandstone, the Gubberamunda Sandstone and across the whole of the Injune Creek Group which includes the Walloon Coal Measures and the Eurombah Formation. The Westbourne Formation component of the Injune Creek Group is a major aquitard.

Case 2. Water was being contributed from the Hutton Sandstone aquifer alone and was moving across the Hutton Sandstone aquifer, the Eurombah Formation and the Walloon Coal Measures.

Case 3. Water was being contributed from the Hutton Sandstone aquifer and was moving upwards across the Hutton Sandstone aquifer, the Eurombah Formation and half of the Walloon Coal Measures. At the same time water was being contributed from the overlying Gubberamunda Sandstone aquifer and was moving vertically downward across the Gubberamunda Sandstone aquifer, the Westbourne Formation and half of the Walloon Coal Measures.

In order to compare relative effects, each case was analysed at the time period 5 years (1,825 days) after commencement of pumping

The volumes transferred for each of the cases were as follows:

Case 1 3 m^3/day;

Case 2 113 m^3/day;

Case 3 218 m^3/day from the Hutton Sandstone and 9.1 m^3/day from the Gubbermunda Sandstone.

Case 3 is the most likely scenario as the upper part of the Injune Creek Group is very impermeable and it is more likely that any transfer that does occur will come preferentially from the Hutton Sandstone. However, the Gubberamunda Sandstone should be monitored during the wellfield operation to check that this assumption is valid.

It is also possible that some water transferring from the overlying and underlying aquifers will be intercepted by the coal seams and pumped to the surface by the gas wells. This situation has not been analysed.

3.4.2.2.2 Drawdowns Outside the Wellfield

Since the transfer from the Gubberamunda Sandstone is so small, this analysis has considered only the impact on the Hutton Sandstone aquifer.

The water transferring from the Hutton Sandstone aquifer into the Walloon Coal Measures has to be derived from outside the wellfield and flow horizontally through the outer perimeter of the area of influence of the wellfield and then vertically upwards.

The magnitude of the wellfield and the large distances from the centre of the wellfield to the perimeter of influence make the use of the normal radial groundwater flow equations inappropriate to determine the consequential radial extent of and the magnitude of drawdown within the area of influence within the Hutton Sandstone aquifer. For this reason, an approximation has been made based on normal Darcy flow and the flow through the wellfield perimeter area.

On the basis of this analysis (which is included in **Appendix H**) the drawdown in the Hutton Sandstone aquifer at the perimeter of the CSG wellfield and the radius of influence of that impact in the Hutton Sandstone aquifer are shown in **Table 3-7** and the profiles for drawdown in the Hutton Sandstone 5,10,15 and 20 years after commencement of operation are shown in **Figure 3-21**. DNRW bores located within the Walloon at the Roma CSG Field exist to the north of the wellfield and will not be affected by pumping by 2028.

Table 3-7 Drawdown Effects in Hutton Sandstone Aquifer – Roma CSG Field

Time Since Operation Began (Years)	CSG-related Drawdown in Hutton Sandstone at Perimeter of CSG Wellfield Area (m)	CSG-related Radius of Influence in Hutton Sandstone Beyond Perimeter of CSG Wellfield Area (km)
5	1.8	28
10	3.0	39
15	3.2	47
20	3.2	54

The drawdown within the perimeter of the area of influence of the wellfield will increase towards the centre of the wellfield until the perimeter of the wellfield itself is reached. At this stage, the pressure differential between the Walloon Coal Measures and the Hutton Sandstone remains relatively uniform under the wellfield and the drawdown in the Hutton Sandstone aquifer could be expected to remain reasonably constant for the rest of the wellfield area.

All bores within this zone of influence and drawing water from the Hutton Sandstone aquifer are expected to be impacted to varying degrees depending on their distances from the centroid of the wellfield. Towns which fall within this zone are; Roma, Muckadilla, Wallumbilla, Yuleba, Jackson, Dulacca, Surat, Gunnewin, and Injune. None of these have town water supply bores which draw water from the Hutton Sandstone aquifer.

While there is a significant area impacted by the removal of water from the coal seams, the magnitude of the drawdown impact in the Hutton Sandstone aquifer is relatively small.

In order to implement measures to offset any adverse impact resulting from the operations it is necessary to set values at which such measures should come into play. At this stage, no such trigger values have been set. Legislation (refer to Section 253 in **Table 2-7**) puts the onus on the petropeum tenure holder to ask what trigger levels apply. Only after this request has been made can the chief executive officer set them. To date no such request has been made. However, David Free (a Hydrogeologist with DNRW) has suggested that the trigger value for impact in the consolidated confined aquifers within the CSG fields should be 5 m. If 5 m is used as a trigger value then the withdrawal of water from the Walloon Coal Measures, even after 20 years of operation, will not have any significant impact on the water levels in the adjacent Hutton Sandstone aquifers.

Profiles of drawdowns in the Hutton Sandstone aquifer which are related to CSG extraction are shown in **Figure 3-21**.

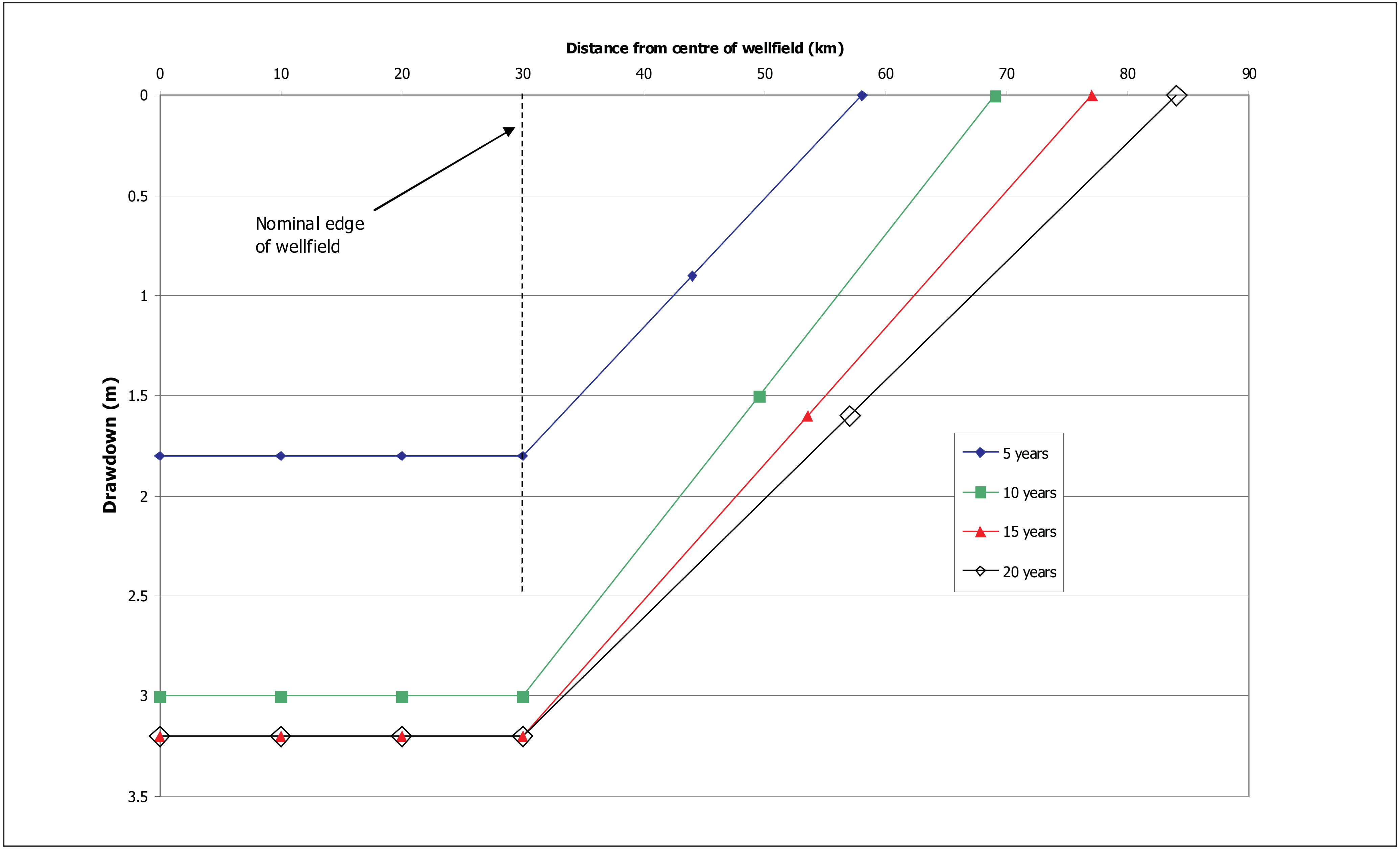

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Figure 3-21 Profies of Hydraulic Drawdowns in Hutton Sandstone at 5, 10, 15 and 20 Years - Roma CSG Field

3.4.3 Reduction of Landholder Bore Yields

The impact on landowner bore yields as a result of CSG operations is directly related to the magnitude of the drawdown interference at that bore as a result of the gas extraction. The actual impact can be determined reasonably accurately by comparing the magnitude of the drawdown interference with the available drawdown in the bore. Thus if the pump is set 100 m below the standing water level in the bore and the interference is 10 m then the reduction in yield is 10%. In many cases such an impact can be offset by lowering the pump suction setting.

However, if the impacted bore is a flowing artesian bore and the drawdown interference significantly reduces the static head in the bore, and hence the flow, then it may be necessary to equip the bore with a pump.

Each situation will have to be examined individually.

From **Table 3-7** it can be seen that the drawdown in the Hutton Sandstone aquifer is quite small at the edge of the wellfield even after 20 years of operation. The drawdown in the Gubberamunda Sandstone will be even smaller. However, monitoring bores should be installed to assess the drawdowns resulting from CSG extraction over the years. In addition, a survey of existing bores should be carried out to obtain baseline information on the present operational condition of the bores in the area surrounding the CSG wellfield.

3.4.4 Reduction in Stream Baseflow as a Result of Reduced Groundwater Discharge

The occurrence of springs and baseflow in the Comet Ridge area is controlled largely by the underlying stratigraphy and structural geology. For example, the Police Lagoons area to the north of the township of Taroom is associated with the boundary between the Hutton Sandstone and the younger, less-permeable Injune Creek Group. While the occurrence of shallow groundwater discharge may infer the presence of geologic faults, the relative permeability of adjacent formations may be sufficient to control the locations of such discharge.

Most springs in the area are associated with the boundaries between the Hutton Sandstone and its overlying and underlying aquicludes (DNRM, 2005). However, groundwater levels in the Hutton Sandstone are unlikely to be affected by CSG operations.

The Precipice Sandstone is the aquifer most likely to be affected by CSG operations and springs are common in Precipice Sandstone outcrop areas; some of these springs are perennial. Baseflow from this unit is significant in two places; the Hutton Creek-Dawson River confluence and the Nathan Gorge area.

Of the groundwater discharge sites within the Comet Ridge area, baseflow to the Hutton Creek-Dawson River confluence is most likely to be affected by groundwater drawdown in the Precipice Sandstone associated with CSG operations.

At the Utopia Downs gauging station downstream of the Hutton Creek-Dawson River confluence, the minimum monthly streamflow in a year is generally of the order of 0.1 cumecs (equivalent to 9 ML/d). The streamflow at this river reach is contributed to by baseflow from the Precipice Sandstone and from upstream formations. While the minimum streamflows are related to baseflow during the same periods, this rate of streamflow is not directly proportional to total groundwater discharge from the Precipice Sandstone. Riparian vegetation and groundwater extraction are also expected to utilise groundwater discharge. Therefore, annual variations in minimum monthly baseflow are expected to show more temporal variation than predicted rates of groundwater discharge.

Baseflow in at the Hutton Creek-Dawson River confluence is a minor component of the mass balance of the total groundwater flow model (**Appendix G**). For the five scenarios considered during sensitivity analysis, discharge to the river cells was 13 ML/d in all cases. Drawdowns at this locality were less than 5 m in all cases and were significantly less than the hydraulic head difference between the aquifer and the river. Due to artesian conditions persisting in the Precipice Sandstone in this area, there is always positive outflow.

3.4.5 Water Quality

The extraction of CSG from the coal seams is not expected to have a detrimental impact on the quality of the water in any of the adjacent aquifers. Even though the quality of the water in the coal seams in all CSG fields is worse than that of the waters in the adjacent aquifers, all transfer of waters is from the adjacent aquifers into the coal seams. This results in a reduction in water volume but has no impact on water quality.

3.4.6 Subsidence of the Land Surface Overlying the Wellfields

Subsidence has not been an issue in other CSG fields and it is not expected to be an issue in the Roma CSG filed or the Comet Ridge CSG fields.

Subsidence generally occurs as a result of one of two processes or a combination of both. These are:

- Collapse of the overburden. This occurs when the solid mined commodity such as coal, is removed and the overburden collapses to fill the void resulting from such removal. This type of collapse does not occur with the extraction of coal seam gas because the solid rock mass is not removed.
- Depressurisation of the storage component. When a fluid such as gas, oil or water is stored under pressure in a rock matrix both the fluid and the matrix are influenced by the applied pressure. The water is compressed and the pore pressure exerted by the fluid tends to expand the solid matrix. This results in an increase in the volume of fluid stored as a consequence of the compressed water and expanded matrix and is referred to as elastic storage. If the pressure is reduced by removing the water, in this case, from the pores of the matrix then the matrix compresses or compacts and occupies a smaller volume. This can result in subsidence at the ground surface if the rock material above is not competent enough to resist it. It must be stressed, however, that when such subsidence does occur, its magnitude is influenced more by the type of aquifer and the magnitude of the pressure reduction than by the volume of fluid removed. As an example, large volumes of water are removed from the sandstone aquifers of the GAB with apparently very little subsidence occurring. However, the extraction bores in the GAB are normally more widely spaced, lower yields, have much smaller drawdowns (pressure reductions) and the aquifers from which the water is being withdrawn are cemented sandstones which are reasonably competent.

In most recorded cases when subsidence occurs as a result of groundwater extraction, the water-bearing material is unconsolidated, i.e. sands, gravels, silts or clays.

Even though the magnitude of the depressurisation in the CSG situation is large, the material associated with the depressurisation is mainly consolidated sandstone or shale neither of which will deform easily.

The aquifer from which the water is being drawn is comprised of coal measures which will more easily deform than the sandstones and shales and it is quite likely that the coal seams will deform to some extent. However, the magnitude of the deformation will be small. If the porosity of the coal seams is taken as 5% and the cumulative coal seam thickness is 10 m then the maximum deformation that could occur would be 0.5 m. In reality, this does not occur because if all the porosity was sealed by compression there would be no passageway for the water and gas to be removed and this continues to happen during the life of the field. In addition, the competency of the overlying sandstones and shales and the structural strength of those rocks as a result of folds, faults and other interlocking mechanisms would tend to prevent the rocks from slumping.

However, while land subsidence is not considered to be a likely possibility it is perceived to be so by some landowners and should be considered in future monitoring.

3.5 POTENTIAL GROUNDWATER IMPACTS – POST CSG EXTRACTION

3.5.1 Comet Ridge CSG Fields

The mass balance carried out as part of the numerical modelling of the Comet Ridge fields indicated that, 20 years after operations begin, approximately 50% of the water being extracted from the wellfields was being drawn from the Precipice Sandstone aquifer (**Appendix G**).

