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ARROW ENERGY SURAT GAS PROJECT GROUNDWATER IMPACT ASSESSMENT REPORT

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Report Date: 15 February 2012
Project Ref: ENAUBRIS107040AC

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ENAUBRIS107040AC-GW EIS-RPT6.docx

RECORD OF DISTRIBUTION

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1	NSYSBRIS07040AA-GW EIS DRAFT-RPT1.docx	Working Draft	26 February 2010	Arrow Energy Pty Ltd	SD
1	NSYSBRIS07040AA-GW EIS DRAFT-RPT1.docx	Draft	19 March 2010	Coffey Environments Pty Ltd	SD
1	NSYSBRIS07040AA-GW EIS DRAFT-RPT2.docx	Revised Draft	7 May 2010	Coffey Environments Pty Ltd	SD
1	ENAUBRIS107040AC-GW EIS DRAFT-RPT3.docx	Revised Draft	23 May 2011	Coffey Environments Australia Pty Ltd	JG
1	ENAUBRIS107040AC-GW EIS DRAFT-RPT3a.docx	Revised Draft	09 June 2011	Coffey Environments Australia Pty Ltd	JG
1	ENAUBRIS107040AC-GW EIS DRAFT-RPT3b.docx	Revised Draft	10 June 2011	Arrow Energy Pty Ltd	JE
1	ENAUBRIS107040AC-GW EIS DRAFT-RPT4a.docx	Final Draft	15 August 2011	Arrow Energy Pty Ltd	BP
1	ENAUBRIS107040AC-GW EIS DRAFT-RPT4b.docx	Revised Final Draft	04 October 2011	Arrow Energy Pty Ltd	MB
1	ENAUBRIS107040AC-GW EIS DRAFT-RPT4c.docx	Revised Final Draft	17 November 2011	Arrow Energy Pty Ltd	MB
1	ENAUBRIS107040AC-GW EIS-RPT5.docx	Final	6 December 2011	Arrow Energy Pty Ltd	MB
1	ENAUBRIS107040AC-GW EIS-RPT6.docx	Revised Final (to include DERM comments)	15 February 2012	Arrow Energy Pty Ltd	MB

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GLOSSARY OF TERMS

Abstraction	The removal of water from a resource e.g. the pumping of groundwater from an aquifer.
Adsorption	The adhesion of molecules of gas, liquid, or dissolved constituents to a surface (compare Desorption)
Aeolian	Sedimentary deposits formed by wind.
Alluvium	Unconsolidated deposits such as sands, gravels and clays deposited by flowing water such as rivers and streams.
Anistropy	Anisotropy is the property of being directionally dependent, as opposed to isotropy, which implies homogeneity in all directions.
Anthropogenic	Caused by human activity.
Aquatic Ecosystems	The abiotic and biotic components, habitats and ecological processes contained within rivers and their riparian zones and reservoirs, lakes, wetlands and their fringing vegetation.
Aquifer	A saturated geological layer or formation that is permeable enough to yield economic quantities of water.
Aquiclude	A geological formation having zero permeability to water, such as un-fractured crystalline rock.
Aquitard	A geological formation having low (but not zero) permeability to water, such as a silty or clayey layer.
Argillaceous	A geological formation containing significant proportions of clay minerals.
Artesian Aquifer	A confined aquifer with the potentiometric level above ground level.
Artesian Bore	A borehole where the potentiometric level is above ground level.
Attenuation	The reduction in concentration of a contaminant. This may be due to degradation, dispersion or dilution.
Avulsion	Abandonment of an old river channel and the creation of a new one.
Baseflow	Sustained flow of a stream in the absence of direct run-off, due to groundwater discharge.

GLOSSARY OF TERMS

Bore	A hole drilled in the ground to obtain samples of soil or rock, intersect groundwater for extractive use, monitoring or investigation, or for a range of other purposes. In Australia is also a commonly used term for a constructed groundwater well.
Brackish	Water containing moderate salt concentrations significantly less than sea water, with Total Dissolved Solids typically between 1,000 and 10,000 mg/L. (Compare Fresh, Saline and Brine).
Brine	Saline water with a total dissolved solids concentration greater than 40,000 mg/L or coal seam gas water after it has been concentrated through water treatment processes and/or evaporation.
Calcareous	Containing significant proportions of calcium carbonate.
Catchment	An area which discharges to a common point.
Coal Seam Gas Water	Groundwater that is necessarily or unavoidably brought to the surface in the process of coal seam gas exploration or production. Coal seam gas water typically contains significant dissolved salts, has a high sodium adsorption ratio (SAR) and may contain other components that have the potential to cause environmental harm if released to land or waters through inappropriate management. Coal seam gas water is a waste, as defined under the section 13 of the Environment Protection Act. (DERM, 2011).
Colluvium	Sedimentary deposit formed primarily by gravity forces, typically at the base of a slope or a cliff.
Cone of Depression	The area of drawdown produced in the watertable or groundwater potentiometric surface due to pumping.
Confined Aquifer	An aquifer in which groundwater is confined under pressure.
Confining Layer	Geological material through which significant quantities of water cannot move, located below unconfined aquifers, above and below confined aquifers.
Contaminant	A contaminant can be a gas, liquid or solid, an odour, an organism (whether alive or dead), including a virus, energy (including noise, heat, radioactivity and electromagnetic radiation), or a combination of contaminants.
Contamination	The release (whether by act or omission) of a contaminant into the environment.

GLOSSARY OF TERMS

Cuesta	A ridge formed by gently tilted sedimentary rock strata.
Desorption	The processes releasing molecules of gas, liquid, or dissolved constituents from a surface (compare Adsorption).
Discharge	Removal of water from or flow out of an aquifer, including flow to surface water, another aquifer, or artificial means such as pumping. See also 'abstraction'.
Discharge Area	An area where groundwater flows out of an aquifer.
Disconformity	A break in the sequence of sedimentary deposition followed by resumed sedimentation, where the buried non-depositional surface lies between parallel strata on a regional scale.
Dissolved Solids	Soluble compounds such as salts which are in solution.
Down Warp	A downward bend in sedimentary layering caused by tectonic movement.
Drawdown	The drop in the watertable or potentiometric level when water is being pumped from a well.
Ecosystem	A system made up of the community of living things (animals, plants, and microorganisms) which are interrelated to each other and the physical and chemical environment in which they live.
Facies	A horizon of sedimentary rock formed under a particular set of environmental conditions, resulting in a distinct assemblage of sedimentary structures, mineralogy, grainsize, fossils and other features.
Fault	A structural discontinuity in a rock mass or geological formation.
Fluvial	Pertaining to a river or stream.
Fluvio-Lacustrine	Pertaining to a combined environment involving a river or stream and lake conditions.
Flux	The rate of flow (mass transport) of a fluid or other material or compound transported by that fluid.
Formation	A geological structure such as a rock mass or layer.
Fresh Water	Water containing low salt concentrations, typically less than 1,000 mg/L. (Compare Brackish, Saline and Brine).

GLOSSARY OF TERMS

Gilgai	A group of undulations and closed depressions at the soil surface, caused by the presence of swelling clays and seasonal movement due to changes in moisture content. Gilgai may range in size from a few meters up to 100 m across, and have a typical vertical amplitude of 30-50 cm.
Groundwater	Any sub-surface water, generally present in an aquifer or aquitard.
Groundwater Flow	The movement of water in an aquifer.
Heavy Metals	Metallic elements of atomic weight greater than that of Iron (e.g. Copper Arsenic, Mercury, Chromium, Cadmium, Lead, Nickel and Zinc).
Heterogeneous	Having different properties or composition at different locations.
Hydraulic Conductivity	A standard measure of the permeability of a geological formation or its ability to transmit groundwater flow.
Hydraulic Gradient	The slope of the watertable in an unconfined aquifer, or the potentiometric surface in a confined aquifer.
Hydraulic Head	A measure of the pressure head of water in aquifer, commonly measured as the elevation to which water will rise in a constructed well.
Hydrogeology	The study of the inter-relationships of geologic materials and processes with water, especially groundwater.
Hydrostatic Pressure	The pressure exerted by a fluid at equilibrium due to the force of gravity.
Indurated	Pertaining to a rock or soil hardened by mineral recrystallisation due to heat, pressure or chemical precipitation.
Infiltration	Rainfall penetration into the soil profile or sub-surface. Infiltrated water that accesses the watertable is one component of groundwater recharge.
Jumpups	The flat tops of mesas formed by erosional processes.
Labile	Unstable, likely to change or decompose.
Lateritisation	A process of weathering, dissolution and leaching resulting in a hard crust dominated by iron and aluminium oxides.
Lithology	The physical composition of a rock.
Marine Regression	A period of sea level fall over geological time.
Marine Transgression	A period of sea level rise over geological time.

GLOSSARY OF TERMS

Meander Scar	A remnant landform caused by the abandonment of a stream bend which has first produced a cutoff-meander, oxbow lake or billabong, and been gradually infilled by sediment such that it no longer contains open water.
Mesa	An elevated area of land with a flat top and sides that are usually steep cliffs.
Montmorillonite	A clay mineral with swelling properties.
Mound spring	A naturally occurring outlet of upwelling groundwater, with a characteristic mound or crater shape formed by deposition of minerals.
Nutrients	A chemical that an organism needs to live and grow, or a substance used in an organism's metabolism obtained from its environment.
Onlap	A sedimentation regime occurring during a marine transgression.
Offlap	A sedimentation regime occurring during a marine regression.
Palaeochannel	Unconsolidated sediments or semi-consolidated sedimentary rocks deposited in ancient, currently inactive river and stream channel systems.
Peat	A sedimentary deposit dominated by partially-decomposed plant material, and considered to be an early stage in the formation of coal.
Perched Aquifer	An unconfined aquifer of limited extent located above the true watertable.
Perennial	A stream or river (channel) that has continuous flow in parts of its bed all year round during years of normal rainfall.
Permeability	The ability to transmit fluids through a porous medium.
Piezometer	A type of well specifically constructed in an aquifer for monitoring purposes, and screened at a specific depth to provide measurements of pressure head at that point.
Piezometric Level	The pressure head of water measured in a piezometer, from a specific depth or point in an aquifer.
Porosity	The ratio of void spaces in a geological formation compared to the bulk formation volume.
Potable Water	Water of suitable quality for human consumption.
Potentiometric Level	A measure of the pressure head of water in an aquifer at a given location, usually used in reference to a confined aquifer.