On this basis, while detailed modelling of the recovery of the wellfield water levels post CSG extraction has not been carried out, it can be concluded that the time required for an 80% recovery of the water levels in the Precipice Sandstone should be approximately twice the life of the fields. This can be accurately modelled in the future but it would be desirable to have access to monitoring data before such an analysis is carried out.

3.5.2 Roma CSG Field

Because the Walloon Coal Measures have been dewatered and the only source of replenishment is the Hutton Sandstone, it is expected that the rate of recovery of water levels in the Walloon Coal Measures will be very slow and drawdown in the Hutton Sandstone aquifer will continue for many hundreds of years after operations cease. However, while the radius of influence will continue to spread with time, the magnitude of the drawdown near the wellfield will not increase after the wellfield has ceased to operate.

4 MITIGATION MEASURES

The drawdown of groundwater heads within CSG aquifers is a necessary process and an unavoidable impact associated with the extraction of CSG. The depressurisation of the target coal seam may inevitable reduce groundwater levels within overlying and underlying aquifers.

Santos has an unlimited right to take water as part of petroleum production as stated under section 185 (1) *Petroleum and Gas (Production and Safety) Act 2004*. To alleviate and monitor potential impacts of petroleum production on existing groundwater users, numerous mitigation measures can be emplaced by Santos. These include measures to stem the decline in water levels in adjacent aquifers and monitoring to assess whether make good measures are required as stated under section 250(1) *Petroleum and Gas (Production and Safety) Act 2004* (**Table 2-7**).

In the first instance, mitigation essentially involves the development of comprehensive monitoring networks and monitoring programs. Based on later interpretation of monitoring results, the need for further mitigation measures can be assessed.

Should groundwater users be assessed as being unduly impacted, mitigation measures are recommended:

- restoration measures;
- injection of extracted groundwater; and
- rehabilitation of uncontrollable artesian wells.

4.1 GROUNDWATER MONITORING

Groundwater monitoring should be undertaken during and post-extraction as a very necessary pre-requisite to any mitigation measures. The aim of the monitoring is to assess the impact CSG extraction has on the surrounding groundwater environment, both in radial extent and in the magnitude of the drawdown area. Monitoring should provide early warning of any variation of the groundwater system from that predicted. This will enable the undertaking of mitigation measures to minimise impact on surrounding groundwater users.

Predicted drawdowns provide a basis for determining the location of monitoring bores. Ideally, monitoring bores should be located both within and outside the areas of predicted impact to confirm the groundwater drawdown impact extent. Monitoring bores must also be located not only in the aquifer from which the water is being extracted but also in overlying and underlying aquifers.

It is proposed that a network of near field monitoring locations and regional monitoring locations be added to the existing monitoring bores at Comet Ridge and Roma fields. Proposed locations for monitoring sites are indicated in **Figure 4-1** and **Figure 4-2.** Monitoring bores within the Comet Ridge fields are proposed to be installed within the Hutton Sandstone, Precipice Sandstone and the Bandanna Formation. Details of these bores and their sampling regimes are listed in **Table 4-1**. Monitoring within the Roma CSG field should include the Mooga and Gubberamunda Sandstone, Hutton Sandstone and Walloon Coal Measures (**Table 4-2**). Because of the excessive depth of some of these aquifers tensiometers may be used rather than open-hole monitoring bores for monitoring water levels.

Groundwater level fluctuation monitoring should be undertaken in groundwater bores. The proposed groundwater monitoring program should consist of quarterly water level measurements. Existing bores will be monitored as per the proposed monitoring program where possible.

Water quality is also an important parameter which needs to be monitored. However, because groundwater moves so slowly, water quality changes at a particular point are also very slow. Monitoring of groundwater quality is much more difficult than monitoring water levels because of the large volume of water required to be removed to conform to monitoring standards. For these reasons water quality could be monitored on a less frequent basis than water levels (e.g. biannually).

An initial comprehensive analysis for all major ions and contaminants of concern should be carried out as part of the first sampling round (during bore installations). In following sampling rounds, less comprehensive sampling may be adequate. Depending on initial results, the target parameters in subsequent rounds may possibly only include field parameters (e.g. pH, EC, TDS and temperature).

As part of establishing a monitoring network, a survey of existing bores should be carried out to obtain baseline information on the present operational condition of the bores in the area surrounding the CSG wellfield.

The water levels in landholder water bores within and surrounding the Petroleum Leases of the individual fields should be monitored on a biannual basis. It is proposed that a bore census be conducted to locate landholder bores within a 30 kilometer radius of the boundary of the wellfields to accurately locate and assess the present status of all landowner bores in the area. Some bores will already be registered and recorded in the DNRW Database but some may not as it is not necessary for all bores to be registered.

If suitable and acceptable to the owner, some of these bores could be included in the ongoing monitoring programme.

Groundwater monitoring reporting will be in accordance with the *Petroleum and Gas (Production and Safety) Act 2004*. Reports will be submitted annually comparing water level data from monitoring bores with predicted reduction in water levels due to CSG extraction.

Table 4-1 Proposed Groundwater Monitoring Bores – Comet Ridge CGS Fields

Comet Ridge CSG Fields			
Bore	**Screened Formation**	**Parameter**	**Frequency**
GWMC01	Hutton/Precipice Sandstone	Groundwater level	Quarterly
		Groundwater quality	Initial – All cations & anions, ph, EC, TDS, °C Biannual – ph, EC, TDS, °C
GWMC02	Bandana Coal Measures	Groundwater level	Quarterly
		Groundwater quality	Initial – All cations & anions, ph, EC, TDS, °C Biannual – ph, EC, TDS, °C
GWMC03	Bandana Coal Measures	Groundwater level	Quarterly
		Groundwater quality	Initial – All cations & anions, ph, EC, TDS, °C Biannual – ph, EC, TDS, °C
GWMC04	Hutton/Precipice Sandstone	Groundwater level	Quarterly
		Groundwater quality	Initial – All cations & anions, ph, EC, TDS, °C Biannual – ph, EC, TDS, °C
GWMC05	Bandana Coal Measures	Groundwater level	Quarterly
		Groundwater quality	Initial – All cations & anions, ph, EC, TDS, °C Biannual – ph, EC, TDS, °C
GWMC06	Hutton/Precipice Sandstone	Groundwater level	Quarterly
		Groundwater quality	Initial – All cations & anions, ph, EC, TDS, °C Biannual – ph, EC, TDS, °C
GWMC07	Hutton/Precipice Sandstone	Groundwater level	Quarterly
		Groundwater quality	Initial – All cations & anions, ph, EC, TDS, °C Biannual – ph, EC, TDS, °C
GWMC08	Hutton/Precipice Sandstone	Groundwater level	Quarterly
		Groundwater quality	Initial – All cations & anions, ph, EC, TDS, °C Biannual – ph, EC, TDS, °C

Table 4-2 Proposed Groundwater Monitoring Bores – Roma CGS Field

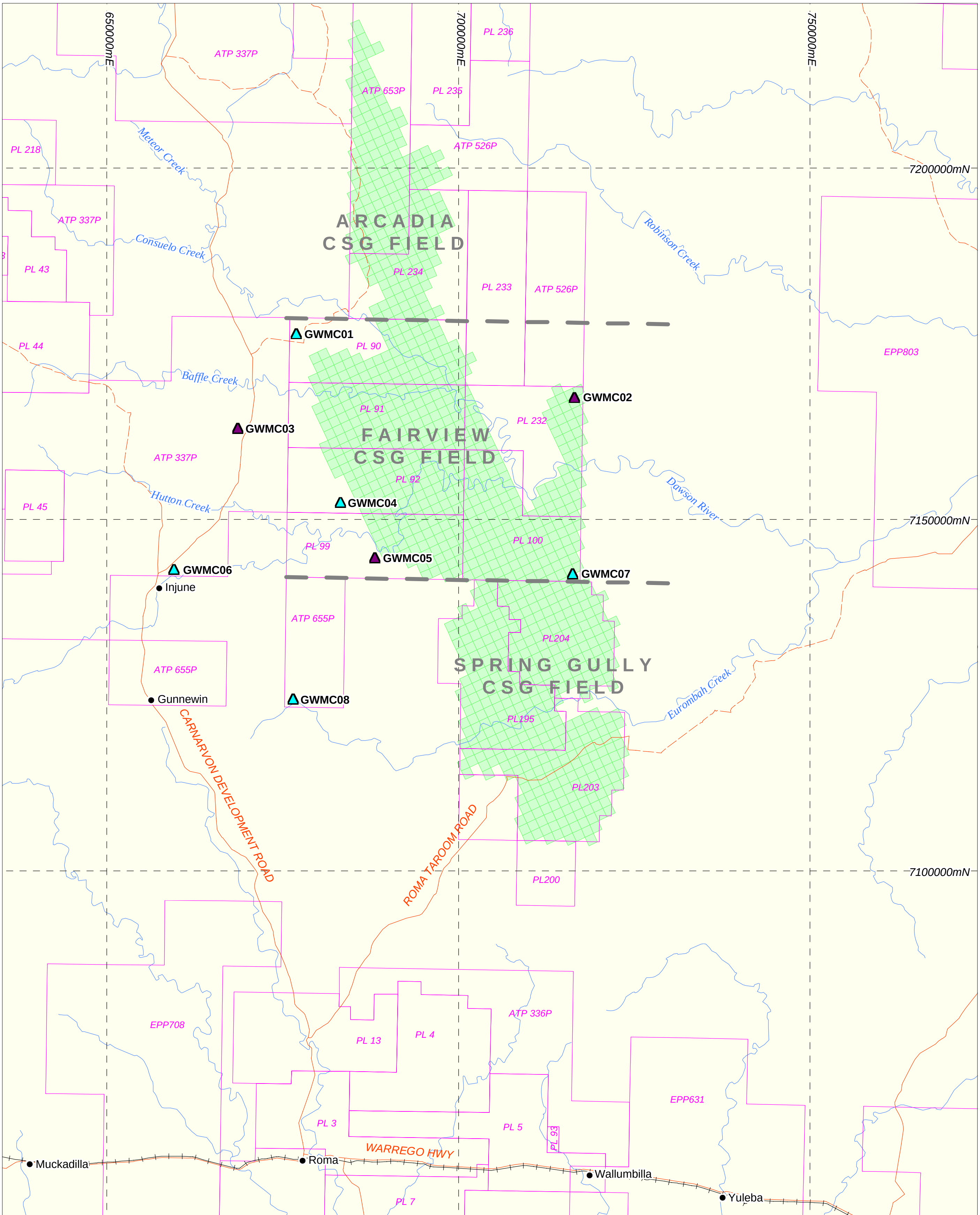
Roma CSG Field			
Bore	**Screened Formation**	**Parameter**	**Frequency**
GWMR09	Mooga/Gubberamunda/Hutton Sandstone Walloon Coal Measures	Groundwater level	Quarterly
		Groundwater quality	Initial – All cations & anions, ph, EC, TDS, °C Biannual – ph, EC, TDS, °C
GWMR10	Mooga/Gubberamunda/Hutton Sandstone Walloon Coal Measures	Groundwater level	Quarterly
		Groundwater quality	Initial – All cations & anions, ph, EC, TDS, °C Biannual – ph, EC, TDS, °C
GWMR11	Mooga/Gubberamunda/Hutton Sandstone Walloon Coal Measures	Groundwater level	Quarterly
		Groundwater quality	Initial – All cations & anions, ph, EC, TDS, °C Biannual – ph, EC, TDS, °C
GWMR12	Mooga/Gubberamunda/Hutton Sandstone Walloon Coal Measures	Groundwater level	Quarterly
		Groundwater quality	Initial – All cations & anions, ph, EC, TDS, °C Biannual – ph, EC, TDS, °C
GWMR13	Mooga/Gubberamunda/Hutton Sandstone Walloon Coal Measures	Groundwater level	Quarterly
		Groundwater quality	Initial – All cations & anions, ph, EC, TDS, °C Biannual – ph, EC, TDS, °C
GWMR14	Mooga/Gubberamunda/Hutton Sandstone Walloon Coal Measures	Groundwater level	Quarterly
		Groundwater quality	Initial – All cations & anions, ph, EC, TDS, °C Biannual – ph, EC, TDS, °C

4.2 Restoration Measures

As previously indicated landholder bores screened in affected aquifers within the radius of influence may experience a loss in groundwater levels owing to CSG extraction. If the drop in the level of water in the bore is more than the trigger threshold the bore has an impaired capacity and as such under Division 2 section 250 (1) *Petroleum and Gas (Production and Safety) Act 2004* the proponent has the obligation to make good.

At this time trigger thresholds for aquifers within Comet Ridge and Roma fields have not been set nevertheless restoration measures may still be delineated. Examples of possible restoration measures to provide an alternative supply of water include:

- deepening the affected bore;
- lowering the pump suction setting in the affected bore;
- drilling a new bore (outside the radius of influence or in an unaffected aquifer); and
- providing a supply of an equivalent amount of water of a suitable quality by piping it from an alternative source (i.e. treated CSG extraction water).



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matrixplus

30/01/2009

LEGEND

- Santos ATP & PL Tenement
- Road
- Track
- Railway
- Watercourse
- Town

Proposed

- Hutton/Precipice SS
- Bandanna Coal Measures

Existing

- Active CSG Field
- CSG Field Boundary

Data Source:
Topography - Geoscience Australia. Tenement - URS

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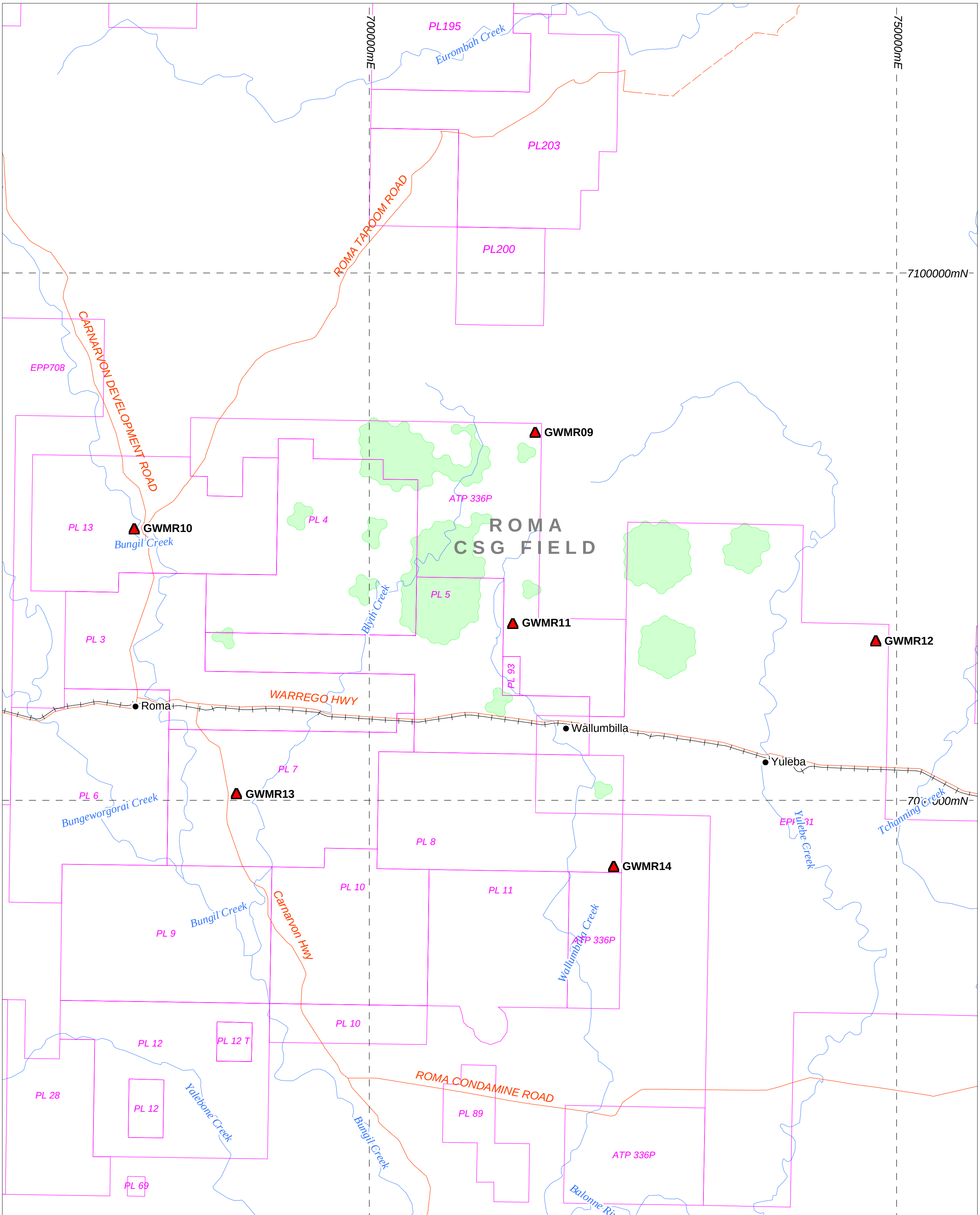
Proposed Monitoring Bore Locations - Comet Ridge CSG Fields

0 10 20
Kilometres

Scale: 1:750,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 4-1



LEGEND

Proposed

- Santos ATP & PL Tenement
- Road
- Track
- Railway
- Watercourse
- Town
- Nested Monitoring Location

Existing

- Active CSG Field

Santos Ltd

Santos GLNG EIS

Proposed Monitoring Bore Locations - Roma CSG Field

0 10 20

Kilometres

Scale: 1:500,000 (A4)

Datum: GDA94
Projection: MGA55

FIGURE 4-2

30/01/2009

Data Source:
Topography - Geoscience Australia. Tenement - URS

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4.3 INJECTION OF EXTRACTED GROUNDWATER

A large volume of water is produced during the extraction of CSG. A common method of disposing of the water produced during CSG extraction is underground injection. However, the success of such a mitigation measure depends on the existence of suitable aquifers into which the water can be injected.

Certain criteria need to be met before reinjection of extracted groundwater is attempted. These include;

- The quality of the water to be injected should not exceed the upper limit of beneficial use of the water in the receiving aquifer.
- The receiving aquifer must be capable of receiving and transmitting the injected water at an acceptable rate for disposal.
- The aquifer parameter of transmissivity for the receiving aquifer must be greater than that of the producing aquifer. If it is equal to or less than the transmissivity of the producing aquifer (i.e. CSG aquifer) then the number of injection wells must be equal to or greater than the number of producing wells.
- Suitable receiving aquifers should be present close enough to the wellfield to make pumping and piping to the disposal site an economical proposition.

If the water quality of the producing aquifer matches that of the chosen receiving aquifer, injection may provide an avenue for recharge of depleted aquifers affected by CSG extraction (Parsons Brinckerhoff, 2004).

4.3.1 Injection into Overlying Aquifers

This option could be considered in the later stages of the lives of the Comet Ridge CSG fields.

As a result of depressurisation of the Bandanna Formation inter-aquifer transfer occurs from the Precipice Sandstone to the Bandanna Formation. The rate of transfer increases from 2009 and by the end of the lives of the fields it constitutes about 50% of the rate of withdrawal from the Comet Ridge fields.

To achieve the dual purpose of disposal of extraction water and to reduce the magnitude of drawdown in the Precipice Sandstone a line of injection wells could be drilled into the Precipice Sandstone within the cone of depression located over the zone of contact between the Bandanna Formation and the Precipice Sandstone. The discharge from the wells located in the western side of the Comet Ridge wellfields (which have better quality production water) could be pumped directly into the injection wells and would recharge the water back into the Precipice Sandstone which would leak back into the Bandanna Formation. Because there is already a reduction of water level within this zone pressure injection would not be required. The existing drawdown in the bore could provide the necessary head for injection.

This recycling system would maintain low water pressures in the wellfield and higher water levels near the Precipice Sandstone. This process could sustainably dispose of a significant volume of the production water and reduce the drawdowns in the Precipice Sandstone.

The recycled water may be poorer quality water than that in the insitu Precipice Sandstone but there should not be a significant adverse impact on the quality of water in the receiving aquifer as most of the water being recycled in the later years of the lives of the Comet Ridge CSG fields is coming from the Precipice Sandstone.

The Mooga and Gubberamunda Sandstone Aquifer overlie the Roma field. These aquifers are used extensively for stock, domestic and feedlot purposes. They also provides significant urban water supplies for surrounding towns including; Muckadilla, Roma, Wallumbilla and Yuleba.

As a result of current demands on the Gubberamunda Sandstone, additional drawdown associated with CSG extraction even though it is considered to be minimal may poses risks to the security of supply for existing users. To combat a background of high historical depletion within the Gubberamunda Sandstone groundwater extracted during CSG production at Roma may be injected into the aquifer. However this may only be considered a viable beneficial use/mitigation measure if the extracted water quality matched that of the Gubberamunda Sandstone. The average water quality in the Gubberamunda is 1,204 µS/cm while the Walloon Coal Measures is significant more saline at 4,438 µS/cm (refer **Table 2-4**). As such the extracted groundwater associated with CSG production at Roma would require substantial treatment to match the quality of the receiving aquifer.

4.3.2 Injection into CSG Aquifers

Injection of extracted groundwater back into coal seams within the existing wellfield would minimise impacts on the surrounding environment. The water quality should not be a problem as the beneficial use of the extracted water and the waters in the receiving aquifer will be the same. However investigations suggest that injection of water back into the CSG aquifer will increase the hydrostatic pressure in the adjacent wells and could reduce gas production.

In addition the CSG aquifer will not accept water at the same rate as it was capable of discharging because the extraction of water and the associated large drawdown will have resulted in compaction of the coal matrix. Consequently, both the transmissivity and the porosity of the coal seams will have reduced.

4.3.3 Injection into Underlying Aquifers

At present, some water from the Fairview field is being injected into the deeper fractured rock formations (i.e. Timbury Formation) under the coal seams in the Fairview field. However, it is unlikely that such an injection programme will be sustainable for the disposal of all of the production water.

These deeper fractured rock formations are likely to have lower transmissivities than the coal seams and the transmissivity will decrease with depth as the fractures become tighter. It is also most unlikely that the fractures in these deeper formations will have sufficient storage volume to be able to accept the large volumes required. They could be used, however, to dispose of the higher salinity waters (i.e. brine stream) which are associated with extraction from some parts of the wellfields particularly in the early stages of production.

As a result of depressurisation of the Walloon Coal Measures at Roma inter-aquifer transfer occurs from the Hutton Sandstone to the overlying Walloon Coal Measures. Injection of treated extraction water or brine stream is not considered to be a viable option. The expected pressure reduction in the Hutton Sandstone is expected to be minimal so the water would have to be injected under considerable pressure.

4.4 Rehabilitation of Uncontrollable Artesian Wells

One of the real or perceived impacts of the extraction of water for the development of CSG projects is the decline in water levels. While it may not be possible to use direct means to increase water levels in an area of decline it may be feasible to do this indirectly by contributing to the rehabilitation of uncontrollable bores and so reduce the rate of pressure decline in other parts of the Great Artesian Basin.

It may be possible to partially compensate for the predicted drawdown on the Hutton Sandstone aquifer within the Roma field area by reducing the extraction from this aquifer elsewhere. This can be achieved by controlling some bores which are at present flowing uncontrolled. Such work is currently carried out within the framework of the Great Artesian Bain Sustainability Initiative (GABSI), a joint Commonwealth/state programme. Monitoring bore data collected since the GABSI commenced in 1999 shows that 345 bores have increased in pressure by up to 8 m and 30 bores have increased by more than 8 m.

5 CONCLUSIONS

The following are key findings of modelling and subsequent reporting:

- The maximum drawdown of groundwater levels within the coal seam aquifers in the CSG fields is expected to be in the order of 600 m with the drawdowns in some wells located in the extreme east of the Fairview CSG field ranging up to 1000 m;
- Landholder bores screened in affected aquifers which are located within the predicted radius of influence may experience a level of reduced groundwater heads;
- In the Arcadia Valley and Fairview CSG fields (which were modelled in conjunction with the neighbouring Spring Gully CSG field) the radius of influence of drawdown within the coal seam aquifer is expected to spread well outside the perimeter of the CSG fields;
- Groundwater drawdowns in the coal seam aquifer within the Arcadia Valley and Fairview CSG fields are expected to result in inter-aquifer transfer from the overlying Precipice Sandstone. Groundwater head loss within the Precipice Sandstone could range up to a maximum of 15 m at the end of 2013 and up to a maximum of 65 m at the end of 2028; (These impacts also include the effect of the Spring Gully CSG field);
- It is anticipated that 4 existing bores which are drilled into the Precipice Sandstone aquifer may be impacted by the groundwater drawdowns in the coal seam aquifer within the Arcadia Valley and Fairview CSG fields. One bore, (14988), is located inside the well field area, and 3 others, (16091, 14838 and 16785) are situated outside the well field area. It is anticipated that these bores will be impacted by a maximum 7 – 25 m of drawdown by 2028 depending on their locations within the area of influence.
- In the Roma CSG field, the radius of influence of drawdown within the coal seam aquifer is expected to be confined to an area proximal to the CSG field;
- Groundwater drawdowns within the Roma field are expected to result in minor inter-aquifer transfer from the underlying Hutton Sandstone. After 20 years of operation, as a result of inter-aquifer transfer, the groundwater levels within the Hutton Sandstone will decline by approximately 3 m at the edge of the CSG field and by lesser values further out from the CSG field;
- No landowner bores are expected to be impacted as a result of groundwater withdrawal from the Roma CSG field;
- No town water supply bores are likely to be impacted as a result of groundwater withdrawal from the Roma CSG field or from the Fairview and Arcadia Valley CSG fields;
- Drawdown of groundwater heads within the Precipice Sandstone as a result of groundwater extraction at Arcadia Valley and Fairview CSG fields is not expected to significantly alter the baseflow contributions to the perennial portion of the Dawson River and groundwater discharge volumes to springs located in the vicinity;
- Groundwater drawdown and associated inter-aquifer transfer is unlikely to have an adverse impact on the water quality of the CSG aquifer and the deep aquifers surrounding the CSG fields; and
- It is not expected that ground surface subsidence will occur as a result of groundwater withdrawal from the coal seam aquifers in the Roma CSG field or from the Fairview and Arcadia Valley CSG fields.

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Description of Aquifer Parameters

APPENDIX A

This Appendix contains a detailed description and discussion of the various aquifer parameters used in the analysis of the groundwater system associated with the CSG environment and in the development of the associated groundwater models.

1 HYDRAULIC CONDUCTIVITY (K)

1.1 ISOTROPIC MEDIA

The hydraulic conductivity of an aquifer refers to the ease with which a fluid will pass through it. It varies with the nature of the matrix through which the fluid is passing and with the properties of the fluid itself. It is defined as the rate of flow of fluid through a unit area of the aquifer (at right angles to the direction of flow) under a unit gradient. If the flow is expressed as m^3/d, the area as m^2 and the hydraulic gradient as m change in hydraulic head per m of horizontal distance, then the units of K are $m^3/d/m^2$ or simply m/d.

Hydraulic conductivity is expressed by Darcy's Law as:

$$Q = -KiA$$

where

Q = flow rate (m^3/d)
K = hydraulic conductivity (m/d)
i = hydraulic gradient (m/m)
A = cross sectional area at right angles to the direction of flow (m^2).

1.2 ANISOTROPIC MEDIA

The hydraulic conductivity normally refers to horizontal flow through a homogeneous isotropic medium. However, in anisotropic media the hydraulic conductivity can vary, not only in the different horizontal directions, but more importantly in the vertical direction. Because of the layering nature of sedimentation the vertical hydraulic conductivity (K_z) is normally much smaller than the horizontal hydraulic conductivity (K_h). This is an important consideration when considering the possibility of inter-aquifer transfer of water between the depressurized Coal Measures and the underlying and overlying aquifers.

In calculating the inter-aquifer transfer mechanism, the electricity analogy was used. Electrical flux, heat flux and groundwater flow are all based on analogous physical principles.

For electrical flux:

$$I = V / R$$

or

$$I = - C\,dE / dL$$

where

I = current (amps)
V = voltage drop (volts)
E = voltage potential (volts) (same units as V)
R = resistance to electrical flow (ohms)
L = length of the flow path
C = electrical conductivity.

While Darcy's Law defines the groundwater flux in normal horizontal flow in an aquifer, the movement of water from the underlying and underlying water-bearing aquifers through layers of differing hydraulic resistances is also analogous to the flow of electric current through a circuit with a number of resistances in series. The total resistance in such a circuit is the sum of the individual resistances.

In groundwater hydraulics, the flow through an anisotropic medium with a series of layers of varying *K* can be determined in the following manner:

$q = - K\,\mathrm{d}h / \mathrm{d}L$

or

$q = \mathrm{d}h / c$

where (c) the hydraulic resistance = b' / K'

If flow is at right angles through a series of layers of thicknesses b_i', hydraulic conductivities K_i' and hydraulic resistances c_i then

$c_{total} = c_1 + c_2 + c_3 + \ldots$

$= (b_1' / K_1' + b_2' / K_2' + b_3' / K_3' + \ldots)$

$K_{eff} = b / c_{total}$

$q = K_{eff}\, i$

i.e.

$$K_{eff} = \frac{b}{\frac{b_1'}{K_1'} + \frac{b_2'}{K_2'} + \frac{b_3'}{K_3'} + \cdots}$$

where

K_{eff} = effective hydraulic conductivity of the anisotropic system

b = sum of individual thicknesses of all layers through which water has passed
b_1' = saturated thickness of the semi-pervious layer 1

K_1' = vertical hydraulic conductivity of the semi-pervious layer1

Δh = total head loss (drawdown) in achieving a flow of q through the layers
$q = (b / c_{total})(\Delta h / b)$
$Q = (b / c_{total})(\Delta h / b)\, A$
i = hydraulic gradient ($\Delta h / b$).

In calculating the hydraulic resistance of each layer the vertical hydraulic conductivity was taken as 10% of the horizontal hydraulic conductivity. This takes into account layering effects and is a reasonable assumption. The actual value may in fact be less than 10% so the leakage coefficient estimates may be conservative.