GLOSSARY OF TERMS

Potentiometric Surface	An imaginary layer which defines the potentiometric levels for a confined aquifer. In an unconfined aquifer it is more commonly termed as the watertable.
Pyroclastic	Material which is deposited from air-borne particles ejected by a volcanic eruption.
Recharge	Addition of water to or flow into an aquifer (generally) from rain. Also used to describe water entering an aquifer from surface water, groundwater, or artificial means.
Recharge Area	An area in which water enters an aquifer.
Reactivated Fault	A pre-existing fault in a geological setting which becomes the preferred surface to accommodate movement during a new period of tectonic activity.
Regolith	The unconsolidated or weathered geological material at the Earth's surface.
Runoff	Rain water that flows across the land surface without entering the sub-surface.
Saline Water	Water containing high levels of dissolved salts, typically between 10,000 and 40,000 mg/L. (Compare Fresh, Brackish and Brine).
Saturated Zone	The zone in which the voids in the rock are completely filled with water. The watertable represents the top of the saturated zone in an unconfined aquifer.
Sediment	Unconsolidated geological material which has been formed by a process of deposition as discrete particles.
Sedimentary Sequence	A succession of layers of sedimentary rock caused by sequential deposition.
Semi-Confined Aquifer	A confined aquifer having a leaky confining layer.
Specific Yield	The ratio of the volume of water a rock will release by gravity drainage to the bulk volume of the rock.
Spring	The land to which water rises naturally from below the ground and the land over which the water then flows.

GLOSSARY OF TERMS

Standing Water Level	The depth below natural ground surface to the water level in a well or bore when it is at equilibrium with the surrounding formation (i.e. 'at rest' or 'fully recovered' from pumping). Also referred to as Static Water Level.
Storage Coefficient	A measure of the ability of aquifer material to store water, due to volumetric storage (Specific Yield) plus elastic storage.
Storativity	A measure of the ability of an aquifer to store water. Storativity is a function of storage coefficient and aquifer thickness.
Stratigraphy	The sequential classification of geological materials based on their age of formation.
Sustainable Yield	Amount of water that can be abstracted from an aquifer over a long period of time without dewatering the aquifer or impacting the resource.
Total Dissolved Solids	Concentration of dissolved salts (TDS).
Through Flow	The horizontal movement of water beneath the ground surface, including flow in the unsaturated zone (eg. soil) or saturated zone (eg. aquifer).
Transmissivity	The rate at which an aquifer can transmit water. It is a function of properties of the aquifer material and the thickness of the porous media.
Travertine	A mineral commonly found in caves, composed of finely crystalline calcium carbonate which has been precipitated from solution in groundwater.
Unconfined Aquifer	An aquifer with no confining layer between the water table and the ground surface where the water table is free to rise and fall.
Unsaturated Zone	The part of the geological stratum above the saturated zone, also called the vadose zone. The unsaturated zone may be dry, or may contain water under partially saturated conditions.
Uplift	The relative upward movement of rocks due to tectonic forces.
Vertical Anisotropy	Differing properties of a geological material in the vertical direction compared to horizontal direction.
Watertable	The top of the saturated zone in an unconfined aquifer.
Well	A hole drilled into a groundwater resource (aquifer), oil or gas resource reservoir) and constructed with a casing and screen or similar. In Australia also commonly referred to as a 'bore'.

GLOSSARY OF TERMS

Well Field	A group of boreholes in a particular area having a common use, such as for groundwater, oil or gas extraction.
Well Yield	The flow rate obtainable from an extraction well or bore.

LIST OF ABBREVIATIONS

ADWG	Australian Drinking Water Guidelines
ALOS	Advanced Land Observation Satellite
BOM	Bureau of Meteorology
BTEX	Benzene, Toluene, Ethylbenzene, Xylene
CMA	Cumulative Management Area
Coffey	Coffey International Limited
DERM	Queensland Department of Environment and Resource Management (formerly known as EPA)
DEEDI	Department of Employment, Economic Development and Innovation
DEM	Digital elevation model
DME	Department of Mines and Energy (currently known as DEEDI)
DNRW	Department of Natural Resources and Water (currently known as DERM)
EIS	Environmental Impact Statement
EM Plan	Environmental Management Plan required under Environmental Protection Act 1994 (Qld)
EPA	Queensland Environmental Protection Agency (currently known as DERM)
EP Act	Environmental Protection Act 1994 (Qld)
EP Regulation	Environment Protection Regulation 1998 (Qld)
EPP (Water) Policy	Environmental Protection (Water) Policy 2009
FID	Financial Investment Decision
GAB	Great Artesian Basin
GABCC	Great Artesian Basin Coordinating Committee
GMA	Groundwater Management Area
IPF	Integrated Production Facility

LIST OF ABBREVIATIONS

LNG	Liquefied Natural Gas
MNES	Matters of national environmental significance
NHMRC	National Health and Medical Research Council
NRMMC	Natural Resource Management Ministerial Council
NATA	National Association of Testing Authorities
NEPM	National Environment Protection Measure
PB	Parsons Brinckerhoff
QGC	Queensland Gas Company
QWC	Queensland Water Commission
SAR	Sodium Adsorption Ratio
SIMS	Springs Impact Management Strategy
SKM	Sinclair Knight Merz
SOP	Standard Operating Procedure
SWL	Standing Water Level
TDS	Total Dissolved Solids
TOR	Terms of Reference
UWIR	Underground water impact report
WCM	Walloon Coal Measures
WERD	Water Entitlements Registration Database

UNITS

1P	Proved reserves
2P	Proved and probable reserves
3P	Proved, probable and possible reserves
Bbl	Barrels. One barrel = 42 US gallons = 158.99 Litres
Bcf	Billion cubic feet
^{o}C	Degrees Celsius
GJ	Gigajoules
km^{2}	Square kilometres
m	metres
m/day	Metres per day
m^{2}/day	Metres squared per day
mAHD	Measurement in metres relative to the Australian Height Datum
Mbgl	Metres Below Ground Level
Mbgs	Metres Below Ground Surface
mg/L	Milligrams per litre
MJ	Megajoules
ML	Megalitres
ML/day	Megalitres per day
mm	Millimetres
mm/y	Millimetres per year
Mmbbl	1,000,000 barrels
MPa	Megapascal
Mscf/d	Thousand standard cubic feet per day, a common measure for volume of gas. Standard conditions are normally set at 60^{o}F and 14.7 psia.

UNITS

Mtpa	Million tonnes per annum
MW	Megawatt
PJ	Petajoules (= 1,000 TJ)
psi	Pounds-force per square inch – a unit of pressure
psia	Pounds-force per square inch absolute – a unit of pressure (gauge pressure plus local atmospheric pressure)
TDS	Total Dissolved Solids
TJ	Terrajoules (= 1,000,000 MJ)
TJ/d	Terrajoules per day
µS/cm	Microsiemens per centimetre

EXECUTIVE SUMMARY

Coffey Environments Australia Pty Ltd was commissioned by Arrow Energy Pty Ltd to provide the groundwater assessment component of the Environmental Impact Statement (EIS) for the Surat Gas Project. Arrow proposes expansion of its coal seam gas operations in the Surat Basin through the Surat Gas Project. The project development area covers approximately 8,600 km^2 and extends from Wandoan in the north towards Goondiwindi in the south, in an arc adjacent to Dalby.

The conceptual Surat Gas Project is premised upon peak gas production from Arrow's Surat Basin gas fields of approximately 1,050 terrajoules per day (TJ/d). A project life of 35 years has been adopted for EIS purposes. Ramp-up to peak production is estimated between 4 and 5 years commencing from 2014. Peak gas production of 1,050 TJ/d will be sustained for approximately 20 years, after which production is expected to decline.

This report is based on the requirements of the Terms of Reference provided by the Department of Environment and Resource Management. These require the EIS to cover all aspects of the proposed development and production of the gas resource.

Scope of Work

The scope of work included in the groundwater assessment is listed below:

- Reviewing the legislative framework relevant to the groundwater aspect of the project.
- A desktop review of relevant Great Artesian Basin, Surat Basin and coal seam gas literature.
- Describing the environmental values associated with groundwater assets in the project development area and ranking the sensitivity of those values.
- Numerical groundwater modelling to assess impacts (with Schlumberger Water Services).
- An assessment of the unmitigated magnitude of project activities on groundwater environmental values to determine the significance of those impacts.
- Proposing management and mitigation measures to protect environmental values.
- Providing a residual impact significance ranking to the identified environmental values after mitigation measures are implemented.
- Providing recommended monitoring and commitment options.
- Assessing potential cumulative impacts of the project.

Numerical Groundwater Modelling

The numerical modelling conducted considered three scenarios that investigated the effects of groundwater abstraction from Arrow, QGC, Origin Energy and Santos coal seam gas developments on the regional groundwater system. The three scenarios are:

1. Arrow only reference case. This scenario seeks to determine the unmitigated impacts on the groundwater system resulting from Arrow coal seam gas operations alone.
2. Combined base case. This scenario seeks to determine the unmitigated impacts on the groundwater system resulting from a combination of Arrow coal seam gas operations and other coal seam gas projects that have taken Final Investment Decision prior to 31 January 2011. Abstraction from Arrow, QGC and Santos coal seam gas wells is considered.

3. Cumulative case. This scenario seeks to determine the unmitigated impacts on the groundwater system resulting from all coal seam gas operations in the Surat Basin. Abstraction from Arrow, QGC, Santos and Origin coal seam gas wells is considered.

Impacts and Mitigation

The impact of the project on groundwater systems in the region is related to the environmental values and their sensitivity to change. These environmental values and the sensitivity assigned to them will be present throughout the lifetime of the project and should, therefore, be a constant consideration as the project moves through design, construction, operation and decommissioning phases. A significance assessment approach was adopted for this study, which considers both the sensitivity of the environmental values and the magnitude of the identified impact. The impacts were assessed for all major aquifer systems.

Potential impacts of the project on the groundwater systems of the study area, without implementation of management and mitigation measures, indicate that groundwater environmental values such as groundwater pressure (i.e. levels) and water quality could be impacted. Management and mitigation measures are identified to counter the identified impacts and these are considered appropriate for the reduction of impacts, and an assessment of residual impacts has been made.

Management and Monitoring Program

The implementation of environmental protection measures is considered necessary to assess the impacts of the Surat Gas Project operations on associated environmental values and groundwater quality and quantity. A robust groundwater baseline assessment and groundwater monitoring program has been proposed to underpin this. This program will provide:

- Baseline conditions against which potential impacts can be assessed.
- A mechanism for early detection of potential impacts.
- A basis for implementing appropriate contingency and management plans.

The objectives of the proposed groundwater monitoring program are to:

- Provide a configuration of bores that allows identification of drawdown across the project development area and within key aquifers.
- Gain further understanding of aquifer interactions and verify the understanding of regional hydrogeology.
- Identify long-term groundwater level trends and potential cumulative effects from current and future coal seam gas development.
- Provide information to differentiate effects between operating gas fields and other sources of groundwater variability.
- Develop an “early warning system” that identifies areas potentially impacted by project activities and allows early intervention.
- Provide a mechanism for continuous improvement of the numerical groundwater model.
- Share information with regulatory authorities.

1 INTRODUCTION

Coffey Environments Australia Pty Ltd (Coffey Environments) has been commissioned by Arrow Energy Pty Ltd (Arrow) to provide the groundwater assessment component of the Environment Impact Statement (EIS) for the Surat Gas Project (the project).