2 TRANSMISSIVITY (*T*)

The transmissivity (T) of an aquifer also refers to the ease with which a fluid can pass through it. It is defined as the rate of flow of fluid through a unit width of the aquifer (at right angles to the direction of flow) under a unit gradient. It is then simply K multiplied by the thickness of the aquifer. Its units are m^3/d/m or simply m^2/d. It is a more useful parameter than K in analysing aquifers. It is more accurately determined from pumping tests and its value is representative of the average of the aquifer conditions through which the fluid moves to flow to the extraction well.

$T = K\,b$

where

T = transmissivity (m^2/d)
b = aquifer thickness (m).

3 INSTRINSIC PERMEABILITY (*k*)

Intrinsic permeability (*k*) is also a measure of the relative ease with which a porous medium can transmit a fluid under a potential gradient. It is a property of the medium alone and is dependent only on the size and shape of the pores; it is independent of the nature of the fluid and of the force field causing the movement.

k is related to hydraulic conductivity as follows:

$$k = \frac{K\eta}{\rho g} \text{ or } k = \frac{K\upsilon}{g}$$

where

k = intrinsic permeability (m^2) (expressed as millidarcys in the gas industry)
K = Hydraulic conductivity (m^2/d)
η = dynamic viscosity of the fluid (mass/length time)
g = acceleration of gravity (length/time^2)
υ = kinematic viscosity (length^2/time).

It should be emphasised that permeability characteristics of a porous medium are expressed by *k* (length^2) and not by *K* (length/time). The value of *k* is independent of the properties of the fluid, whereas *K* depends not only on the properties of the porous material, but also on the properties of the fluid.

In the gas industry, *k* is expressed as millidarcys (mD). In order use the data (obtained from drill stem tests) in the equations used in the groundwater model they are converted to consistent (SI) units. The conversion used to convert *k* values permeability (mD) into *K* values (m/d) (assuming water as the fluid) is:

1 mD = 8.64 x 10^{-4} m/d.

4 POROSITY (*O*)

Porosity of a material is defined as the ratio of the volume of voids to the total volume of the material. It is dimensionless and is normally expressed as a percentage. It then defines the total volume of a fluid which can be stored within a porous medium. Porosity is typically of two forms: primary and secondary porosity. Primary porosity is related to granular material, while secondary porosity refers to openings in joints and faults in hard rock, and solution openings in limestone, dolomite, gypsum or other soluble rocks.

Groundwater occurs within the coal seam aquifers of the Surat and Bowen Basins. In the case of coal seams, primary porosity (voids within the coal matrix) is typically a less significant conduit for groundwater flow than secondary porosity, the coal cleats formed during coal maturation. Consequently, there is a relationship between the effective porosity of coal measures and the coal rank. For saturated flow conditions, i.e. when the potentiometric surface is considerably higher than the upper surface of the coal measures, the porosity of the coal is insignificant in controlling groundwater pressure fluctuations compared to the more important aquifer properties; transmissivity (*T*) and storativity (*S*).

5 STORATIVITY (OR STORAGE COEFFICIENT) (*S*)

Like porosity, storativity (or storage coefficient) (*S*) is a dimensionless measure of the storage capacity of a formation. However, unlike porosity, *S* is a measure of the change in water storage with change in pressure of a saturated aquifer, i.e. it is directly dependent on the elasticity of both the water within the pores and the aquifer matrix. *S* can be thought of as the strain in the saturated aquifer as a result of an imposed stress. As result, *S* can be many orders of magnitude less than porosity. A typical porosity for coal is 5%, whereas storativity may be as low as 10^{-6} for a one metre thickness of aquifer. This distinction underlies the critical difference between confined and unconfined aquifers. Drawdowns in confined aquifers are more widespread.

Storativity is defined as follows:

$$S = b\rho g(\beta\theta + \alpha(1-\theta))$$

where

S = storativity (or storage coefficient) (-)
b = aquifer thickness (net pay) (m)
ρ = density of fluid (kg/m^3)
g = acceleration of gravity ($length/time^2$)
β = compressibility of fluid (for water = 4.8×10^{-7} $(kPa)^{-1}$)
α = compressibility of matrix (-)
θ = porosity (-).

S is not an easy parameter to determine. It is best determined by analysing the drawdown effects of a pumping well at an observation well remote from the pumping well. However, this is not always feasible. The minimum value of *S* can be determined solely from the compressibility of water, i.e. the first part of the equation given above. It is expressed approximately as:

$$S_{min} = 5 \times 10^{-6}\ b\,\theta$$

The true value of *S* will be somewhat larger than this minimum value as the coal matrix is far more compressible than the water within it.

This relationship has been used to estimate *S* for the equations used in the model. In addition, another estimate attempting to take into account the compressibility of the matrix has been used. These two values are then used as part of a sensitivity analysis for the model outputs. The smaller value of *S* will result in a larger radius of influence of the pumping wells than will occur in practice and will, therefore, be conservative.

6 HYDRAULIC RESISTANCE (*C*)

The hydraulic resistance (*c*) is a property of the confining layer of a semi-confined aquifer. It is the resistance against vertical flow and is defined as:

$$c = \frac{b'}{K'}$$

where

b' = the saturated thickness of the semi-pervious layer
K' = the hydraulic conductivity of the semi-pervious layer for vertical flow.

If Darcy’s Law is applied to the confining layer, then *c* may be thought of as the drawdown in the aquifer that is required to achieve a unit discharge per unit area from the confining layer.

This is the parameter which needs to come into play if inter-aquifer transfer is to occur from overlying or underlying aquifers through the confining layers.

If $c = \infty$, then the aquifer is confined.

Hydraulic resistance has dimensions of time; the units used are days.

7 LEAKAGE COEFFICIENT (OR VERTICAL LEAKAGE) (V_L)

The leakage coefficient is a property of the confining layer of a semi-confined aquifer. It is the inverse of hydraulic resistance.

Leakage Coefficient $V_L = K' / b'$

where

b' = the saturated thickness of the semi-pervious layer
K' = the hydraulic conductivity of the semi-pervious layer for vertical flow

8 LEAKAGE FACTOR (L)

The leakage factor is a property of the semi-confined aquifer. It is defined as:

$$L = \sqrt{Kbc}$$
$$= \sqrt{Kb\,b'/K'}$$
$$= \sqrt{Tc}$$

where

c = hydraulic resistance of the semi-pervious layer
K = hydraulic conductivity of the aquifer material
b = thickness of the aquifer
T = transmissivity of the aquifer.

N.B.: This parameter has not been used in the above analyses but its definition has been included for the sake of completeness.

Groundwater Flow Equations

APPENDIX B

In the steady state radial flow situation (which seldom occurs in nature), a constant discharge from a well is accompanied by a constant drawdown in water level. However, in order to satisfy the principle of conservation of matter, for the non-steady or transient state situation a constant rate of discharge from a well is accompanied by a reduction in volume stored in the aquifer. The equation defining such a flow is:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=\frac{S}{T}\frac{\partial h}{\partial t} \qquad (1)$$

where

h = the potentiometric head (m)
x, *y* and *z* are Cartesian coordinates
S = storage coefficient
t = time since pumping started (days) and
T = transmissivity (m^2/d).

Theis' solution to this equation for radial flow to a well is given by

$$s=\frac{Q}{4\pi T}\left(-\gamma-\ln u+u-\frac{u^2}{2.2!}+\frac{u^3}{3.3!}-......\right) \qquad (2)$$

$$s=\frac{Q}{4\pi T}W(u) \qquad (3)$$

where

s = drawdown (m) at distance *r* from the pumping well
Q = flow rate (m^3/d)
T = transmissivity (m^2/d)
W (*u*) is known as the well function of *u* (where $u = r^2S/4Tt$)
S = storage coefficient
γ = Euler constant (0.5772)
t = time since pumping started (days), and
r = distance from the pumping well (m).

For most situations, the Theis solution for non-steady state radial flow to an extraction well in porous media can be modified to a semi-logarithmic straight line solution – the Jacob straight line equation:

Jacob's modified non-steady state flow equation is applicable when the dimensionless term *u* is very small. Equation 2 can be rewritten as:

$$s=\frac{Q}{4\pi T}\ln\frac{2.25Tt}{r^2S} \qquad (4)$$

or

$$s=\frac{2.3Q}{4\pi T}\log\frac{2.25Tt}{r^2S} \qquad (5)$$

Equation 3 or equation 5 can be used to determine the drawdown at a point at a distance r from the pumping well.

For the pumping well itself, the drawdown is more complex. At distance from the pumping well, the flow is laminar or Darcian flow and the drawdown is proportional to *Q*. However, within the pumping well itself the drawdown is a combination of laminar flow and non-Darcy flow which is predominantly turbulent and proportional to Q^2. This "skin effect" or pressure loss due to turbulent flow may be significant for extraction wells. In addition, because of construction techniques, the effective radius of the well is not well-defined.

The equation to drawdown within the pumping well is given by:

$$s = (a + b\log t)Q + CQ^2 \qquad (6)$$

where $a = \frac{2.3}{4\pi T}\log\frac{2.25T}{r_w{}^2 S}$

b = 2.3 / (4 π T)
r_w = the effective radius of the well and
C is a constant for a particular well.

This equation to drawdown for the pumping well and the value of transmissivity for the aquifer are normally determined by carrying out controlled pumping tests in which discharge and drawdown are measured at set time intervals from the start of pumping. The value of storage coefficient is normally determined by measuring the drawdown effects at observation wells remote from the pumping well. However, if no such data are available then reasonable estimates of storage coefficient can be made from the knowledge of porosity, compressibility of water, compressibility of the aquifer matrix and the thickness of the aquifer. Upper and lower limits of the values can be used in the equations to obtain ranges of drawdown effects.

The turbulent head loss can only be determined accurately by analysing tests at different rates of pumping.

The total drawdown in each well is the sum of the drawdown in the well resulting from pumping from that well and the drawdown at that well caused by all other wells pumping. This drawdown can be determined by the theory of superposition.

This theory of superposition was used in developing the analytical model for the Roma field. In all, 501 wells were included in the model. In most cases the distances between bores were so large that that the value of u was not small enough for the Jacob's modified non-steady flow equation to be applicable and the Theis equation had to be used. The series given in equation 2 above was used for values up to u^{15}.

Determination of Aquifer Parameters - Comet ridge Fields

APPENDIX C

matrixplus

1 TRANSMISSIVITY

Although there is a plethora of production pumping data for the Fairview and Spring Gully wells, none of it is suitable for reliable calculation of a *T* value for either of these fields. There were no well test data available to enable an estimate of *T* for the Arcadia field.

The Santos data included permeability values for the Fairview field which ranged from 1 millidarcy (mD) to 9,000 mD. This was too large a range to provide a reasonable value of *T* for use in the model. The extraction wells within the coal seams in this field cavitate thus making it very difficult to obtain reliable values of drill stem *k* tests and the origin of the data was not immediately apparent. In addition, the ground locations of individual values were not included in the available data. For these reasons the *T* of the coal seams was estimated by other means.

As there were reliable values of total water extraction from the field and an adequate number of potentiometric levels to draw a significant portion of the potentiometric surface contours (based on bottom hole pressures) the contours and extraction rates were used to estimate *T*.

While there are more accurate determinations of the bottom hole pressure for a few bores in more recent years, the most comprehensive set of bottom hole pressures was available from the pressure surveys conducted in 2004. Daily extraction volumes were also available for this period. Even though the extraction rates have changed significantly in later years, an analysis of these data enabled a reasonably accurate determination of *T* to be made. *T* is assumed to be essentially constant for the life of the field, i.e. it is essentially a time-invariant property, so it does not matter when it is determined.

When calculating the potentiometric level, it was assumed that the bottom hole pressure was measured at the top of the Bandanna coal (the top of the B seam). The bottom hole pressure was determined by utilising a combination of depth to water level, casing pressure and column of gas and the water level was calculated by using casing joints, so the accuracy of the potentiometric level is only about +/- 9 m. However, with the magnitude of the gradients being used it was considered that this would still give a reasonable estimate of *T*.

The potentiometric level reduced to AHD was determined as follows:

Potentiometric level (m AHD) = $EL - Coal\_top + .BHP$

where

EL = reference point at ground surface (mAHD)

$Coal\_top$ = depth from ground surface to top of Bandanna coal (B seam) (m)

BHP = Bottom Hole Pressure corrected to the top of the B seam (m).

The potentiometric level contours were drawn for pressure measurements taken in March and May 2004. These were not comprehensive enough in areal extent to enable the whole cone of depression to be defined but were sufficient to define the southern half.

The average extraction rate for water for the whole field during the three month period February to May 2004, was 5,430 m^3/d (or 2,715 m^3/day for half of the area of influence). As the cone of depression was the cumulative effect of all of the pumping which had taken place since the field was commenced in December 1994, the average pumping rate for the life of the field was also used in the estimation of *T*. The average pumping rate for the whole field was 4,245 m^3/d (or 2,122 m^3/d for half of the area of influence) over the 9.4 year life of the field as at May 2004.

The potentiometric level gradient was 0.017; a drop of 150 m over a distance of 9 km.

For that section of the contours analysed for the southern half of the cone of depression, the average width of the area through which the water was flowing in the Bandanna coal under the above gradient was 29 km.

From these figures, *T* was calculated using Darcy's Law, as 5.6 m^2/d (when only the 3 month period was considered) and 4.3 m^2/d (when applied to the whole life of the field). A value of 5 m^2/d was adopted as an average value for the Fairview field. The value of *T* does of course vary throughout the field and this distribution is determined later.

The thickness of the coal seams in the Bandanna coals varies from 6 m to 15 m with an average thickness of 9 m. The hydraulic conductivity then varies from 0.83 m/d to 0.33 m/d with an average value of 0.56 m/d This equates to *k* values ranging from 981 mD to 390 mD with an average of 661 mD for the cone of depression. The values were confirmed by utilising the Theis well function to compare the expected drawdown figures with the actual cone of depression for the life of the field as at May 2004.

These values agree fairly well with the upper values of hydraulic conductivity for the Bandanna coals used in previous groundwater assessments of the Comet Ridge area (AHA, 2003; SKM, 2006). However, it is believed that the hydraulic conductivity decreases downdip and this was taken into account when developing the present model.

In order to get a better estimate of the distribution of *T* across the various fields, the wells were analysed individually.

There is an approximate relationship between the specific capacity (the discharge rate divided by the drawdown) of a well and the *T* of the aquifer. In this field, where the units used are metres and days, the specific capacity at one day is of the order of 1.2 times *T*.

Because the available data was not detailed enough to allow the determination of drawdowns, it was assumed that the drawdowns in each well was the same at the time that each was tested. On this basis, the *T* was proportional to the maximum discharge rate which was normally within a day of the start of pumping. A comparison of the maximum pumping rates was used to give a comparison of *T* values.

It was assumed that 5 m^2/d, the *T* estimated from the potentiometric level contours in 2004, was related to the average pumping rate at that time and the other *T* values were determined proportionally.

In this manner, *T* was estimated for 96 wells in the Fairview field and 102 wells in the Spring Gully field. Contours of *T* for the Fairview field are given in **Figure 3-2**.

The average values determined were 5.8 m^2/d for the Fairview field and 1.9 m^2/d for the Spring Gully field. In the absence of any other data, a value of 0.5 m^2/d was assumed for the Arcadia field. In constructing the numerical model for the Fairview and Arcadia fields, *T* values were distributed across the fields in accordance with the values determined from the above analysis.

2 STORATIVITY (STORAGE COEFFICIENT)

Storativity (*S*) is best determined by analysing the drawdown effects of a pumping well at an observation well remote from the pumping well. However, this cannot always be arranged. In the absence of drawdown data at an observation well, *S* was calculated using the equation:

$$S = b\rho g(\beta\theta + \alpha(1-\theta)$$

where

S = storativity (or storage coefficient)

b = aquifer thickness (net pay) (m)

ρ = density of fluid (kg/m^3)

g = acceleration of gravity (length/$time^2$)

β = compressibility of fluid (for water 4.8×10^{-7} $(kPa)^{-1}$

α = compressibility of matrix

θ = porosity

The minimum value of *S* can be determined solely from the compressibility of water, i.e. the first term in the right hand side of the equation given above. It is expressed approximately as:

$$S_{min} = 5 \times 10^{-6}\ b\,\theta$$

The true value of *S* will be somewhat larger than this minimum value as the coal matrix is far more compressible than the water within it.

This relationship has been used to estimate *S* for the equations used in the model. In addition, another estimate attempting to take into account the compressibility of the matrix has been used. These two values are then used as part of a sensitivity analysis for the model outputs. The smaller value of *S* will result in a larger radius of influence of the pumping wells than will occur in practice and will then be conservative.

The drawdown effects resulting from the minimum *S* estimate will be conservatively large. The value of *S* can be changed in the model as more reliable data become available or to carry out a sensitivity analysis.

The value of storativity for the Comet Ridge area was initially estimated to be 10^{-4}, this was later refined during the calibration of the numerical model. The value obtained was 1.3×10^{-4}.

Aquifer Parameters in Surrounding Geologic Formations - Comet Ridge and Roma Fields

APPENDIX D

To enable this study to be carried out as accurately as possible with the data available, *T* values for the water producing aquifers were determined from flow and pressure tests which had been carried out on bores in the area of interest. The raw data for these analyses was extracted from the DNRW groundwater database. A total of 239 static (recovery) tests were analysed within an area of some 310 km by 180 km. As these tests were for bores tapping a multitude of aquifers, it was possible to obtain an indication of *T* values for various aquifers in the area. Many of the bores were outside the immediate area of the wellfield but the aquifer parameters and thickness of the aquifer for that period of deposition were still of more use than having no data at all and were of use in determining the effect of wellfield extraction on surrounding groundwater users. These static tests were frequently part of a more comprehensive series of tests which included flow recession (constant drawdown) tests and dynamic (step drawdown) tests. However, because an indication of the magnitude of *T* was all that was required and not an exact figure, the effects of the antecedent flow conditions were not taken into account when analysing the static tests. The values are certainly of the right order of magnitude.

The groundwater database listed many geologic formations encountered during the drilling of water bores but not all formations were tested. **Table D-1** lists the details of formations recorded in drilling logs for bores and the resultant parameters from analyses.

Table D-1 Geologic Formations and Aquifer Parameters – Comet Ridge and Roma Fields

Formation	Average thickness (m)	*T* (m^2/d)	*K* (m/d)	Parameter Source	No. of Samples analysed	Comments
Bandanna Formation	134 (70-250)	0.1 – 18 (Ave. 5.8 Fairview, 1.9 Spring Gully 0.5 Arcadia)	0.04	Production & Hyd. Head Contours	Period Feb-May 2004	Gas producing coal seams
Boxvale Sandstone	46	10	0.2	Flow Tests	2	Aquifer
Bungil Group	112 (80 – 230)	4.6	0.04	Flow Tests	2	Confining bed with some aquifers
Clematis Sandstone	144 (10 – 200)	13 820	0.09 1.97 -	Flow Tests	50 7	Aquifer. Aquifer thickness not available for high *T* bores. Probably very thick and *K* of order of 0.2.
Eurombah	50 (20-80)	6.8	0.14	Flow Tests	2	Confining beds some aquifer layers. *K* value seems too high.
Evergreen Formation	105 (10-260)		0.008	AHA Report		Confining bed
Griman Creek	57 (- 480)					
Gubberamunda Sandstone	84 (20-260)	11	0.13	Flow Tests	1	Aquifer. Most highly developed aquifer in Surat Basin. *K* probably higher.
Hutton Sandstone	150 (100-350)	21	0.14	Flow Tests	20	Aquifer
Injune Creek Formation	396 (-1,000)	32	0.08	Flow Tests		Confining beds some permeable beds
Minmi Member	22 (20–70)					Minor aquifer
Mooga Sandstone	86 (25–200)	19	0.22	Flow Tests	42	Aquifer
Moolayember Formation	80 (10-500)	66	0.82	Flow Tests	10	Confining beds

Formation	Average thickness (m)	*T* (m^2/d)	*K* (m/d)	Parameter Source	No. of Samples analysed	Comments
Orallo Sandstone	107 (70 – 270)					Aquifer
Precipice Sandstone	≈100 (20-140)	50 (8 – 200)	0.5	Flow Tests	4	Aquifer T of 50 from model calibration
Reids Dome Beds	280					
Rewan Group	173 (50 - 600)		0.00001	Assumed negligible		Confining Bed
Southlands Formation	113					
Springbok Sandstone	71.5					Layers of minor aquifers
Surat Siltstone	110 (- 150)					Confining bed
Wallumbilla Formation	220 (140-340)	13	0.06	Flow Tests	3	Confining beds
Walloon Coal Measures	227 (100 - 460)	0.36	0.002	Flow Tests	2	Gas producing coal seams. *T* values obtained from Coxon Ck. gas production tests.
Westbourne Formation	110 (60-200)		0.0001			Confining beds
Wandoan Formation	330					