Arrow proposes expansion of its coal seam gas operations in the Surat Basin through the Surat Gas Project (Figure 1.1). The need for the project arises from the growing demand for gas in the domestic market and global demand and the associated expansion of liquefied natural gas (LNG) export markets.

The project development area covers approximately 8,600 square kilometres (km^2) and is located approximately 160 km west of Brisbane in Queensland's Surat Basin. The project development area extends from the township of Wandoan in the north towards Goondiwindi in the south, in an arc adjacent to Dalby. Townships within or in close proximity to the project development area include (but are not limited to) Wandoan, Chinchilla, Kogan, Dalby, Cecil Plains, Millmerran, Miles and Goondiwindi (Figure 1.2). Arrow's existing gas fields at Tipton West, Daandine, Stratheden and Kogan North near Dalby are shown in Figure 1.3. Project infrastructure including coal seam gas production wells and production facilities (including both water treatment and power generation facilities where applicable) will be located throughout the project development area but not in towns. Facilities supporting the petroleum development activities such as depots, stores and offices may be located in or adjacent to towns.

The conceptual Surat Gas Project design presented in the EIS is premised upon peak gas production from Arrow's Surat Basin gas fields of approximately 1,050 terrajoules per day (TJ/d). The peak gas production comprises 970 TJ/d for LNG production (including a 10% fuel gas requirement for facility operation) and a further 80 TJ/d for supply to the domestic gas market.

A project life of 35 years has been adopted for EIS purposes. Ramp-up to peak production is estimated to take between 4 and 5 years, and is planned to commence in 2014. Following ramp-up, gas production will be sustained at approximately 1,050 TJ/d for at least 20 years, after which production is expected to decline.

Infrastructure for the project is expected to comprise:

- Approximately 7,500 production wells drilled over the life of the project at a rate of approximately 400 wells drilled per year.
- Low pressure gas gathering lines to transport gas from the production wells to production facilities.
- Medium pressure gas pipelines to transport gas between field compression facilities and central gas processing and integrated processing facilities.
- High pressure gas pipelines to transport gas from central gas processing and integrated processing facilities to the sales gas pipeline.
- Water gathering lines (located in a common trench with the gas gathering lines) to transport coal seam gas water from production wells to transfer, treatment and storage facilities.
- Approximately 18 production facilities across the project development area expected to comprise of 6 of each of the following:
    - Field compression facilities.

  - o Central gas processing facilities.
  - o Integrated processing facilities.
- A combination of gas powered electricity generation equipment that will be co-located with production facilities and electricity transmission infrastructure that may draw electricity from the grid (via third party substations).

Further detail regarding the function of each type of compression and production facilities is detailed below.

Field compression facilities will receive gas from production wells and are expected to provide 30 to 60 TJ/d of first stage gas compression. Compressed gas will be transported from field compression facilities in medium pressure gas pipelines to multi-stage compressors at central gas processing facilities and integrated processing facilities where the gas will be further compressed to transmission gas pipeline operating pressure and dehydrated to transmission gas pipeline quality. Coal seam gas water will bypass field compression facilities.

Central gas processing facilities will receive gas both directly from production wells and field compression facilities. Central gas processing facilities are expected to provide between 30 and 150 TJ/d of gas compression and dehydration. Coal seam gas water will bypass central gas processing facilities and be pumped to an integrated processing facility for treatment.

Integrated processing facilities will receive gas from production wells and field compression facilities. Integrated processing facilities are expected to provide between 30 and 150 TJ/d of gas compression and dehydration. Coal seam gas water received at integrated processing facilities is expected to be predominantly treated using reverse osmosis and then balanced to ensure that it is fit for purpose. Coal seam gas water received from the field, treated water and brine concentrate will be stored in dams adjacent to integrated processing facilities.

It is envisaged that development of the Surat Gas Project will occur in five development regions: Wandoan, Chinchilla, Dalby, Kogan/Millmerran and Goondiwindi. Development of these regions will be staged to optimise production over the life of the project.

Arrow has established a framework to guide the selection of sites for production wells and production facilities and routes for gathering lines and pipelines. The framework will also be used to select sites for associated infrastructure such as access roads and construction camps. Environmental and social constraints to development that have been identified through the EIS process coupled with the application of appropriate environmental management controls will ensure that protection of environmental values (resources) is considered in project planning. This approach will maximise the opportunity to select appropriate site locations that minimise potential environmental and social impacts.

Arrow has identified 18 areas that are nominated for potential facility development to facilitate environmental impact assessment (and modelling). These are based on circles of approximately 12 km radius that signify areas where development of production facilities could potentially occur.

Arrow intends to pursue opportunities in the selection of equipment (including reverse osmosis units, gas powered engines, electrical generators and compressors) and the design of facilities that enable the cost effective and efficient scaling of facilities to meet field conditions. This flexibility will enable Arrow to better match infrastructure to coal seam gas production. It will also enable Arrow to investigate the merits of using template design principles for facility development, which may in turn generate further efficiencies as the gas reserves are better understood, design is finalised, or as field development progresses.

1.1 Proponent

Arrow is an integrated energy company with interests in coal seam gas field developments, pipeline infrastructure, electricity generation and proposed LNG projects.

Arrow has interests in more than 65,000 km^2 of petroleum tenures, mostly within Queensland's Surat and Bowen basins. Elsewhere in Queensland, the company has interests in the Clarence-Moreton, Coastal Tertiary, Ipswich, Styx and Nagoorin Graben basins (Figure 1.1).

Arrow's petroleum tenures are located close to Queensland's three key energy markets; Townsville, Gladstone and Brisbane. The Moranbah Gas Project in the Bowen Basin and the Tipton West, Daandine, Kogan North and Stratheden projects in the Surat Basin near Dalby comprise Arrow's existing coal seam gas production operations. These existing operations currently account for approximately 20% of Queensland's overall domestic gas production.

Arrow supplies gas to the Daandine, Braemar 1 and 2, Townsville and Swanbank E power stations which participate in the National Electricity Market. With Arrow's ownership of Braemar 2, and the commercial arrangements in place for Daandine and Townsville power stations Arrow has access to up to 600 megawatts (MW) of power generation capacity.

Arrow and its equity partner AGL Energy have access rights to the North Queensland Pipeline which supplies gas to Townsville from the Moranbah Gas Project. They also hold the pipeline licence for the proposed Central Queensland Gas Pipeline between Moranbah and Gladstone.

Arrow is currently proposing to develop the Arrow LNG Project, which is made up of the following aspects:

- Arrow LNG Plant – The proposed development of an LNG Plant on Curtis Island near Gladstone, and associated infrastructure, including the gas pipeline crossing of Port Curtis.
- Surat Gas Project – The upstream gas field development in the Surat Basin, subject of this assessment.
- Arrow Surat Pipeline Project – (Formerly the Surat Gladstone Pipeline), the 450 km transmission pipeline connects Arrow's Surat Basin coal seam gas developments to Gladstone.
- Bowen Gas Project – The upstream gas field development in the Bowen Basin.
- Arrow Bowen Pipeline – The transmission pipeline which connects Arrow's Bowen Basin coal seam gas developments to Gladstone.

1.2 Purpose and Objectives of the Groundwater Assessment

The purpose of this report is to satisfy the requirements of the Terms of Reference (TOR) provided by the Department of Environment and Resource Management (DERM).

1.3 EIS Terms of Reference

The TOR requires that the EIS cover all aspects of the proposed development and production of the gas resource. This will include construction of infrastructure, operation and later rehabilitation, for the entire life of the project.

1.4 Scope of Work

For the purpose of this assessment, Coffey Environments was commissioned to conduct the following major tasks:

- Desktop review of Great Artesian Basin (GAB), Surat Basin and coal seam gas literature.
- Describe the quality, current yields and capacities, and other physical features of the groundwater resources in the project development area and surrounding study area.
- Describe the environmental values associated with groundwater environments in the project development area and assign a sensitivity ranking to those values.
- Liaise regularly with Schlumberger Water Services (Australia) Pty Ltd (Schlumberger) to develop a numerical groundwater model sufficient for the purpose of impact assessment, and to assist with model calibration and simulations.
- Identify and assess likely impacts of the project activities on groundwater environmental values within the project development area and any significant State or Nationally significant environmental assets. Assess the potential magnitude of these impacts on the environmental values.
- Provide an unmitigated impact significance ranking to the identified environmental values as a function of their sensitivity and the potential magnitude of impact.
- Review and identify measures for management and mitigation of groundwater risks and impacts.
- Provide a residual impact significance ranking to the identified environmental values as a function of their sensitivity and the potential magnitude of impact after mitigation measures are implemented.
- Provide recommended monitoring and commitment options.
- Assess potential cumulative impacts of the project.

1.5 Legislative Framework

The primary legislative requirements that will guide the management and development of groundwater components for the project are summarised below.

1.5.1 Environment Protection and Biodiversity Conservation Act (EPBC Act) 1999

The EPBC Act is Commonwealth legislation that provides for the protection of matters of national environmental significance (MNES), including groundwater dependant ecosystems and MNES species that rely on groundwater springs. Any action with the potential for significant impacts to these must be referred to the Minister for Sustainability, Environment, Water, Population and Communities, and may require approval under this Act.

1.5.2 ***Petroleum and Gas (Production and Safety) Act 2004*** (reprinted as in force on 1 July 2011)

The Petroleum Act 1923 is the original Act regulating the petroleum industry and was not repealed when the Petroleum and Gas (Production and Safety) Act 2004 (P&G Act) commenced.

The P&G Act and the Petroleum Act 1923 govern groundwater management in relation to the proposed gas field development. The purpose of the P&G Act is to facilitate and regulate the carrying out of responsible petroleum activities and the development of a safe, efficient and viable petroleum and fuel gas industry.

Under the P&G Act, the petroleum tenure holder, under Section 185, may take or interfere with groundwater to the extent that it is necessary and unavoidable during the course of an activity authorised under the petroleum tenure. The right to take water for or during petroleum purposes as defined in the P&G Act include:

- No limit to the volume of water that may be taken (Section 185 (3)).
- Underground water taken or interfered with, under subsection (1)(a), from a petroleum well is associated water (also termed coal seam gas water within this report).
- The associated water can only be used for the authorised petroleum activity or for domestic and stock purposes only on the land covered by the tenure or on adjoining land to the tenure or by any land owned by the same landowner which joins the tenure area (Section 186).

Section 187 of the P&G Act further identifies requirements for water monitoring for associated water. Water monitoring is required for assessing compliance with the underground water obligations for the tenure. The underground water obligations are defined in Chapter 3 of the Water Act (Qld) 2000. A petroleum tenure holder may also apply for a water monitoring authority (Section 190) which may include land outside the tenure area to allow the holder to comply with the tenure requirements.

The petroleum tenure holder also has ‘make good’ obligations if the petroleum activity causes an existing water bore to have an impaired capacity. These obligations are defined in Chapter 3 of the Water Act (Qld) 2000.

1.5.3 ***Water Act (Qld) 2000*** *(Reprinted as in force 27 June 2011)*

The primary purpose of the Water Act (Qld) 2000 is to provide for the sustainable management of water and other resources, and the establishment and operation of water authorities. In particular, the Act:

- Provides a comprehensive regime for the planning and management of water resources (including vesting to the State the rights over the use, flow and control of all surface water, groundwater, rivers and springs) in Queensland.
- Regulates water use and the obligations of coal seam gas producers in relation to groundwater monitoring, reporting, impact assessment and management of impacts on other water users.
- Provides a framework and conditions for preparing a Baseline Assessment Plan and outlines the requirements of bore owners to provide information the petroleum holder reasonably requires to undertake a baseline assessment of any bores.
- Sets out the process for applying for a Water Licence (where water is to be utilised outside of a Petroleum Lease or not on adjacent land owned by the same person).

- Sets out the process for assessing, reporting, monitoring and negotiating with other water users regarding the impact of coal seam gas production on aquifers.

Chapter 3 of the Water Act (Qld) 2000 provides for the management of impacts on underground water caused by the exercise of underground water rights by petroleum tenure holders. This is achieved primarily by:

a) providing a regulatory framework to:

- (i) require petroleum tenure holders to monitor and assess the impact of the exercise of underground water rights on water bores and to enter into 'make good' agreements with the owners of the bores potentially affected;
- (ii) requires the preparation of underground water impact reports that establish underground water obligations, including obligations to monitor and manage impacts on aquifers and springs. This is undertaken by the Queensland Water Commission (QWC) for declared cumulative management areas (CMA) and the tenure holder outside of the CMA.
- (iii) manage the cumulative impacts of the exercise of 2 or more petroleum tenure holders' underground water rights on underground water (by the QWC declaring a CMA); and

(b) giving the chief executive (Queensland Water Commission) and the commission functions and powers for managing underground water.

Where the petroleum tenure holder reasonably believes that a water bore has an impaired capacity, the holder must use best endeavours to negotiate and enter into a 'make good' agreement with the bore owner about the following matters:

- The reason for the bore's impaired capacity.
- The measures the holder will take to ensure the bore owner has access to a reasonable quantity and quality of water for the authorised purpose.
- Any monetary or non-monetary compensation payable to the bore owner for impact on the supply.

The obligations of a petroleum tenure holder for bores within an immediately affected area are:

- Undertake a bore assessment as required under division 2;
- Enter into a 'make good' agreement with the bore owner as required under Division 3;
- Comply with the 'make good' agreement; and
- Vary the make good agreement under Section 424 (if asked).

Sections 411 to 419 provide the methodology and obligations on when and how to undertake a bore assessment and the definition of 'impaired capacity' of a water bore. These sections also provide information on the obligations of the water bore owner when assessing the capacity of the water bore.

Sections 420 to 424 define 'make good agreement' and 'make good measure' for a water bore. Examples provided for make good measures include:

- Bore enhancement by deepening the bore or improving its pumping capacity.
- Construction of a new bore.

- Providing an alternative supply of an equivalent amount of water of suitable quality
- Compensation.

Sections 425 to 437 outline the processes to follow if there are disputes about make good measures/obligations between a petroleum tenure holder and the owner of a water bore.

The result of multiple coal seam gas proponents operating concurrently will have cumulative impacts on underground water. A CMA is declared if the chief executive considers an area containing 2 or more petroleum tenures may be affected by the exercise of underground water rights by the tenure holders. The Water Act (Qld) 2000 provides the responsibilities and requirements of petroleum tenure holders within the CMA and the role of the chief executive (Queensland Water Commission) in this instance.

The role of the Queensland Water Commission – Cumulative Impacts

The Queensland Government changed legislation in relation to the management of water in the petroleum and gas industry. The changes, to the Water Act (Qld) 2000 have been driven by the rapid expansion of the coal seam gas industry. The changes have created a new role for the QWC in managing the impacts of coal seam water extraction on groundwater resources.

In areas of concentrated coal seam gas development, the impacts on water levels caused by individual petroleum and gas projects can overlap. The state government may declare these areas to be CMAs. The area of planned concentrated coal seam gas development in Queensland has been declared as the Surat CMA.

The QWC will prepare an underground water impact report (UWIR) for the Surat CMA. A regional groundwater flow model is being developed by the QWC to predict future water level impacts in the coal seams as well as in adjacent aquifers in the Surat CMA. The model will be a key tool in the development of the UWIR. The UWIR will include:

- Maps showing predicted water level impacts.
- An ongoing water monitoring program.
- Information about management of springs that could be affected by decline in water levels.
- An assignment of responsibilities for individual petroleum and gas operators to carry out activities such as specific parts of the regional monitoring program.

The maps in the Surat UWIR that show predicted future water level impacts will define, for each aquifer, the areas where water levels are expected to fall by more than specified trigger thresholds within three years. These areas will become ‘immediately affected areas’. When the Surat UWIR is approved by DERM, petroleum and gas companies will need to enter into agreements with bore owners about arrangements to maintain water supply in immediately affected areas. These arrangements are designed to ensure that the agreements will be in place before any potential impairment of water supply occurs.

If at any time a bore supply is impaired due to water extraction by a petroleum or gas company, the company must work out a solution to the problem with the bore owner. This applies regardless of whether the bore is inside or outside the immediately affected area. The Department of Environment and Resource Management (DERM) can assist with resolving any disagreements.

The QWC will update the Surat UWIR every three years. The groundwater flow model will be updated incorporating new information emerging from monitoring data and other sources. Through this process, predictions about future water levels will be progressively refined.

Outside the CMA, individual petroleum tenure holders will need to prepare underground water impact reports for approval by DERM. The QWC may advise DERM about the adequacy of these reports.

The QWC will maintain a database of information collected under monitoring plans carried out in accordance with monitoring programs in approved UWIRs. The database will also store baseline data collected by petroleum and gas operators as a part of their obligations under the Water Act (Qld) 2000.

1.5.4 *Water Supply (Safety and Reliability) Act 2008*

The Water Supply (Safety and Reliability) Act 2008 aims to provide for the safety and reliability of water supply in Queensland. It sets out the process for applying to be a water service provider where the owner of any water supply infrastructure intends to charge for supply. Water service providers must submit and maintain several management plans including:

- Environmental Management Plan.
- Strategic Asset Management Plan.
- System leakage Management Plan.
- Drought Management Plan.
- Drinking Water Quality management Plan (only if supplying drinking water).

The Act also sets out the obligations in relation to the potential to impact on drinking water supplies and the requirement for Recycled Water Management Plans. The coal seam gas industry is automatically captured by this process for injection, direct supply or discharge of water, however an exemption can be applied for.

1.5.5 *Water Resource (Great Artesian Basin) Plan 2006*

The Water Resources (Great Artesian Basin) Plan 2006 is the primary legislation for groundwater management of the GAB in Queensland. Associated water under the P&G Act is excluded from the allocation and management of water in the plan area. The Surat Gas Project development area is within the Eastern Downs, Surat East, Surat and Surat North management areas.

1.5.6 Great Artesian Basin Resource Operations Plan 2007

The Great Artesian Basin Resource Operations Plan 2007 implements the Water Resource (Great Artesian Basin) Plan 2006. Twenty-five 'groundwater management areas' and associated 'groundwater management units' are identified in the plan. A groundwater management unit corresponds to a formation or to a group of formations. For each unit a specified upper annual allocation of water is identified. Specifically, the Surat Basin is divided into seven groundwater management areas and 26 groundwater management units. The plan also stipulates that for new licence applications, a minimum separation distance from existing licensed bores be maintained to ensure a drawdown of no more than 5 metres (m). Associated water under the P&G Act is excluded from the allocation and management of water in the plan area.

1.5.7 Queensland Coal Seam Gas Water Management Policy 2010

This policy aims to ensure that salt produced through the generation of coal seam gas water does not adversely impact the environment, and to maximise the opportunities for beneficial use of the water. Under the policy, producers of coal seam gas water are required to meet appropriate treatment standards prior to disposal or supply of coal seam gas water to third parties. In addition, evaporation dams are to be discontinued as a primary means for coal seam gas water disposal, and all new coal seam gas water aggregation and storage dams must be fully lined to standards defined by DERM. The policy also requires the preparation of a coal seam gas water management plan and provides options for management and disposal options for saline effluent and solid salt wastes. This policy was under review at the time of writing.

1.5.8 Environmental Protection Act 1994 (EP Act)

Regulations associated with the Environmental Protection Act 1994 include the Environmental Protection Regulation 2008, the Environmental Protection (Waste Management) Policy 2000 and the Environmental Protection (Waste Management) Regulation 2000. This framework regulates the quality of groundwater through conditions imposed in the Environmental Authority.

The EPA 1994 classified waste streams from industrial activities, including coal seam gas production, as a by-product and therefore a waste product. Waste streams may be approved as a ‘resource’ under Part 6A (Environmental Protection (Waste Management) Regulation 2000) if a beneficial use can be demonstrated.

1.5.9 Environmental Protection (Water) Policy 2009

The Environmental Protection (Water) Policy 2009 seeks to achieve the objective identified by the Environmental Protection Act 1994 (EP Act) to protect Queensland's waters while allowing for development that is ecologically sustainable.

This purpose is achieved within a framework that includes identifying environmental values for waters (aquatic ecosystems, water for drinking, water supply, water for agriculture, industry and recreational use), and deciding and stating water quality guidelines and water quality objectives to enhance or protect the environmental values.

1.5.10 Murray-Darling Basin Plan 2011

The pending Murray-Darling Basin Plan is proposed to operate under the Water Act 2007 (Commonwealth Water Act) which requires the Murray-Darling Basin Authority to determine the volume of water necessary to maintain and restore environmental assets within the Murray-Darling system. At present, a guide to the proposed Basin Plan has been released. It is proposed that the Basin Plan will set out environmental water requirements and volumes of water that can be taken for consumptive uses (sustainable diversion limits). The Guide to the Basin Plan refers to groundwater assets in the project development area – specifically the Condamine-Balonne and Border River region shallow aquifers, however GAB aquifers, including the Walloon Coal Measures, are not legislated under the Plan.

1.5.11 Sustainable Planning Act 2009

The purpose of this Act is to seek to achieve ecological sustainability by:

- Managing the process by which development takes place, including ensuring the process is accountable, effective and efficient and delivers sustainable outcomes;

- Managing the effects of development on the environment, including managing the use of premises; and
- Continuing the coordination and integration of planning at the local, regional and State levels.

The Act regulates the development of infrastructure outside of a petroleum tenure and provides details of the Development Approval/Operational Works approval process for construction of such infrastructure.

2 STUDY APPROACH AND PREVIOUS OR RELATED STUDIES

2.1 Basis of Study Approach to EIS

The study approach includes a 'Significance Assessment' based core component for impact and mitigation assessment. The methodology adopted is outlined below.

2.1.1 Methodology

The objectives of the groundwater assessment were to identify and characterise the groundwater resources and evaluate the potential impacts associated with coal seam gas extraction. The groundwater assessment adopted the following methodology:

Phase 1: Review of information and establishment of baseline data.