Comet Ridge Numerical Model Geometry

APPENDIX E

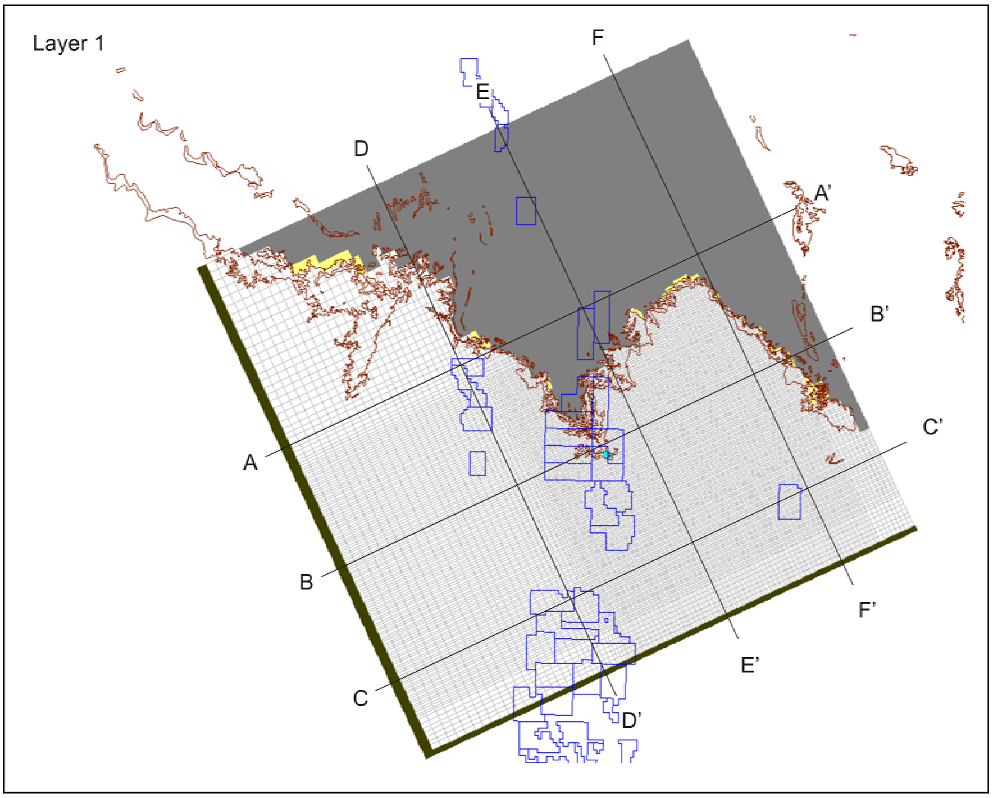

Figure E-1 Layer 1 Model Geometry

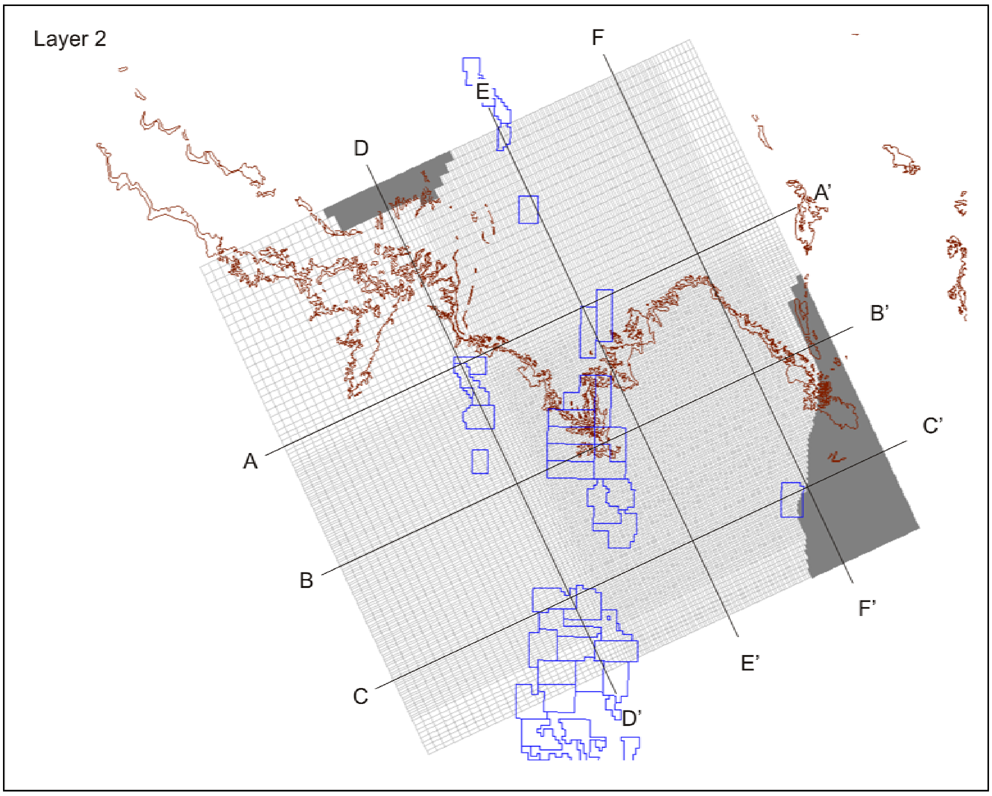

Figure E-2 Layer 2 Model Geometry

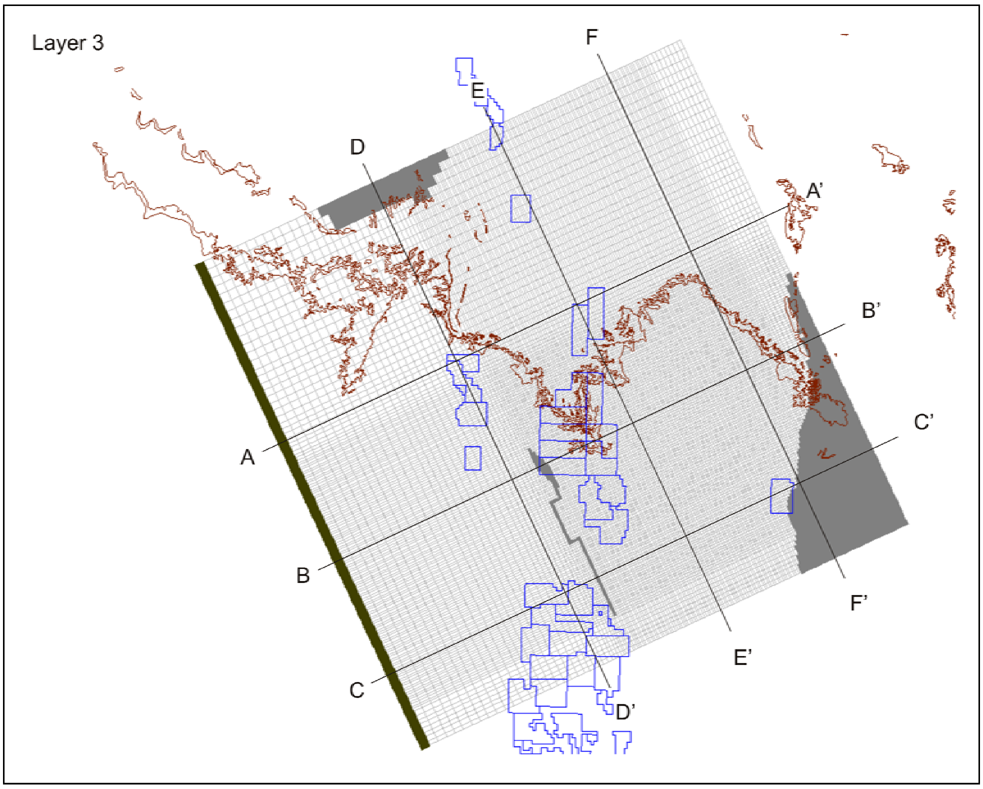

Figure E-3 Layer 3 Model Geometry

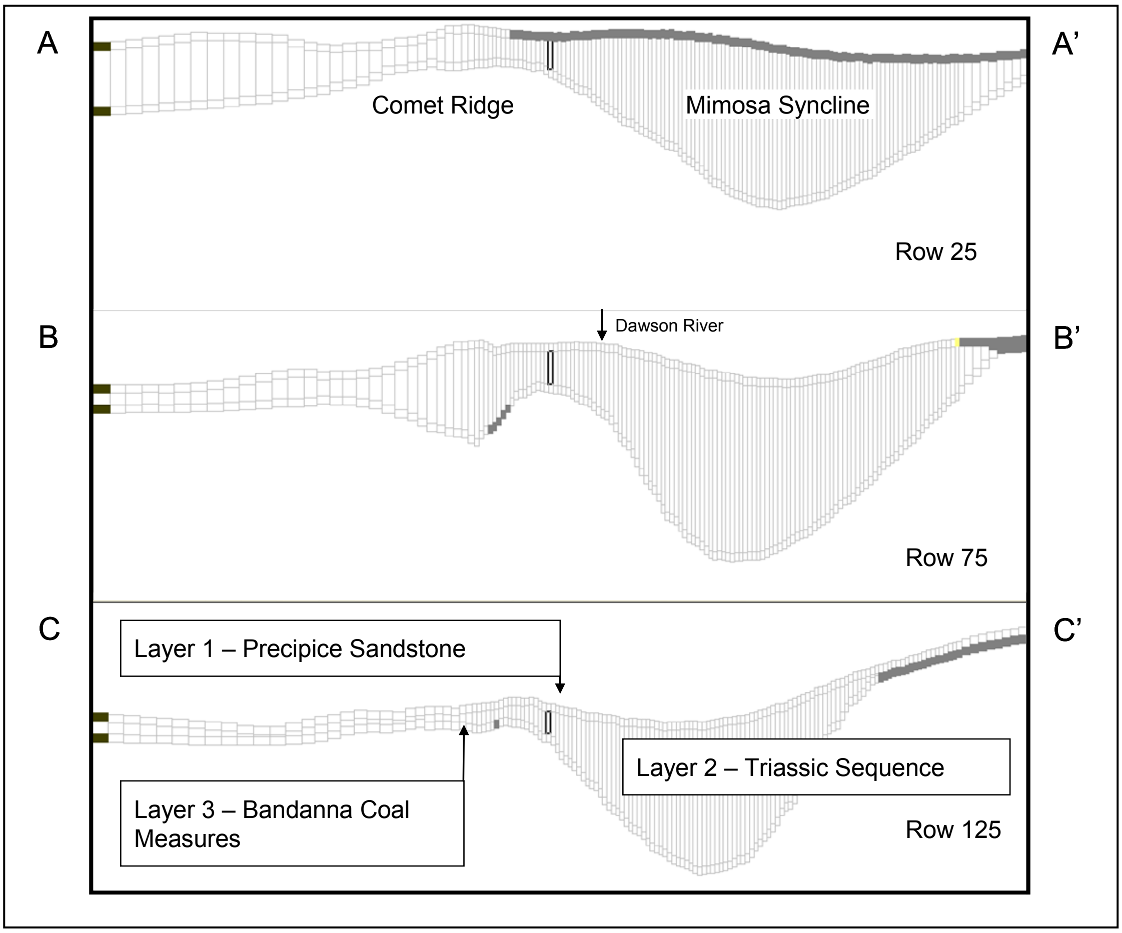

Figure E-4 Model Grid Sections - Rows

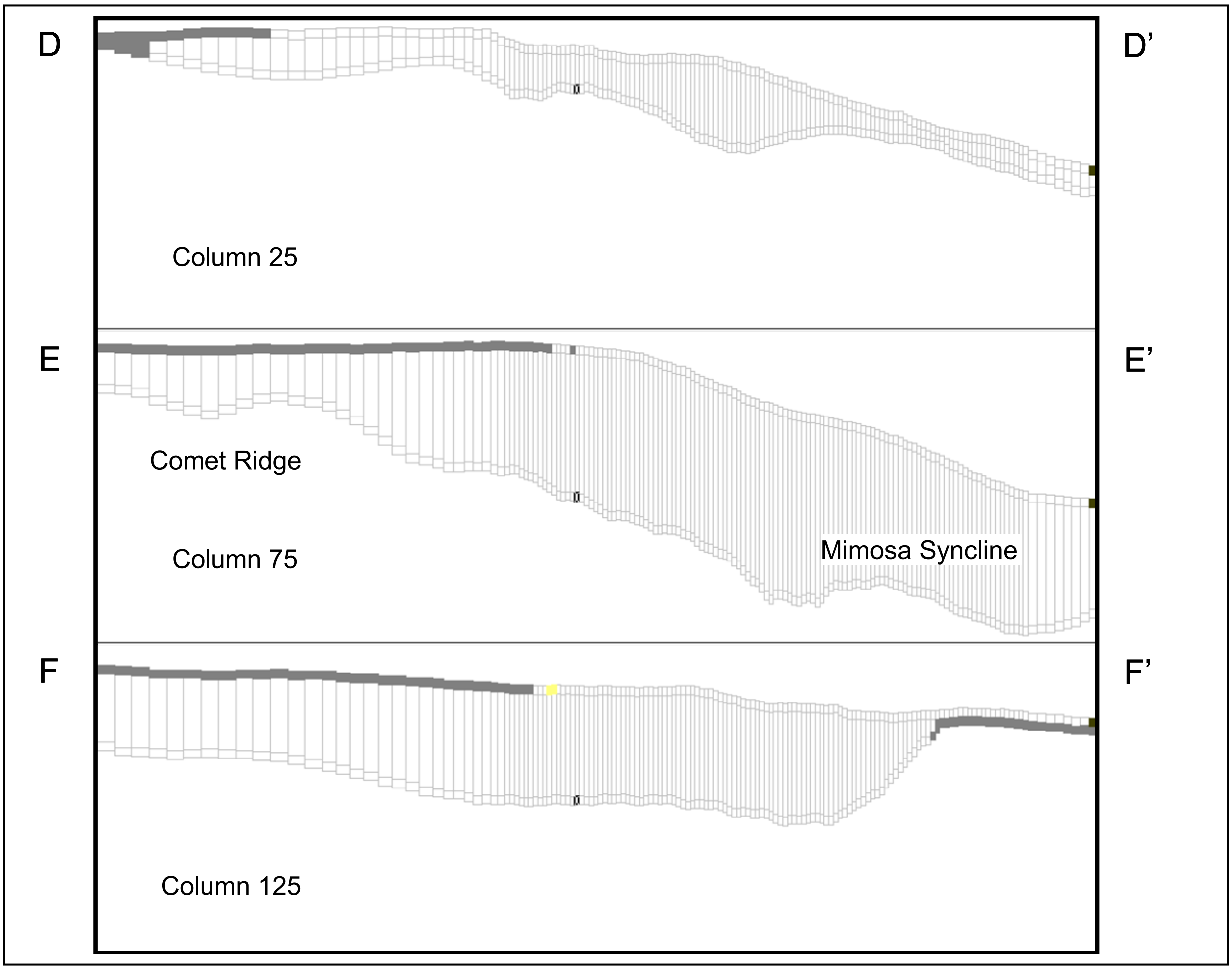

Figure E-5 Model Grid Sections - Columns

Comet Ridge Numerical Model Calibration

APPENDIX F

Table F-1 Numerical model calibration

Well Name	Date	Calculated head (mAHD)	Simulated head (mAHD)	Residual (m)	Well Name	Date	Calculated head (mAHD)	Simulated head (mAHD)	Residual (m)
FV2	1-Mar-07	41.86	-1.78	43.64	FV47	1-May-04	222.69	228.33	-5.64
FV5	4-Apr-95	303.51	336.27	-32.76	FV47	4-Mar-07	166.63	181.98	-15.35
FV5	1-Mar-04	25.7	3.95	21.75	FV49	1-Mar-04	23.26	48.80	-25.54
FV6	1-Mar-04	42.4	39.76	2.64	FV49	1-Mar-07	-19.14	15.18	-34.32
FV6	1-Nov-04	44.3	30.37	13.93	FV50	1-Mar-04	72.74	102.62	-29.88
FV6	5-Mar-07	-33.97	5.35	-39.32	FV58	1-Mar-04	179.49	170.75	8.74
FV8	19-Nov-96	365.26	345.07	20.19	FV93	16-Feb-07	52.05	59.25	-7.20
FV9	23-May-95	349.28	324.25	25.03	FV94	5-Mar-07	57.45	41.08	16.37
FV9	1-Mar-04	86.84	29.49	57.35	FV96	2-Jun-06	161.79	93.65	68.14
FV9	1-Nov-04	5.97	21.46	-15.49	FV96	19-Dec-06	99.87	81.36	18.51
FV10	16-Jun-95	311.79	331.91	-20.12	FV97	2-Jun-06	72.27	59.87	12.40
FV10	1-Mar-04	23.28	55.38	-32.10	FV101	25-Sep-06	172.31	92.76	79.55
FV10	1-Nov-04	-5.58	45.84	-51.42	FV102	25-Sep-06	163.41	128.24	35.17
FV11	6-Jun-95	305.33	336.71	-31.38	FV102	19-Dec-06	113.83	123.00	-9.17
FV11	20-Dec-06	-23.65	10.44	-34.09	FV105	24-Feb-07	119.71	105.30	14.41
FV12	27-May-95	294.74	321.59	-26.85	FV118	25-Feb-07	114.5	117.28	-2.78
FV13	1-May-04	73.6	65.58	8.02	FV124	3-Jan-07	141.23	163.95	-22.72
FV14	12-Aug-95	299.93	333.76	-33.83	FV173	4-Apr-08	127.57	141.63	-14.06
FV15	29-Aug-95	318.68	342.65	-23.97	FV191	10-Jan-08	162.62	183.54	-20.92
FV16	16-Mar-97	370.1	336.82	33.28	FV193	10-Jan-08	215.55	206.88	8.67
FV27	1-Mar-04	38.96	47.96	-9.00	FV198	14-Apr-08	239.07	215.64	23.43
FV39	1-Oct-04	151.67	168.22	-16.55	FV199	14-Apr-08	226.72	212.36	14.36
FV44	1-Mar-04	241.59	189.06	52.53	FV202	14-Apr-08	279.26	255.30	23.96
FV45	1-Mar-04	251.39	214.18	37.21	FV203	14-Apr-08	272.34	277.56	-5.22
FV46	2-Mar-07	166.81	186.39	-19.58	FV205	14-Apr-08	226.04	224.84	1.20

Table F-2 Calibrated Parameters

Aquifer Parameter	Value
Storativity – Layer 3	1.3e-4
Transmissivity – Zone 1, Layer 3 (T0)	Variable (0.1 – 20) m^2/day
Transmissivity – Zone 1, Layer 3 (T2)	9.3 m^2/day
Transmissivity – Zone 1, Layer 3 (T3)	4.5 m^2/day
Transmissivity – Zone 1, Layer 3 (T4)	0.1 m^2/day

Transmissivity – Zone 1, Layer 3 (T5)	7.7 m^2/day
Transmissivity – Zone 1, Layer 3 (T6)	0.06 m^2/day
Transmissivity – Zone 1, Layer 3 (T7)	7 m^2/day
Transmissivity – Zone 1, Layer 3 (T8)	0.003 m^2/day

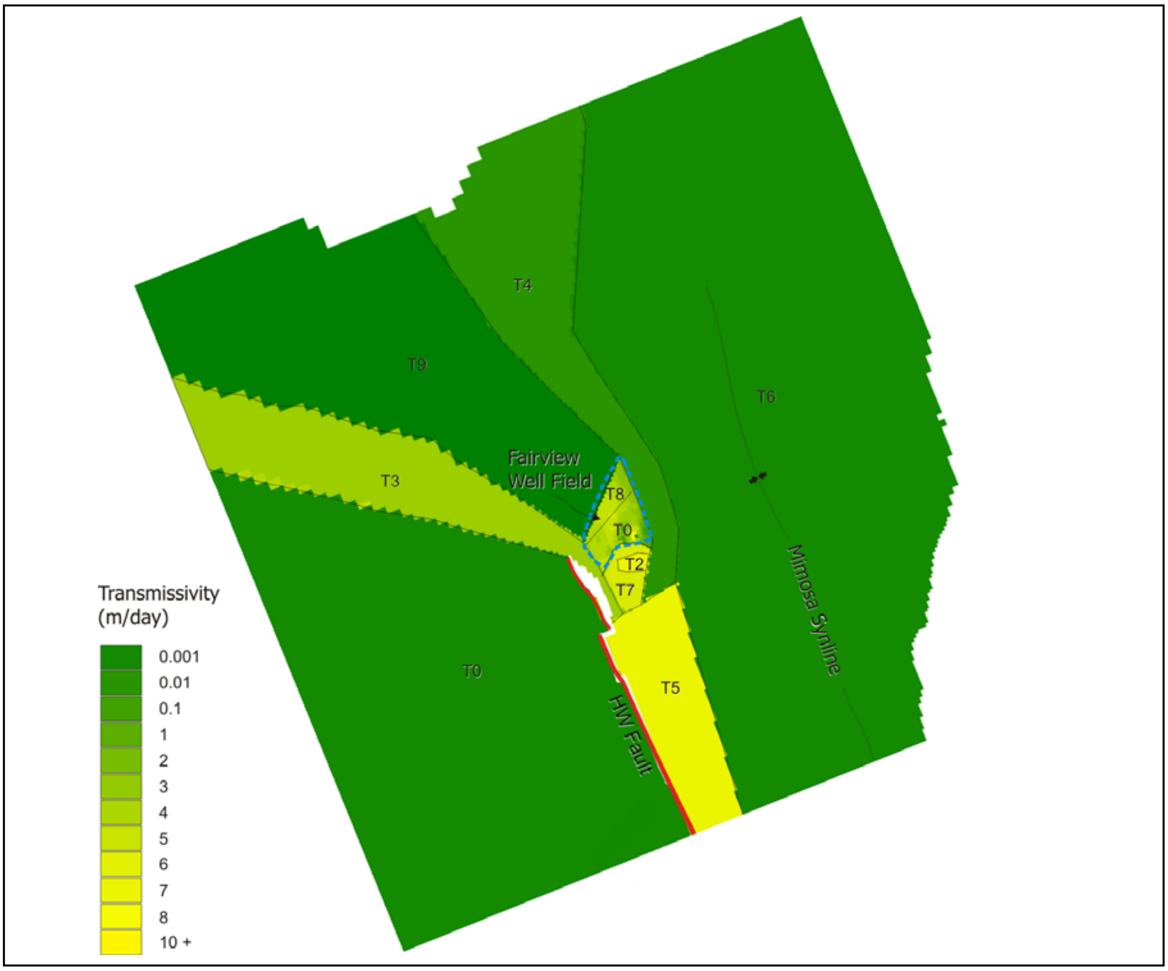

Figure F-1 Calibrated T Zones – Comet Ridge Numerical Model

Comet Ridge Numerical Mass Balance

APPENDIX G

Table 1 Whole-of-Model Mass Balance - 5 years

Flow Component	Cumulative		Current Rate	
Flow Component	Cumulative		Current Rate	
	In (ML)	Out (ML)	In (ML/d)	Out (ML/d)
Storage	95,368	113,989	51	31
Constant Heads (CSG Wells)	2,081	42,393	1.7	26
Layer 3 Interflow*	-	-	5.5	5.5
Drains (Seepage Faces)	0	99,117	0	54
River (Baseflow)	0	24,173	0	13
Head-Dependent Boundaries (Flow In/Out Of Model Grid)	42,013	80,949	23	45
Recharge	170,387	0	93	0
Totals	309,850	309,888	169	169
% Discrepancy	-0.01		-0.01	

*included for comparison - excluded from totals

Table 2 Whole-of-Model Mass Balance - 10 years

Flow Component	Cumulative		Current Rate	
	In (ML)	Out (ML)	In (ML/d)	Out (ML/d)
Storage	198,186	123,293	61	26
Constant Heads (CSG Wells)	8,186	95,545	5	41
Layer 3 Interflow*	-	-	10	10
Drains (Seepage Faces)	0	199,272	0	55
River (Baseflow)	0	48,239	0	13
Head-Dependent Boundaries (Flow In/Out Of Model Grid)	83,608	164,416	23	46
Recharge	340,774	0	93	0
Totals	630,687	630,765	182	182
% Discrepancy	-0.01		-0.01	

*included for comparison - excluded from totals

Table 3 Whole-of-Model Mass Balance- 15 years

	In (ML)	Out (ML)	In (ML/d)	Out (ML/d)
Storage	306,201	169,734	54	25
Constant Head (CSG Wells)	19,217	170,795	6	37
Layer 3 Interflow*	-	-	13	13
Drains (Seepage Faces)	0	300,218	0	55
River (Baseflow)	0	72,111	0	13
Head-Dependent Boundaries (Flow In/Out Of Model Grid)	125,254	249,150	23	46
Recharge	511,161	0	93	0
Totals	961,888	962,008	177	177
% Discrepancy	-0.01		-0.01	

*included for comparison - excluded from totals

Table 4 Whole-of-Model Mass Balance - 20 years

Flow Component	Cumulative In (ML)	Cumulative Out (ML)	Current Rate In (ML/d)	Current Rate Out (ML/d)
Storage	399,601	214,881	49	25
Constant Head (CSG Wells)	25,138	228,183	2.4	29
Layer 3 Interflow*	-	-	15	15
Drains (Seepage Faces)	0	401,277	0	55
River (Baseflow)	0	95,776	0	13
Head-Dependent Boundaries (Flow In/Out Of Model Grid)	167,454	333,886	23	46
Recharge	681,642	0	93	0
Totals	1,273,835	1,274,003	168	168
% Discrepancy	-0.01		-0.02	

*included for comparison - excluded from totals

Inter-Aquifer Transfer Methodology

APPENDIX H

matrixplus

In the Roma CSG field, gas is extracted from the Walloon Coal Measures, overlain by a number of aquifers including the Springbok Sandstone, Gubberamunda Sandstone, Mooga Sandstone and the Orallo Formation and underlain by the Hutton Sandstone, all of which are sources of water supply for local landowners. In addition there are many coal seams within the Walloon Coal Measures that are supplying gas. All of these formations are separated by beds of relatively impermeable material.

Extraction of water from each coal seam is accompanied by a reduction of hydrostatic pressure within that seam and a subsequent differential in pressure between the water within it and other formations above and below it. This pressure differential has the potential to transfer water vertically from one aquifer to another through the intervening material. The magnitude of this transfer is limited by the pressure differential which exists and on the ability of the intervening layer to transmit the water vertically through it.

The transfer mechanism is illustrated in **Figure 3-5**. Even though the beds dip in a southerly direction and bed thicknesses vary spatially, the various layers can be considered to be reasonably uniform throughout the field and the potential to move vertically is also reasonably uniform throughout the field.

In the Roma CSG field, the process of transfer from the bounding aquifers to the depressurised layer is the same over the whole field. Thus the total rate of transfer from the underlying and overlying aquifers is the sum of the incremental discharges multiplied by the area through which those incremental discharges occur.

i.e. $Q = \Sigma(qA)$

$= K_{eff}\, \Sigma\, (A\, dh)$

And:

The sum of all of the incremental areas (annuli) multiplied by the drawdown effecting each annulus is equal to the total volume depressurised (V).

Therefore:

$Q = V \times K_{eff}$

where

q = discharge per unit area (m/d)

Q = total discharge rate (m^3/d)

K = horizontal hydraulic conductivity (m/d)

c = hydraulic resistance (days)

h = change in hydraulic head or drawdown (m)

l = length of flow path (m)

b' = saturated thickness of the semi-pervious layer

K' = vertical hydraulic conductivity of the individual semi-pervious layer

K_{eff} = effective vertical hydraulic conductivity for all layers combined

V = volume of depressurised zone

A = area of the annulus (m^2) through which water is moving vertically under drawdown of h.

In calculating the hydraulic resistance of each layer, the vertical hydraulic conductivity was taken as 10% of the horizontal hydraulic conductivity. This takes into account layering effects and is a reasonable assumption. The actual value may in fact be less than 10% so the leakage values may be conservative.

The effective hydraulic conductivity for flow through an anisotropic medium as derived is

$$K_{eff} = \frac{b}{\frac{b_1^{'}}{K_1^{'}} + \frac{b_2^{'}}{K_2^{'}} + \frac{b_3^{'}}{K_3^{'}} +}$$

where

K_{eff} = effective hydraulic conductivity through the various layers in the anisotropic medium

b = total thickness of all layers through which flow occurs

b_1' = thickness of Layer 1

K_1' = hydraulic conductivity of Layer 1 at right angles to the direction of flow.

The hydrostatic pressure differential between the Hutton Sandstone aquifer and the overlying material resulting from the drawdown in the Walloon Coal Measures can cause an upward vertical movement of water from the Hutton Sandstone aquifer. Likewise, the hydrostatic pressure differential between the overlying aquifers and the underlying material resulting from the drawdown in the Walloon Coal Measures can cause a downward vertical movement of water from those aquifers. The total pressure differential will be dissipated through the depressurised zone and result in a movement of water through the various confining layers. The rate of vertical movement through a particular layer will depend on the ability of the confining layer to transmit water and will vary with the magnitude of the pressure differential. It will then be greater near the centre of a wellfield and reduce towards the edge. However, all of the water moving vertically up from the Hutton Sandstone and vertically down from the overlying aquifers has to be supplied as horizontal flow through these aquifers from outside of the area of influence of the wellfield extraction. The extraction of water from storage within these aquifers has the potential to cause water level declines in those aquifers outside the wellfield area.

In this analysis, transfer between individual coal seams has not been considered; in fact each well is assumed to be extracting water from all seams simultaneously even though each seam is contributing at different rates depending on the relative hydraulic parameters.

By using drawdown impact contours, volume depressurised and values of vertical hydraulic conductivity for each of the intervening layers, the rates of extraction from the Hutton Sandstone and the other aquifers were calculated and the lateral extent and magnitude of drawdowns within those aquifers was determined for a number of time periods after gas extraction begins.

It was assumed that the water would flow into the Hutton and Gubberamunda Sandstone aquifers (and any other contributing aquifer) as horizontal flow but would have to flow vertically through them to move to the formation from which the water was being extracted i.e. the Walloon Coal Measures.

The length of the flow path in each layer was taken as the average thickness of that layer as determined from the DNRW groundwater database or from actual drilling information supplied by Santos.

The values used in the calculations are listed in **Table H-1**:

Table H-1 Parameters Used for Calculation of Inter-Aquifer Transfer

Formation	Ave. Thickness (m)	Vertical Hydraulic Conductivity (m/d)	Vertical Hydraulic Resistance (d)
Gubberamunda Sandstone	90	0.04	2,250
Injune Creek Formation	400	0.00001	40,000,000
Westbourne Formation	120	0.00001	12,000,000
Walloon Coal Measures	200	0.0002	1,000,000
Eurombah Formation	50	0.01	5,000
Hutton Sandstone	150	0.014	10,700
Precipice Sandstone	100	0.05	2,000
Rewan Group	173	0.000001	173,000,000

Volume Transferred

In assessing the potential volume transferred from the overlying and underlying aquifers to the Walloon Coal Measures, three possible cases were considered:

Case 1. Water was being contributed from both the Gubberamunda and Hutton aquifers and was moving across the total thickness of the Hutton Sandstone, the Gubberamunda Sandstone and across the whole of the Injune Creek Formation which includes the Walloon Coal Measures and the Eurombah Formation. The Westbourne Formation component of the Injune Formation is a major aquitard.

Case 2. Water was being contributed from the Hutton Sandstone aquifer alone and was moving across the Hutton Sandstone aquifer, the Eurombah Formation and the Walloon Coal Measures and

Case 3. Water was being contributed from the Hutton Sandstone aquifer and was moving upwards across the Hutton Sandstone aquifer, the Eurombah Formation and half of the Walloon Coal Measures. At the same time water was being contributed from the overlying Gubberamunda Sandstone aquifer and was moving vertically downward across the Gubberamunda Sandstone aquifer, the Westbourne Formation and half of the Walloon Coal Measures.

In order to compare relative effects, each case was analysed 5 years (1,825 days) after commencement of pumping

Using

$Q = V \times K_{eff}$

where

Q = total discharge rate (m^3/d)
K_{eff} = effective vertical hydraulic conductivity for all layers combined
V = volume of depressurised zone.

At 5 years,

The volume of the depressurised zone is 21.0 x 10^{10} m^3.

Case 1.

K_{eff} = 1 / (10,700 + 40,000,000 + 2,250)
= 2.5 x 10^{-8} m/d

The vertical transfer into the Walloon Coal Measures is then 5,250 m^3 over 1,825 days or 3 m^3/d

Case 2.

K_{eff} = 1 / (10,700 + 1,000,000 + 5,000)
= 9.8 x 10^{-7} m/d

The vertical transfer into the Walloon Coal Measures is then 205,800 m^3 over 1,825 days or 113 m^3/d.

Case 3.

For transfer from the Hutton Sandstone

K_{eff} = 1 / (10,700 + 500,000 + 5,000)
= 1.9×10^{-6} m/d

For transfer from the Gubberamunda Sandstone

K_{eff} = 1 / (2250 + 12,000,000 +500,000)

= 7.9×10^{-8} m/d

The vertical transfer into the Walloon Coal Measures is then 399,000 m^3 from the Hutton Sandstone and 16,590 m^3 from the Gubberamunda Sandstone over 1,825 days,

i.e. 218 m^3/d from the Hutton Sandstone and 9.1 m^3/d from the Gubberamunda Sandstone.

Case 3 is the most likely scenario as the upper part of the Injune Creek Formation is very impermeable and it is more likely that any transfer that does occur will come preferentially from the Hutton Sandstone. However, the Gubberamunda Sandstone should be monitored during the wellfield operation to check that this assumption is valid.

It is also possible that some water transferring from the overlying and underlying aquifers will be intercepted by the coal seams and pumped to the surface by the gas wells. This situation has not been analysed.

Drawdowns Outside the Wellfield

Since the transfer from the Gubberamunda Sandstone is so small, this analysis has considered only the impact on the Hutton Sandstone aquifer.

The water transferring from the Hutton Sandstone aquifer into the Walloon Coal Measures has to be derived from outside the wellfield and flow horizontally through the Hutton Sandstone, through the outer perimeter of the area of influence of the wellfield and then travel vertically up to the Walloon Coal Measures.

The magnitude of the wellfield and the large distances from the centre of the wellfield to the perimeter of influence make the use of the normal radial groundwater flow equations inappropriate to determine the consequential radial extent and the magnitude of drawdown within the area of influence within the Hutton Sandstone aquifer. For this reason an approximation has been made based on normal Darcy flow and the flow through the wellfield perimeter area.

As an example of the methodology used the following calculations are based on a time period 1,825 days (5 years) after pumping began.

At time 5 years after commencement of operations the rate of transfer from the Hutton Sandstone to the Walloon Coal Measures is some 218 m^3/d.

As the Hutton Sandstone has a T of 21 m^2/d, the hydraulic gradient needed to achieve this flow rate through the Hutton Sandstone is 6.5×10^{-5} or 0.065 m/kilometre. Gradients for the rates of transfer at other times are shown in **Table H-2** below.

Table H-2 Calculation of Hydraulic Gradients and Flow Rates in Hutton Sandstone

Time Since Operation Began (Years)	Ave. Rate of Transfer from Hutton Sandstone (m^3/d)		Gradient in Hutton Sandstone (-)
	Total	Per km Circumference of Wellfield	
5	218	1.4	6.5×10^{-5}
10	258	1.6	7.7×10^{-5}
15	230	1.4	6.8×10^{-5}
20	198	1.2	5.9×10^{-5}

The perimeter of the wellfield is approximately 160 km, so the flow from the Hutton Sandstone aquifer is approximately 1.4 m^3/d per km of circumference of the wellfield.

Because the perimeter is so large, it can be assumed that the volume extracted per km width of perimeter from the Hutton Sandstone is extracted from elastic storage in a wedge 1,000 m wide, 1,000 times '*a*' m long and 0.065 times '*a*' deep at the perimeter of the wellfield; where '*a*' is a variable multiplier.

At 1.4 m^3/d/km, the volume of water removed per km over 5 years (1,825 days) is 2,550 m^3.

Taking the storage coefficient of the Hutton Sandstone aquifer as 10^{-4}, the volume of the depressurised wedge is 2.55 x 10^7 m^3.

This volume is also 3.25 a^2 x 10^4 m^3.

Thus a = 28 at 5 years.

The effect of the wellfield on the Hutton Sandstone aquifer extends 28 kilometres outside the wellfield area of influence and has a drawdown of 1.82 m at the perimeter of wellfield influence.

Taking into account the different rates of transfer, the gradients required to cause those rates of transfer and the different total volumes transferred, the corresponding values for other time intervals are given in the **Table H-3** below.

Table H-3 Drawdown Effects in Hutton Sandstone Aquifer

Time Since Operation Began (Years)	CSG-related Drawdown in Hutton Sandstone at Perimeter of CSG Wellfield Area (m)	CSG-related Radius of Influence in Hutton Sandstone Beyond Perimeter of CSG Wellfield Area (km)
5	1.8	28
10	3.0	39
15	3.2	47
20	3.2	54

The drawdown within the perimeter of the area of influence of the wellfield will increase towards the centre of the wellfield until the perimeter of the wellfield itself is reached. At this stage the pressure differential between the Walloon Coal Measures and the Hutton Sandstone remains relatively uniform under the wellfield and the drawdown in the Hutton Sandstone aquifer could be expected to remain reasonably constant for the rest of the wellfield area.

All town water supply bores and landowner bores within this zone of influence, and drawing water from the Hutton Sandstone aquifer, are expected to be impacted to varying degrees depending on their distances from the centroid of the wellfield. Towns which fall within this zone are; Roma, Muckadilla, Wallumbilla, Yuleba, Jackson, Dulacca, Surat, Gunnewin, and Injune but none of these have bores which draw water from the Hutton Sandstone aquifer.

While there is a significant area impacted by the removal of water from the coal seams the magnitude of the drawdown impact in the Hutton Sandstone aquifer is relatively small.

Pumping Test Analyses

- Roma Field

APPENDIX I

The most reliable way to determine the aquifer parameter of transmissivity for a well is to carry out a pumping test where simultaneous recordings of drawdown and discharge are made at selected times after the pumping began. Such test data should also be free of antecedent pumping conditions which would impact on the test. There were no such tests available for the Roma field or for the Comet Ridge fields.

However, on examination of the production test data for the various wells in the Roma field it was found that there were two periods; 21 June to 7 November 2007 for Coxon Creek No. 2 Well and 26 June to 21 July 2007 for Coxon Creek No. 4 Well, where antecedent conditions were acceptable and readings of bottom hole pressure and discharge rates were such that the data could be analysed to provide a reasonable estimate of the transmissivity.

The analysis is based on the theory of radial flow to a well. If a well is pumped at a constant discharge rate of Q then the drawdown (i.e. difference in bottom hole pressure from no flow (or static) bottom hole pressure) in the well increases (a) with the logarithm of time since discharge began and (b) at a rate which is proportional to the transmissivity of the aquifer.

Thus a plot of drawdown against the logarithm of time since discharge began will result in a straight line with a slope proportional to the transmissivity.

If the slope of the straight line i.e. the drawdown per log cycle, is called Δs then the transmissivity is given by:

$$T = \frac{2.3Q}{4\pi\Delta s}$$

where :

T = transmisivity (m^2/day)

Q = discharge rate (m^3/day)

Δs = drawdown per log cycle (m)

The actual drawdown in the discharging well depends not only on the theoretical drawdown in the aquifer but also has additional components which are related to well construction and well development.

The actual drawdown in the well is more accurately described by the equation 6 in **Appendix B**.

$$s_w = (a + b\log t)Q + CQ^2$$

where

s_w = drawdown in the discharging well at time t after discharge began (m)

$$a = \frac{2.3}{4\pi T}\log\frac{2.25T}{{r_w}^2 S}$$

t = time since discharge began (days)

Q = discharge rate (m^3/day)

An attempt was made to evaluate *a* by assuming that the turbulent head loss was zero and estimating the static bottom hole pressure for each of the two wells.