Phase 2: Groundwater modelling.

Phase 3: Identification of environmental values.

Phase 4: Identification of potential impacts to groundwater.

Phase 5: Significance assessment and impact mitigation.

Phase 6: Development of mitigation, management, and monitoring plans.

The study area includes the areas both within and beyond the defined project development area (Figure 1.2) that may be potentially affected by the groundwater withdrawals associated with the development. The full extent of the study area (beyond the project development area) is defined in the modelling section of this report.

2.1.1.1 Phase 1 – Review of information and establishment of baseline data

The groundwater assessment is based on a desktop review of available geological and hydrogeological information. The review and evaluation of data allowed for the compilation of the baseline groundwater descriptions and assessment of possible impacts. The assessments were based on the information obtained from the following data sources:

- A search of the DERM groundwater database for registered bores (extracted 6 October 2009) located within the Surat Gas Project development area. The distribution of registered groundwater bores in the Surat Gas Project development area is shown on Figure 2.1.
- A search of the Queensland Water Entitlements Registration Database (WERD) extracted 17 February 2010 for licensed bore users within the Surat Gas Project development area.
- These datasets provided information such as stratigraphy, bore casing, water levels and water quality.
- Geological Maps and Surat Basin stratigraphy provided by Arrow Energy.

The data was collated in an in-house relational database (MS Access). This facilitated the assessment of available geological and hydrogeological information, and provided a foundation to establish baseline groundwater conditions (i.e. aquifer hydraulics and groundwater chemistry).

The desktop review assumed that all data provided in the DERM and WERD government databases to be accurate, however where data appeared to be anomalous it was excluded from further assessment.

2.1.1.2 Phase 2 – Groundwater Modelling

A detailed conceptual groundwater model and numerical groundwater model of the study area has been developed under contract by Schlumberger to predict potential impacts on the environmental values and other groundwater users. The groundwater model was developed to the requirements specified by Coffey Environments, and under Coffey Environments guidance, and the completed modelling and results were subsequently reviewed by Coffey Environments.

Arrow also engaged the services of a suitably qualified peer reviewer to review the Schlumberger modelling report prior to inclusion in the EIS. This independent third-party review was conducted by Lloyd Townley of NTEC Environmental Technology in Western Australia.

The groundwater modelling domain is illustrated in Figure 2.2. The modelling and results are discussed in section 7 and the report is provided in Appendix B.

2.1.1.3 Phase 3 – Identification of Environmental Values

A key process of this groundwater assessment is to identify and present the environmental values for the study area. The established environmental values then provide a basis for the design of the impact and management process.

2.1.1.4 Phase 4 – Identification of Potential Premitigation Impacts

The potential impacts to environmental values that could arise as a result of the project activities prior to the implementation of any mitigation measures were evaluated. Potential groundwater related impacts arise from:

- Coal seam gas depressurising.
- Gas field development.
- Storage management and handling of coal seam gas water.
- Cumulative impacts caused by other developments.

2.1.1.5 Phase 5 – Significance Assessment and Impact Mitigation

The significance of an impact is assessed by considering both the sensitivity of the environmental value and the magnitude of the impact, before and after the application of mitigation measures. This enables the selection and effectiveness of the proposed mitigation measures in reducing the predicted impact to be assessed.

2.1.1.6 Phase 6 – Mitigation, Management, and Monitoring Plans

Based on the identified potential groundwater related impacts to the environmental values, methodologies and procedures for mitigating and managing impacts were formulated.

2.2 Previous and Related Studies

Habermehl has researched the GAB since the early 1980s and much of his work is referenced in reports relating to the GAB and Surat Basin. Habermehl’s earlier works (1980) documented the hydraulic parameters of the resource aquifers in the Surat Basin. Exon (1976) also provided a summary of the geology of the Surat Basin. Additional stratigraphic and structural descriptions of the Surat Basin have been provided by Green (1997), Goscombe and Coxhead (1995), and Power and Devine (1970).

Over the past few decades, several regional studies of the GAB hydrogeology have focussed on describing the importance of the GAB as a water resource (e.g. Cox and Barron, 1998; Great Artesian Basin Coordinating Committee (GABCC), 2000, Habermehl, 2000; Department of Natural Resources and Mines (DNRM), 2005; Henning 2005). These include studies that focus on the geology and stratigraphy of the GAB, and also those that provide technical resources for GAB management.

More recently, the significant development and extraction of coal seam gas and associated water in gas-bearing coal formations has highlighted concerns regarding the potential impacts associated with coal seam gas development. In 2004, the Queensland government Department of Natural Resources, Mines and Energy (DNRE) commissioned Parsons Brinckerhoff (PB) to undertake a Coal Seam Gas Water Management Study. The PB report considered the potential impacts arising from coal seam gas operations within the Surat Basin, and summarised the potential impacts to groundwater resources.

Additionally, EIS submissions from other coal and coal seam gas projects have provided additional geological and hydrogeological data for the Surat Basin. These include the New Acland Coal EIS compiled by SKM (2009) for New Hope Coal Australia, the Wandoan Coal Project EIS prepared by PB (2008) for Xstrata coal, the Santos GLNG Project EIS completed by URS (2009) for Santos, the QGC Groundwater Study (Surat Basin) prepared by Golder Associates (2009b) for Queensland Gas Company (QGC), and the Australian Pacific LNG Project EIS prepared by Worley Parsons in 2010. Previous related groundwater studies are documented in Table 2.1.

Table 2.1 – List of previous and related studies

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3 GEOLOGY

3.1 Structural Geology and Setting

3.1.1 Basin Structure

The project development area covers the eastern margin of the Surat Basin and the western margin of the Clarence-Moreton Basin. The Kumbarilla Ridge, which passes close to and just west of Dalby, forms the boundary between these two basins and in some areas has a surface expression. Because the geological formations of the project development area are relatively continuous across this structural boundary, for discussion and practical purposes the geology is described below as the Surat Basin. Formations in the Surat Basin generally have a regional dip to the south and southwest at around 5^{o} but dips may increase towards the eastern margins.

The present day Surat Basin is gently structured, with minor warping and small localised faults disturbing the sedimentary sequence. The structural history has been one of general down warp during, and following deposition, followed by some gentle east/west compression during the Tertiary uplift. This has resulted in a pattern of broad folds over the basin, usually associated with basement structures and small reactivated faults.

Disconformably underlying the Surat Basin is a thick, gently folded, Permian to Triassic sequence of the north-south aligned Taroom Trough which is the sub-surface extension of the Bowen Basin. In this area (the Mimosa Syncline) the Surat Basin achieves its maximum thickness of approximately 2500 m.

Figure 3.1 shows important structural elements of the basins and Figure 3.2 shows the surface geology.

3.2 Geological Evolution

Sedimentation in the Surat Basin commenced in the Early Jurassic, approximately 200 million years ago, on an erosional surface, comprising older Triassic, Permian, and Carboniferous rocks (Exon, 1976). Sedimentation has been controlled by sinking of areas overlying older compacting sediments, draping over basement structures, and cycles of marine transgression/regression caused by sea-level changes. The basal Precipice Sandstone was initially laid down in low-lying areas, and following deposition spread over widening areas, with material sourced from eroding elevated blocks in the southwest, northeast and southeast (Exon, 1976).

Jurassic sedimentation was essentially cyclic, with depositional environments from streams, to swamps, lakes and deltas, and finally marine influences evident at the end of some cycles. This cyclic sequence is represented by the fining-upward sequential stratigraphy of the region. During the early Jurassic, deposition was mostly fluvio-lacustrine, while by the Middle Jurassic, coal swamp environments predominated over much of the basin.

Towards the end of the Middle Jurassic (~150 million years ago) fluvial (river) deposition predominated and continued to early Cretaceous times. In the following periods the area experienced a cycle of marine transgression and regression leading to deposition of shallow marine sediments. The subsequent marine regression caused a fairly abrupt return to river, lake and swamp environments before sedimentation ceased in the Early Cretaceous, approximately 110 million years ago.

3.3 Structural Geological Controls

The study area lies within three major structural Mesozoic basins: the Surat Basin to the south and west, which unconformably overlies the Bowen Basin in the north and is separated from the Clarence-Moreton basin by the Kumbarilla Ridge anticline to the east. The Kumbarilla Ridge represents an anticlinal structure. Sedimentary sequences up to 2,500 m thick in the down warped south/southeast to north-northwest trending Mimosa Syncline has been recorded where the Surat Basin overlies the Taroom Trough (Reiser, 1971; Arrow, 2003; URS, 2008).

The Surat Basin stratigraphy is affected by a number of faults and folds. These structures are variously interpreted as fully or partially penetrating through the full geological sequence described above. Major faulting within the Surat basin is generally an expression of boundary faults of the underlying Bowen Basin (Arrow, 2003). Minor Mesozoic faults are also found to the west of the study area. Cainozoic faulting has not been recorded.

Regionally, the Jurassic and Cretaceous sediments dip gently (<5°) to the southwest (Arrow, 2003). This is probably due to continuing basin subsidence and uplift associated with Tertiary volcanic activity (Reiser, 1971). Where Marburg Subgroup sandstone onlaps the Great Dividing Range igneous rocks, the local dip may be as steep as 10°.

3.4 Surface Geology

The surface geology is diverse due to the large extent of the study area (Figure 3.2). However a significant portion of the study area is covered by a deep blanket of unconsolidated colluvium, alluvium and clay. This includes the Condamine alluvium valley fill that occupies eroded valleys in weathered bedrock, with thicknesses up to 140 m (Barnett and Muller 2008).

The characteristics of superficial deposits (alluvium and colluvium) reflect the nature of the source rocks, weathering, transport and depositional conditions. The Brigalow clay sheet blankets the valley floors of the major river valleys. Fine-grained deposits are also associated with erosion of more labile sandstones, siltstones, mudstones and shales. Sandy colluvium, occasionally containing gravels and cobbles, has been transported downslope along the fringes of the Kumbarilla Ridge. Sandy alluvial material is also found along watercourses.

Outcropping consolidated formations are confined mainly to the Kumbarilla Ridge, and the majority of the GAB stratigraphic sequence does not outcrop in the project development area. The most commonly outcropping formations are the older sequences of the Kumbarilla Beds: the late Jurassic Springbok Sandstone and Westbourne Formation. These formations are unconformably overlain by late Jurassic/early Cretaceous Gubberamunda sandstone. Tertiary sandstone outcrops in the north of the study area and laterisation of upland sandstone outcrops is common.

Minor outcrops of igneous rock are found within the project development area. A small Triassic granite dome is present in the south of the project development area. Tertiary basalt caps the mesas close to Captain’s Mountain (in the south) and Guluguba (in the north).

Additional details on the surface geology features within the project development area can be found in the EIS Geology, Landform and Soils Study - Coffey Geotechnics (2011).