The plots and analyses are given below. Since Coxon 4 results appear to be more reliable, the value of *T* and *a* determined from that test have been adopted.

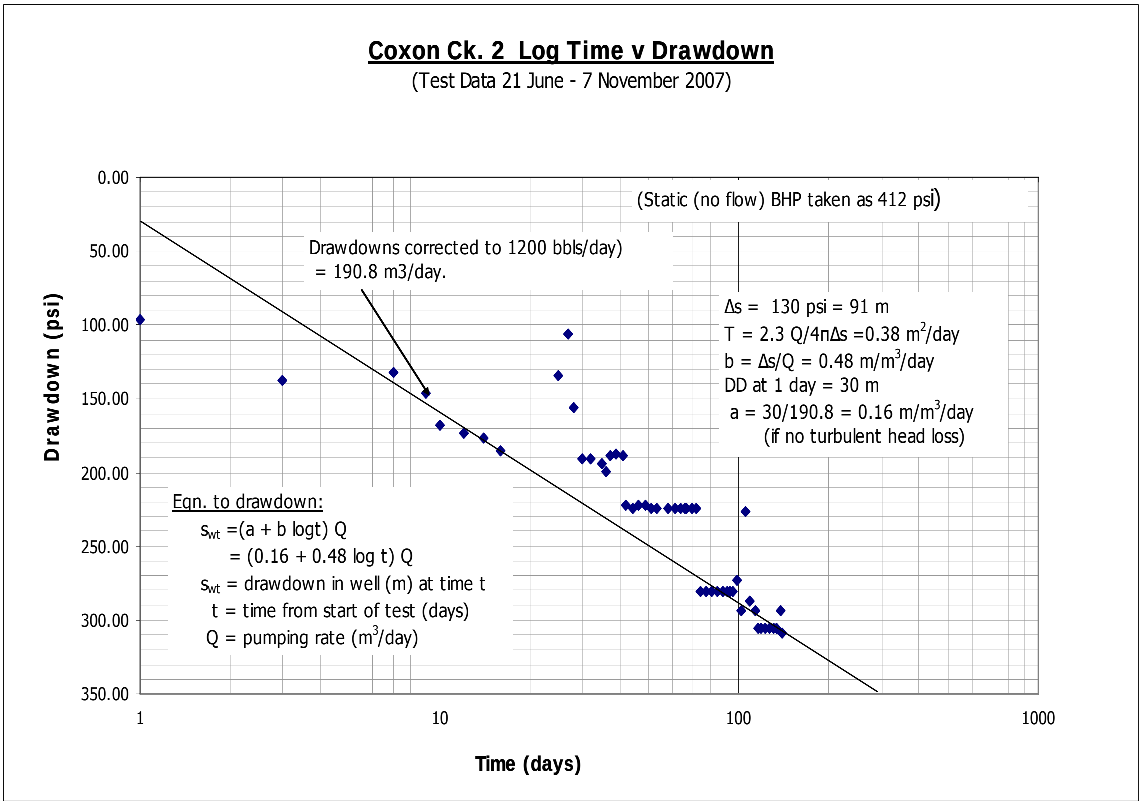

Figure I-1 Coxon Creek No. 2 Well – Log Time v Drawdown

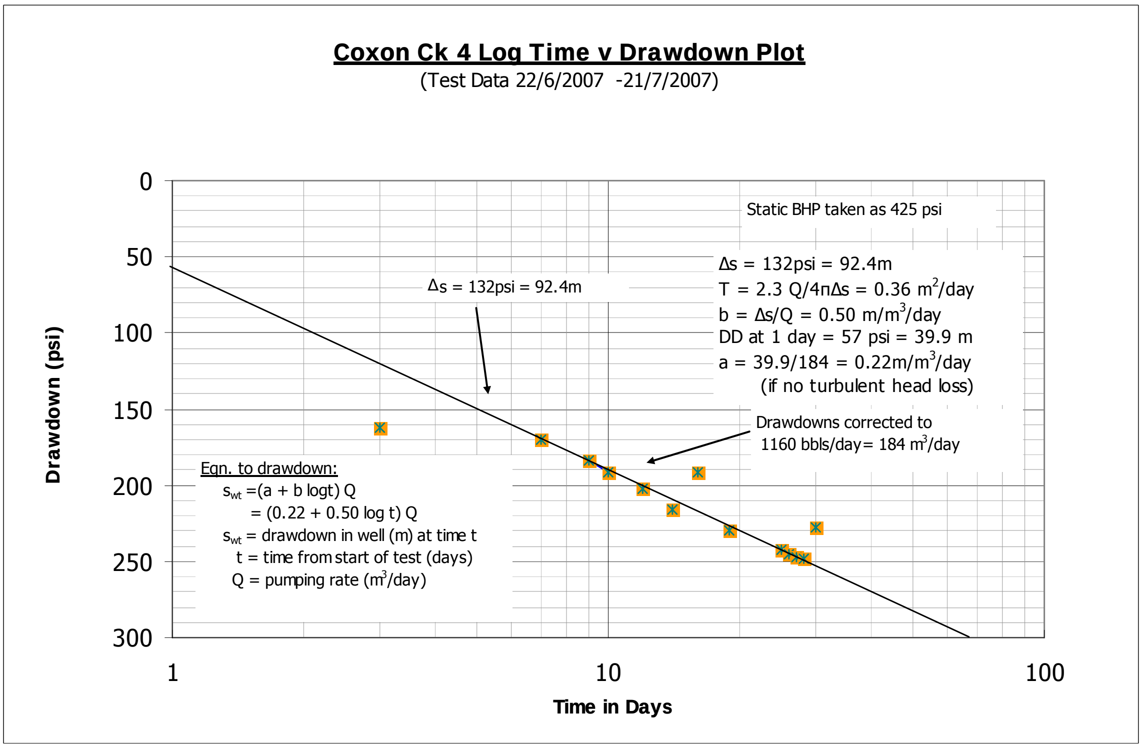

Figure I-2 Coxon Creek No. 4 Well - Log Time v Drawdown

Permeability, Hydraulic Conductivity and Transmissivity Values - Roma Field by Zones

APPENDIX J

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Table J-1 Permeability, Hydraulic Conductivity and Transmissivity Values – Roma Field by Zones

Field	Coal Seam	Net Pay (h) (m)	k (mD)	kh (mD.m)	Coal Depth (mRT)	T= Kh (m2/d)	Ave. T (m2/d)		Zone1
							for Field	for Zone	
Coxon Ck 2	Well		Production Test Data			0.300	0.300		A
Coxon Ck 4	Well		Production Test Data			0.360	0.360		A
Mount Hope 2	Upper Juandah	1.3	420	546	252	0.472	0.680		A
Mount Hope 2	Lower Juandah (Upper)	1.55	47	73	282	0.063			A
Mount Hope 2	Lower Juandah (Lower)	2	75	150	300	0.130		0.410	A
Mount Hope 2	Taroom Upper	2.1	1,140	2,394	387	2.068			A
Rowallon 14	Upper Juandah	4.4	100	440	170	0.380	0.300		A
Rowallon 14	Lower Juandah (Upper)	1.6	155	248	228	0.214			A
Rowallon 14	Lower Juandah (Sand)	2.1	26	55	252	0.047			A
Rowallon 3	Upper Juandah	1.5	490	735	332	0.635	1.350		B
Rowallon 3	Taroom Lower	3	790	2,370	533	2.048			B
Sawpit Creek 2	Lower Juandah (Upper)	1.75	8	14	489	0.012	0.170		B
Sawpit Creek 2	Lower Juandah (Lower)	3.53	30	106	516	0.091			B
Sawpit Creek 2	Taroom Upper	2	230	460	623	0.397			B
Treville Downs 1	Upper Juandah	1.18	700	826	511	0.714	0.190		B
Treville Downs 1	Upper Juandah (Lower)	3.78	11	42	541	0.036		0.430	B
Treville Downs 1	Lower Juandah (Upper)	2.43	80	194	577	0.168			B
Treville Downs 1	Lower Juandah (Lower)	2.9	20	58	626	0.050			B
Treville Downs 1	Taroom Upper	2.13	15	32	750	0.028			B
Treville Downs 1	Taroom Lower	2.98	74	221	771	0.191			B
Wingfield Park 1	Lower Juandah (Upper)	1.63	0.41	0.6683	770	0.001	0.010		B
Wingfield Park 1	Lower Juandah (Lower)	1.4	2.2	3.08	788	0.003			B
Wingfield Park 1	Taroom Upper	2.93	13.7	40.141	920	0.035			B
Pickanjinnie 12A	Upper Juandah	6.36	296	1,883	610	1.627	0.550		C
Pickanjinnie 12A	Lower Juandah (Upper)	1.11	28	31	667	0.027			C

Field	Coal Seam	Net Pay (h) (m)	k (mD)	kh (mD.m)	Coal Depth (mRT)	T= Kh (m2/d)	Ave. T (m2/d)		Zone1
							for Field	for Zone	
Pickanjinnie 12A	Taroom Lower	0.86	0.1	0.1	833	0.000			C
Raslie 7	Upper Juandah	2.5	620	1,550	500	1.339	0.480		C
Raslie 7	Lower Juandah (Upper)	2.9	32	93	550	0.080		0.470	C
Raslie 7	Taroom Upper	2.2	225	495	680	0.428			C
Raslie 7	Taroom Lower	1.5	85	128	703	0.110			C
Washpool Creek 2	Upper Juandah	4.2	400	1,680	699	1.452	0.390		C
Washpool Creek 2	Upper Juandah (Lower)	1.2	0.05	0	745	0.000			C
Washpool Creek 2	Lower Juandah (Upper)	4	40	160	784	0.138			C
Washpool Creek 2	Taroom Lower	1.15	3	3	931	0.003			C
Blyth Creek 8	Lower Juandah (Upper)	1.55	205	318	616	0.275	0.150		D
Blyth Creek 8	Taroom Lower	1.6	22	35	766	0.030			D
Blythdale North 2	Upper Juandah	1.75	1,200	2,100	479	1.814	0.540		D
Blythdale North 2	Lower Juandah (Upper)	1.05	0.6	1	526	0.001			D
Blythdale North 2	Taroom Upper	1.53	260	398	615	0.344			D
Blythdale North 2	Taroom Lower	1	7.5	8	667	0.006		0.330	D
Pine Ridge 16	Lower Juandah (Upper)	1.48	260	384.8	447	0.332	0.220		D
Pine Ridge 16	Taroom Lower	2.38	50	119.0	610	0.103			D
Yanalah 6	Upper Juandah	4.4	394	1734	560	1.498	0.410		D
Yanalah 6	Lower Juandah (Upper)	1.7	50	85	620	0.073			D
Yanalah 6	Taroom Upper	1.3	30	39	717	0.034			D
Yanalah 6	Taroom Lower	1.08	51	55.08	744	0.048			D
Grafton Range 24	Upper Juandah	2.2	215	473	408	0.409	0.420		E
Grafton Range 24	Lower Juandah (Lower)	2.1	15	32	482	0.027			E
Grafton Range 24	Taroom Upper	1.3	1,100	1,430	556	1.236			E
Grafton Range 24	Taroom Lower	1.1	2	2	580	0.002			E
Hermitage North 1	Upper Juandah	1.7	75	128	414	0.110	0.180		E
Hermitage North 1	Lower Juandah (Upper)	1.9	200	380	473	0.328			E

Field	Coal Seam	Net Pay (h) (m)	k (mD)	kh (mD.m)	Coal Depth (mRT)	T= Kh (m2/d)	Ave. T (m2/d)		Zone1
							for Field	for Zone	
Hermitage North 1	Lower Juandah (Lower)	2.88	91	262	509	0.226			E
Hermitage North 1	Taroom Upper	1.55	55	85	619	0.074			E
Niella East 1	Upper Juandah	2.5	4	10	433	0.009	0.070		E
Niella East 1	Lower Juandah (Upper)	1.63	28	46	463	0.039		0.22	E
Niella East 1	Lower Juandah (Lower)	2.85	30	86	520	0.074			E
Niella East 1	Taroom Lower	1.33	130	173	660	0.149			E
Pleasant Hills 25	Lower Juandah (Lower)	1.35	42	57	438	0.049	0.240		E
Pleasant Hills 25	Taroom Upper	2	235	470	544	0.406			E
Pleasant Hills 25	Taroom Lower	1.7	170	289	581	0.250			E
Raslie North 1	Upper Juandah	1.4	345	483	465	0.417	0.210		E
Raslie North 1	Lower Juandah (Upper)	1.6	12	19	522	0.017			E
Raslie North 1	Taroom Upper	1.8	120	216	610	0.187			E
Rowallon 13	Lower Juandah (Upper)	2.6	82	213	373	0.184			E
Rowallon 13	Lower Juandah (Lower)	1.6	2	3	405	0.003			E
Taringa 4	Lower Juandah (Lower)	3.35	130	436	132	0.376	0.190		E
Taringa 4	Taroom Lower	1.3	5.8	8	192	0.007			E

Porosity and Storativity Values - Roma Field

APPENDIX K

Table K-1 Porosity and Storativity values – Roma Field

Well	Sample No.	Depth (mRT)	Total Thickness of Beds (m)	Porosity (%)		S_{min}
				Bed	Ave. For Well	
Blythdale North 2	1'	478.8	5.33	2.2	2.9	7.7 x 10^{-5}
Blythdale North 2	3'	555.5		4.5		
Blythdale North 2	4'	615.5		1.9		
Grafton Range 24	1'		6.7	9.1	6.3	2.0 x 10^{-4}
Grafton Range 24	3'			6.2		
Grafton Range 24	4'			3.6		
Hermitage North 1	4	414.1	8.03	3	3.2	1.3 x 10^{-4}
Hermitage North 1	6	472.15		3.3		
Hermitage North 1	8	503.91		3.6		
Hermitage North 1	10	619.74		3.2		
Hermitage North 1	11	656.6		3.1		
Mount Hope 2	2'		6.95	10.4	9	3.4 x 10^{-4}
Mount Hope 2	6'			9.4		
Mount Hope 2	7'			11.3		
Mount Hope 2	9'			4.1		
Mount Hope 2	11'			9.6		
Pleasant Hills 25	2'		5.05	10.8	8.2	2.1 x 10^{-4}
Pleasant Hills 25	A'			6		
Pleasant Hills 25	6'			9.7		
Pleasant Hills 25	10'			6.3		
Pleasant Hills 25	12'			8.3		
Pickanjinnie 12A	2'	607.8	8.33	6.2	4.8	2.0 x 10^{-4}
Pickanjinnie 12A	3'	686.9		3.4		
Raslie 7	1'		9.1	1.4	2.9	1.3 x 10^{-4}
Raslie 7	3'			1.4		
Raslie 7	7'			6.7		
Raslie 7	C'			1.9		
Rowallon 3	5	482.7	4.5	1.3	1	2.2 x 10^{-5}
Rowallon 3	6	523.4		0.7		
Rowallon 13	2	317.4	4.2	2.5	2.2	4.6 x 10^{-5}
Rowallon 13	6	377.9		1.9		
Rowallon 14	2	168.2	8.1	2.7	2	8.1 x 10^{-5}
Rowallon 14	6	355.9		2		
Rowallon 14	8	388.2		1.3		

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