3.5 Stratigraphy

The Surat Basin contains sediments up to a maximum thickness of around 2,500 m. Many of the formations present are comparatively consistent and continuous over significant distances; however facies changes and the influence of structural controls and other factors result in the presence of laterally equivalent formations or inter-fingered formations varying in characteristics. Figure 3.3 shows the generalised stratigraphy of the Surat Basin, with a focus on formations present in the project development area. Geological cross-sections are provided in the modelling report (Figures 3.2 and 3.3, Schlumberger 2011) within Appendix B.

Nomenclature – Walloon Subgroup and Injune Creek Group

Geological nomenclature has evolved over time, and variations in terminology are common in publications and reports describing the coal seam geology. The nomenclature adopted in this report refers to the Walloon Subgroup (Jones and Patrick 1981) as comprising (from oldest to youngest) the Taroom Coal Measures, Tangalooma Sandstone, and Juandah Coal Measures. The terms Walloon Coal Measures and Walloons are widely adopted in literature, and where used here are synonymous with the Walloon Subgroup.

The Injune Creek Group comprises (from oldest to youngest) the Eurombah Formation, The Walloon Subgroup, The Springbok Sandstone, and The Westbourne Formation.

The main formations present in the basin are described below, from oldest to youngest.

3.5.1 Precipice Sandstone

The Precipice Sandstone is predominantly comprised of quartzose sandstone, with a thicker, coarser, porous and permeable lower part, and a thinner, finer siltstone bearing upper part. The formation was laid down in a geological cycle with the Evergreen Formation. The formation is over 50 m thick in the Mimosa Syncline area north of Goondiwindi, and exceeds 100 m in the northern part of the Mimosa Syncline (Exon, 1976).

3.5.2 Evergreen Formation

This formation is predominantly siltstone, but sandstone is prevalent in some areas. The formation may be up to 160 m thick, and conformably overlies the Precipice Sandstone however the contact may be difficult to define as the finer-grained part of the upper Precipice Formation grades into the Evergreen Formation (Exon, 1976).

3.5.3 Hutton Sandstone

This Lower Jurassic formation consists of sandstone, generally fine- to medium-grained, and commonly cross-bedded. The formation contains some mudstone and siltstone. In the east, the formation grades into the Marburg Subgroup in the vicinity of the Kumbarilla Ridge where the Surat Basin transitions into the Clarence-Moreton Basin sequence. The formation is commonly 120 m to 180 m thick, but can be more variable than this in parts.

3.5.4 Marburg Subgroup (Marburg Sandstone)

The Marburg Subgroup is used here to refer to the Clarence-Moreton Basin lateral equivalent of the Hutton Sandstone and the Evergreen Formation. These Surat Basin formations can be traced to the west of the Kumbarilla Ridge around the margins of the Surat Basin. The Marburg Subgroup includes the Koukandowie Formation, and outcrops north of Dalby and east of Chinchilla. Lithology generally comprises inter-bedded sandstone and mudstone, and some conglomerate. Marburg Subgroup rocks are commonly referred to as Marburg Sandstone.

Photos 1 & 2 – Marburg Subgroup outcrop near Bell. Bell is located 50 km northeast of Dalby

3.5.5 Eurombah Formation

Underlying the Walloon Coal Measures, this formation comprises poorly sorted very fine to very coarse-grained sandstone. The formation is about 100 m thick in the northwest Surat Basin, but thinner in the east and south.

3.5.6 Walloon Coal Measures (Walloon Subgroup)

In the Surat Basin the Walloon Coal Measures consist of coal interbedded with argillaceous sandstones, siltstones and mudstones along with minor calcareous sandstones, impure limestone and ironstone. The sandstone units are typically very fine-to-medium grained and indurated. The stratigraphy of the Walloon Coal Measures is described in more detail in section 3.6. Maximum thicknesses of around 500 m have been recorded in the vicinity of the Mimosa Syncline, west of Miles. The Walloon Coal Measures are the source of the coal seam gas to be extracted during this project.

3.5.7 Kumbarilla Beds

Kumbarilla Beds is a generic formation term used to describe the heavily weathered outcrop equivalent to the Late Jurassic to Early Cretaceous formations, commonly exposed in a north-south trending high east of Dalby (Kumbarilla Ridge). Within the project development area, the beds are predominantly Jurassic units, comprising the Springbok Sandstone, Westbourne Formation, and Gubberamunda Sandstone (Exon, 1968). The Upper Jurassic Orallo Formation and Lower Cretaceous Mooga Sandstone and Bungil Formation are not clearly present in the Kumbarilla Ridge. Published mapping indicates these formations outcrop further west of the project development area.

3.5.7.1 Springbok Sandstone

The Walloon Coal Measures are unconformably overlain by the Springbok Sandstone and Westbourne Formation (Scott et al., 2004). The Springbok Formation comprises mainly medium to thickly bedded sandstone, with some siltstone and mudstone, and thin coal seams.

3.5.7.2 Westbourne Formation

This is a fine-grained unit comprising siltstone and mudstone, and is observed in some well logs overlying the Springbok Sandstone in the project development area. Subsurface thickness is a maximum of 200 m in the Mimosa Syncline, but thinner to the east (Exon, 1968). In much of the basin, the Gubberamunda Sandstone conformably overlies the Westbourne Formation.

3.5.7.3 Gubberamunda Sandstone

This formation is the uppermost Jurassic unit present in the project development area. The formation comprises cross-bedded sub-labile to lithic sandstone (occasionally carbonaceous), with minor siltstone and conglomerate (Exon, 1968).

3.5.7.4 Bungil Formation, Mooga Sandstone and Orallo Formation

These formations are generally of limited extent in the eastern section of the Surat Basin, and generally absent from the project development area. However inclusion is made because of their occurrence to the west of the project development area, where aquifers within the formations could be potentially impacted by project activities (Exon, 1968).

Published geological mapping indicate that the formations are typically comprised of labile to quartzose sandstone, with siltstones, mudstones, minor conglomerate and coal. Sandstone within the Orallo Formation is cross-bedded. The Orallo Formation demarks the Upper Jurassic system, with the Bungil and Mooga differentiated to the Lower Cretaceous Period.

3.5.8 Tertiary Sediments

Tertiary sediments are present in some areas. The Chinchilla Sand which comprises labile sandstone, conglomerate and sandy clay, is commonly found to the east and southeast of Chinchilla. Other areas of Tertiary surface, notably northwest of Chinchilla, include well to poorly sorted sandstone with siltstone.

3.5.9 Tertiary Main Range Volcanics

The Tertiary Main Range Volcanics are located to the east of the basin and typically occur in a large area on the Great Dividing Range. The Tertiary Main Range Volcanics unconformably overlie the Surat Basin and are volcanic and pyroclastic rocks dating from the Late Oligocene to Early Miocene. Minor basalt outcrops within the project development area also occur to the southwest of Millmerran.

Photo 3 – Outcropping Tertiary Volcanics near Mocattas Corner, located approximately 15 km northeast of Dalby

3.5.10 Condamine Alluvium

The Condamine Alluvium uncomformably overlies the Surat Basin and is present within the project development area, and predominately associated with the Condamine River valley.

Alluvium of the Condamine River has been deposited in valleys formed on weathered bedrock (Barnett and Muller, 2008). Hillier (2010) reports that the river is incised into the Walloon Coal Measures. The sequence of alluvial sediments is up to 150 m thick and is comprised of unconsolidated clay, silt, sand and gravel deposited through fluvial processes associated with the Condamine River and its tributaries (DNRM, 2005).

Diffuse recharge through surface soils of the Condamine River Valley due to rainfall or irrigation recharge is understood to be inhibited by the presence of cracking clay soils that have low permeability due to swelling when wet (Barnett and Muller 2008; Hillier, 2010). However significant focussed recharge is associated with drainage systems, through mechanisms of stream bed leakage. In addition, recharge to the alluvium from bedrock formations occurs particularly in tributaries within the eastern and north-eastern areas of the catchment (Barnett and Muller 2008). Recharge may also occur in the western side of the catchment from the Kumbarilla beds.

3.6 Coal Seam Geology of the Gas Production Fields

The petroleum exploration and production tenements held by Arrow in the Surat Basin extend in an arc from Wandoan in the northwest, towards the Dalby area in the southeast, and then beyond Cecil Plains and Millmerran in the south (Figure 1.2).

Coal seams with potential for gas generation under development in the basin are contained within narrow seams in the Walloon Coal Measures. The stratigraphy of the Walloon Coal Measures (Figure 3.4) comprises carbonaceous mudstone, siltstone, minor sandstone, and coal.

The Walloon Coal Measures are formally sub-divided into the following formations:

- Juandah Coal Measures
- Tangalooma Sandstone
- Taroom Coal Measures
- Durabilla Formation

The Juandah and Taroom Coal Measures are in turn further sub-divided at the seam level, as shown on Figure 3.4. The individual coal seams are separated by a complex sequence of interbedded siltstones, mudstone and sandstones. The coal tends to occur as discontinuous lenses and stringers. The overall thickness of the Walloon Coal Measures stratigraphic sequence in the project development area ranges from 100 m to 500 m.

3.7 Description of Study Area

3.7.1 Surat Gas Project Development Area

The project development area is located within southeast Queensland and encompasses a series of exploration tenures and petroleum lease areas ranging from Wandoan in the north to Goondiwindi in the south. Figure 1.2 shows the project development area, including exploration and petroleum lease tenures.

The project development area includes the existing gas production tenures that have been providing gas to domestic and industrial customers (Tipton West, Daandine, Kogan North and Stratheden gas fields; Figure 1.3).

3.7.2 Landuse and Topography

The topography across the study area is predominantly of low relief, ranging between 200 and 400 metres above Australian Height Datum (mAHD) and overall sloping gently towards the southwest. A ridge, which is part of the Great Dividing Range, and is aligned northwest to southeast and rises up to 1100 mAHD defines the northeast boundary of the study area. This area is characterised by dissected foothills, basalt capped mesas, and sandstone cuestas (Figure 3.5). In the region just west of Dalby, the Kumbarilla Ridge provides some relief and outcropping low ridge features. In the south, remnant basalt capped hills (jumpups) are minor relief features on the plains.

Intensive agriculture and settlement has occurred along the Condamine River valley. Black coal mining, metals processing, oil and gas development, agriculture and forestry are the main land uses in the study area. Agriculture includes intensive irrigation, cropping, poultry farming, feedlots and cattle grazing. The project development area is located within the Brigalow Belt bioregion. This bioregion is characterised by remnant woodland and forest communities of brigalow (*Acacia harpophylla*), with scattered ecosystems dominated by other species including eucalypt and cypress pine, acacia species, and grasslands.

The Condamine River is the main regional river system in the region, and flows north through the Cecil Plains-Dalby area, northwest and west towards Chinchilla, then heading southwest from Condamine, eventually becoming the Balonne River that feeds into the Murray-Darling River system.

3.7.3 Physiography

The landscape within the study area is characterised by several major physiographic regions, which are strongly related to the underlying geology and geomorphological evolution of the area (Figure 3.6). These are detailed below:

- Great Dividing Range highlands, to the east of the study area, comprising resistant igneous rocks (granite and basalt) overlying generally coarse-grained sandstones.
- Kumbarilla Ridge uplands, along the west of the study area, comprising resistant sandstones and finer-grained sedimentary rocks. This ridge is the physiographic expression of the underlying Kumbarilla Ridge anticline. The crest of this structure cuts across the Condamine River valley close to Dalby, whereas the sandstone uplands extend north, to near Guluguba.
- Three major river valleys: the Condamine River, cutting between the Great Dividing Range and the Kumbarilla Ridge; the Dawson River, to the north; and the Border Rivers to the south as discussed below.

The major river catchments each have appreciably different landscape characteristics.

Condamine River

The broad valley of the Condamine River separates the Great Dividing Range, to the east, and the Kumbarilla Ridge, to the west. The Condamine River flows northwards through the Darling Downs, turning west to eventually join the Murray-Darling River system. The valley, at its broadest, is approximately 50 km wide. Where the Condamine River has cut through the Kumbarilla Ridge, to the west of Chinchilla, the valley is appreciably narrower, at about 5 km wide. The valley floor is characterised by densely farmed alluvial and Brigalow plains, which are flat to gently undulating. Gilgai pockmark the plains in the north and south of the valley, where Brigalow clay soils are present and broad expanses of gilgai ground can be found on the valley floor around Brigalow, Chinchilla, Millmerran and Bringalily. Smaller gilgai (termed “crabhole” gilgai”) have generally been levelled for agriculture, but larger gilgai (termed “melonhole” gilgai) are still evident.

Watercourses are generally incised, with well-defined channels that are dissociated from their floodplains, particularly along the fringes of the Kumbarilla Ridge. Downcutting of the watercourses has created a higher-elevation relict floodplain which is no longer inundated (Harris *et al.*, 1999). Some watercourses within the catchment have exploited weaker fault zones, e.g. Mile Creek, which follows a lineament along the southern extent of the Burunga Fault, north-northwest of Miles.

Incision, bank erosion, channel migration and avulsion of the rivers and creeks have left palaeochannel meander scars and terraces within the more recent alluvial deposits. Meander scars are particularly evident on historic aerial images. Depositional features, such as levees and sandbars are also common. These features indicate that, in recent geological times, the watercourses have been dynamic systems.

The uplands are composed of more resistant bedrock. The Great Dividing Range, rising to over 800 mAHD, forms the highest peaks of the region. The Kumbarilla Ridge, in contrast, is generally characterised by more gentle slopes, with maximum elevations of around 420 mAHD. To the north, Tertiary sandstone uplands form a broad cuesta dip-slope, rising to around 380 mAHD. Within the latter, pockets of gilgai clays may be found.

Remnant basalt has formed steep-sided, generally elongated, mesas close to Captain's Mountain. These features have a maximum elevation of over 620 mAHD and can rise approximately 150 m above the surrounding slopes. To the south of Millmerran, resistant sandstone remnants have formed small, steep, rounded hills, known as "jumpups". These can rise approximately 50 m above the more gentle slopes of the Kumbarilla Ridge.

Dawson River

The Dawson River catchment is found in the north of the project development area. The major watercourse, a tributary of the Dawson River, is the Juandah River, flowing northeast through Guluguba and Wandoan. The Juandah River valley is characterised by mesas and cuestas with convex gently to moderately sloping Brigalow plains leading to the valley floor. The mesas are capped by basalt, whereas the cuestas are capped by gently dipping laterised sandstone. Basalt does not outcrop widely in this area.

The watercourses are similar in morphology to those of the Condamine River catchment, being generally incised, and having well-defined channels. Sandy alluvium has been deposited along the valley floors adjacent to the creeks.

The catchment is grazing land and is not intensively farmed.

Border Rivers

The Border Rivers catchment is found in the south of the project development area. Major watercourses include Wyaga Creek and Commoron Creek, which flow southwest towards Goondiwindi. The catchment within the project development area falls within two broad terrain types: uplands associated with the sandstone Kumbarilla Ridge falling to broad Brigalow clay and sandy alluvial plains.

Along the western flanks of the Kumbarilla Ridge, resistant sandstone has formed distinct ridges and swarms of jumpups. These ridges and individual hills can rise approximately 40 m to 100 m above the surrounding slopes. The valley floor is generally covered by the thick Brigalow clays. Pockets of melonhole and crabhole gilgai occur. Some gilgai have been levelled for agriculture, but many remain.

Adjacent to the major watercourses, sandy alluvium has been deposited over the floodplain areas. Linear relict fans, terraces and levees composed of reworked alluvium indicate the dynamic nature and down-cutting of the watercourses in recent geological times (Thwaites and Macnish, 1991).

Occasional low, elongated relict dune ridges may also be found on the valley floor.

The Border Rivers catchment, within the project development area, is drier than the Condamine River and Dawson River catchments, being further inland and within the rain-shadow of the Kumbarilla Ridge. The lower rainfall, micro-relief and sandy soils of the area are not conducive to intense arable cropping, and consequently grazing predominates.

3.7.4 Climate

The study area is characterised as temperate with a warm to hot summer.

Table 3.1 presents the mean monthly rainfall (based on 1992-2008 data, considered representative of the climate conditions in the project development area) from the Dalby Airport (Bureau of Meteorology (BOM) Station number 41522) and potential evaporation data for the Daandine area.

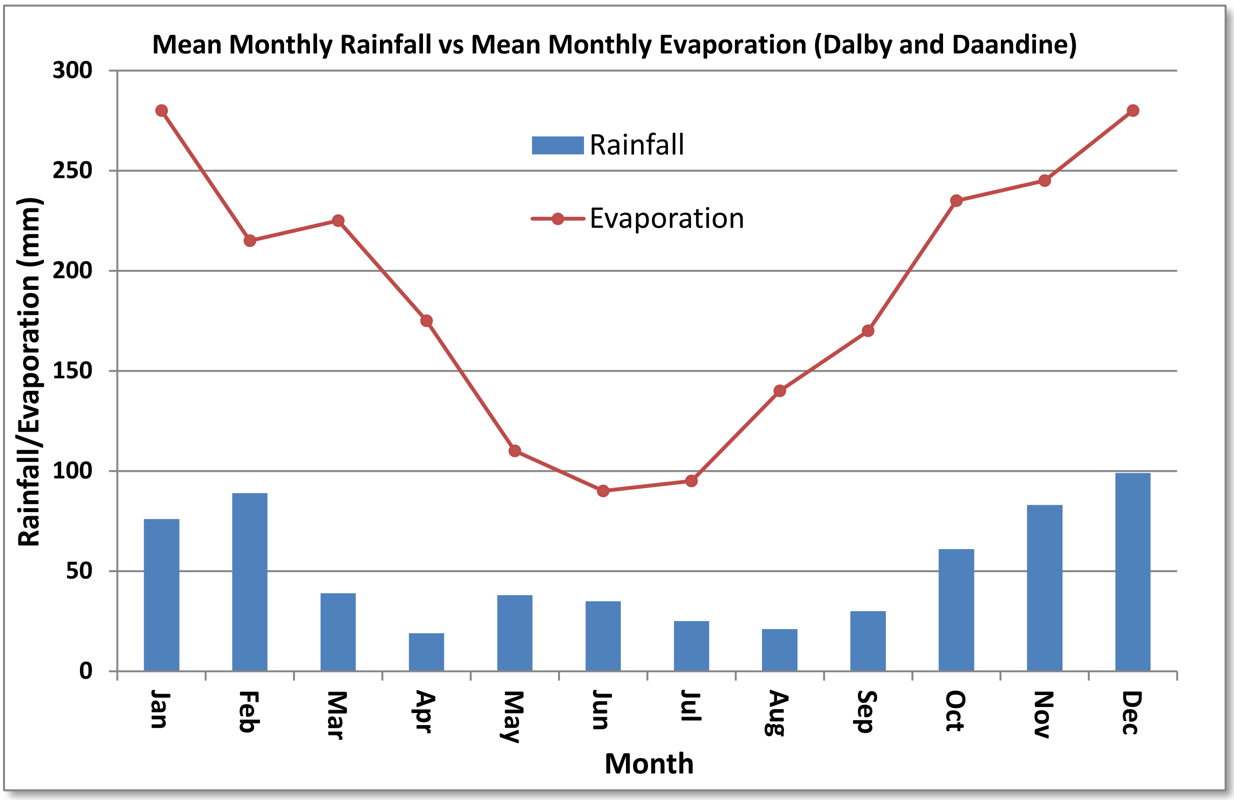
The yearly climate pattern is illustrated in Chart 3.1. Monthly mean evaporation data (Chart 3.1) when compared with the rainfall data shows a seasonal water deficit.

The mean annual evaporation is approximately 2260 millimetres (mm). The mean maximum monthly temperature ranges from 19.7 degrees Celsius (^{o}C) in winter to 32.5^{o}C in summer.

Table 3.1 – Mean climate characteristics

Precipitation (mm)	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Mean	76	89	39	19	38	35	25	21	30	61	83	89	615
Source: Bureau of Meteorology data (www.bom.gov.au) – Dalby Airport (Station number 41522) Nov 2009													
Evaporation (mm)	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Annual**
Mean	280	215	225	175	110	90	95	140	170	235	245	280	2260
Source: Bureau of Meteorology (www.bom.gov.au) – Daandine area (Nov 2009)													

Chart 3.1 – Monthly rainfall versus monthly evaporation



3.7.5 Climate Change

Climate change and the relationships between rainfall and evaporation have implications for groundwater recharge rates.

Investigations into climate in the Condamine-Balonne River system found that the very recent climate (ten-year period from 1997 to 2006) was not statistically different from the long-term average climate for the region (CSIRO, 2008).

CSIRO (2008) provides estimated effects of different climate change scenarios for the Condamine-Balonne region based on a range of future climate models. The results found uncertainty in relation to change, some models predicting a dryer climate, some wetter.

The estimated effects are summarised in Table 3.2.

Table 3.2 – Forecast climate change scenarios - 2030

Component	Scenario		
	Dry	Best Estimate*	Wet
Rainfall	-9% ⇩	**-3% ⇩**	7% ⇧
Runoff	-20% ⇩	**-9% ⇩**	26% ⇧
Evapotranspiration	-9% ⇩	**-2% ⇩**	6% ⇧

*Notes: * = median value*

The largest uncertainty in the forecast future climate results is from the projections of global warming on local rainfall. However the median (best estimate) scenario provided by CSIRO modelling indicates a 3% reduction in rainfall for the region and a 2% reduction in evapotranspiration.

In the more extreme dry climate change scenario, by 2030 it was predicted that:

- Average surface water availability could decrease by 26%.
- Surface water diversions could decrease by 16%.
- End-of-system flows could decrease by 35%.
- The relative level of use under the current water sharing arrangements could increase by 60%.

Irrespective of the scenario, groundwater extractions will remain important for the viability of the region, and demand for groundwater will remain high. Rainfall recharge to groundwater could either increase or decrease as a result of climate change; however, it is thought that any change would not exceed 10% (CSIRO, 2008).

Although climate change impacts on groundwater resources are likely to be minor, changes to extraction rates are likely to be large in comparison (CSIRO, 2008).

4 HYDROGEOLOGY

4.1 Overview – Regional Groundwater

4.1.1 The Great Artesian Basin

The GAB is one of the larger artesian groundwater basins in the world and forms Australia's largest contiguous groundwater resource. The GAB extends across 1.7 million km^2 or about 22% of Australia, and underlies parts of Queensland, New South Wales, South Australia and the Northern Territory. The GAB underlies arid and semi-arid regions and consists of low-lying interior plains and is largely within Australia's rangelands. Rainfall is variable and ranges from an annual average of 600 millimetres per year (mm/year) near the eastern margins to less than 100 mm/year near the south-western parts of the GAB. Potential evaporation reaches almost 4,000 mm/year in some areas (BOM 2010).

The GAB comprises a multi-layered confined aquifer system, with aquifers in Triassic, Jurassic and Cretaceous continental quartzose sandstones (Habermehl, 2002) and complex stratigraphy. The basin is up to 3000 m thick, and forms a large synclinal structure, uplifted and exposed along its eastern margin, and tilted southwest. Recharge occurs mainly in the eastern marginal zone, an area of relatively high rainfall, and large scale regional groundwater movement is generally towards the southern, south-western, western and northern margins (Figure 4.1). Natural discharge occurs in some areas (typically margin areas) from flowing artesian springs, many of which have built up mound-shaped deposits of sediments or carbonates.

Abundant artesian groundwater of good quality is exploited from aquifers in the Lower Cretaceous-Jurassic sequence. The hydrogeological GAB comprises the geological Eromanga, Surat and Carpentaria sedimentary basins and parts of the Bowen, Clarence-Moreton, and Galilee sedimentary basins.

The majority of the project development area encompasses the Surat Basin, and the eastern portion overlaps the Clarence-Moreton Basin as illustrated in Figure 3.1. The Surat Basin contains up to 2,500 m of mainly Jurassic clastic continental sedimentary rocks and lower Cretaceous marine beds largely obscured by Cainozoic alluvium.

The key GAB aquifers in the project development area are described in the following sections.

4.1.2 Overview of the Project Development Area Aquifers and Hydrogeology

Regional hydrogeological information compiled in the explanatory notes (Exon, 1976) provides an overview of aquifers and groundwater use in the project development area.

The main confined aquifers of groundwater resource potential and development present in the project development area include the Precipice Sandstone, Hutton Sandstone, Marburg Subgroup, Springbok Sandstone and Gubberamunda Sandstone. These units have significant groundwater transmissivity and storativity. Variations in stratigraphy are seen in areas more distal to the project development area, and as a result other formations are important as resource aquifers in these areas.

The Walloon Coal Measures form a mixed porous-media/fractured rock aquifer with low-permeability layers, and has resource potential in some areas, particularly in the vicinity of groundwater recharge zones. Elsewhere, poor groundwater quality and/or low-permeability generally limits the groundwater development potential of this formation. Better water quality is observed towards Toowoomba, where recharge occurs, with groundwater flow westwards from this recharge area (Hillier, 2010) and a correspondent deterioration in water quality.

4.1.3 Review of Groundwater Information in the DERM Database

Available geological and hydrogeological information was compiled for the project development area. The available data allowed for an initial assessment of the groundwater resources associated with these units. Section 4.5 provides a summary of groundwater quality data contained within the DERM database. The DERM database was extracted on 6 October 2009 and is considered to be representative of the project area.

It is recognised that the DERM groundwater database contains data which has not been fully validated or verified. Hence, certain inaccuracies are expected. However, the available data is considered sufficient to allow for an initial level assessment of the baseline hydrogeological characteristics for each geological unit within the project development area.

4.2 Surat Gas Project Development Area Resource Aquifers

The project development area contains both unconfined and confined aquifers. Major aquifer formations (i.e. those containing moderate to high transmissivity and satisfactory storage) include:

- Precipice Sandstone aquifer.
- Hutton Sandstone/Marburg Subgroup aquifer.
- Walloon Coal Measures aquifer.
- Springbok Sandstone aquifer.
- Gubberamunda and Mooga Sandstone aquifers.
- Condamine Alluvium aquifer.

These aquifers can be further classified as either shallow, intermediate, coal seam or deep groundwater systems.

- ***Shallow Groundwater Systems.*** Quaternary unconfined or water table aquifers. They include the Condamine Alluvium aquifer.
- ***Intermediate Groundwater Systems.*** Confined aquifers located above the coal seam formations. They include the Gubberamunda Sandstone, Mooga Sandstone and Springbok Sandstone.
- ***Coal Seam Groundwater Systems***. Confined aquifers associated with coal seam gas formations. They include the Walloon Coal Measures, but commonly with low permeability and/or low water quality.
- ***Deep Groundwater Systems.*** Confined porous aquifers located below the coal seam gas formation. They include the Marburg Subgroup, Hutton Sandstone and Precipice Sandstone.

Some of these formations (i.e. Condamine Alluvium aquifer) generally have useful characteristics that make good resource aquifers, such as high permeability (hydraulic conductivity), substantial thickness, good storage characteristics, consistent characteristics over large distances, and good quality groundwater. The Walloon Coal Measures are variable and have low permeability sediments and poor water quality in some areas.

Other geological formations are present, however due to their lower permeability they function as aquitards or confining layers. Figure 4.2 illustrates the relationship between aquifer formation and confining formations within the project development area sedimentary sequence of the Surat basin.

4.2.1 Confined Aquifers

Groundwater is found extensively throughout the study area in confined aquifers. A confined aquifer typically occurs in the sub-surface when a permeable formation (e.g. sandstone) is overlain by a low-permeability formation (e.g. clay or siltstone). The characteristics of the confined aquifers are described below.

4.2.1.1 Precipice Sandstone

Figure 4.3a presents the distribution of boreholes constructed within the deep aquifers. In many areas the Precipice Sandstone can produce substantial quantities of high quality groundwater from high permeability beds. The significant depth (approximately 250 m) of this aquifer limits development in the project development area.

4.2.1.2 Hutton Sandstone and Marburg Subgroup

The Hutton Sandstone/Marburg Subgroup is lithologically distinct from the Walloon Coal Measures, typically consisting of porous and permeable medium to coarse grained quartzose sandstone. These characteristics make it a significant aquifer in the region.

The Eurombah Formation represents a distinct transition between the Hutton/Marburg and Walloon Coal Measures. It consists of inter-bedded siltstones and fine-medium sandstones with very low permeability. The sands are generally labile and high in clay content.

4.2.1.3 Walloon Coal Measures (Walloon Subgroup)

Figure 4.3b presents the distribution of boreholes that access the aquifers within the Walloon Coal Measures. Additional details of the aquifers within the Walloon Coal Measures are provided below.

Juandah Coal Measures

The Kogan seam package is the uppermost member of the Juandah Coal Measures. In many areas it has been removed by erosion from either the overlying Springbok Sandstone or the Tertiary Alluvium. The Kogan seam package generally contains between one and three coal seams with the non-coal material generally grey to dark grey massive to laminated siltstones and grey lithic sandstones. The average gross formation thickness of the Kogan seam package is 35 m. The Macalister seam package generally consists of one to two well developed seams with a number of smaller stringers. The Macalister seam package contains the highest percentage of coal of all the Walloon Coal Measure packages. In some areas the Macalister seams have also been eroded. This may be more significant in terms of downward leakage than erosion of the Kogan as the Macalister is thicker.

The Wambo seam package generally consists of thin, poorly correlated coal seams. It generally contains more silt than the overlying Macalister seam package and averages 55 m thick in the project development area. The Iona seam package generally consists of a small number of relatively thin coal seams. The Iona seam package is the thinnest unit of the Walloon Coal Measures with an average gross thickness of only 28 m over the project development area. The Argyle seam package usually consists of one or two major coal-dominated intervals with banded coal and mudstone. The base of the

Argyle seam package grades into the Tangalooma Sandstone and in eastern parts of the basin are treated by Arrow as one cyclic package. On average, the Argyle seam package including the Tangalooma Sandstone is 66 m thick.

Tangalooma Sandstone

The Tangalooma Sandstone is well developed in the west of the basin, west of the project development area, where it is up to 100 m thick. In the project development area, the Tangalooma Sandstone is very discontinuous and consists of individual sand lenses rather than a consistent sheet and therefore has not been mapped.

Taroom Coal Measures

The Taroom Coal Measures (Auburn, Bulwer and Condamine seam packages) are on average 121 m thick. The Auburn and Bulwer seam packages of the Taroom Coal Measures are not differentiated by Arrow for the purposes of stratigraphic mapping. The Auburn seam package is generally a thick zone of thin coal seams that are very similar to the Argyle seam package in their distribution. The Bulwer seam package is usually difficult to differentiate as a separate seam, but in some cases it forms a relatively thick and continuous seam. The Condamine seam package is occasionally present as a well developed single seam up to 10m thick. It is not however consistent enough to be used as a basin wide marker.

4.2.1.4 Springbok Sandstone

Figure 4.3c presents the distribution of boreholes constructed within the intermediate aquifers. The Springbok Sandstone is an aquifer that can produce substantial quantities of groundwater from high permeability beds. Certain coarse-grained parts of the formation are informally called the “Proud Sandstone”. This unit forms an excellent aquifer, and where in close contact with the coal seams it is often ‘gas charged’ due to leakage of coal seam gas from the Walloon Subgroup (Scott et al., 2006).

4.2.1.5 Westbourne Formation

The Westbourne Formation is an aquifer that consists of interbedded low permeability shales and siltstones and higher permeability quartzose sandstone.

4.2.1.6 Gubberamunda Formation

The Gubberamunda Sandstone consists of medium and coarse-grained, virtually un-cemented quartzose sandstone. The sandstones are permeable and form a major freshwater aquifer, but become finer grained towards the west. This unit is less than 100 m thick, but it increases to greater than 200 m in the central sections of the basin.

4.2.2 Unconfined Aquifers

Groundwater is also found extensively throughout the area in unconfined aquifers, also known as watertable aquifers. An unconfined aquifer exists in the sub-surface where groundwater in an aquifer is free to rise and fall as water is added (recharge) to the system or removed (discharge). The first occurrence of saturated groundwater conditions below the ground surface is normally an unconfined aquifer. Figure 4.2 illustrates the typical relationship between the unconfined aquifers in the project development area, and the deeper confined aquifers.

The Condamine Alluvium forms the main unconfined aquifer in the project development area. From a review of the DERM records, a total of 1522 boreholes within the project development area were identified as completed in the alluvium. The limited and incomplete records indicate a mean construction depth of 30 m. Figure 4.3d presents the distribution of boreholes constructed within the alluvium. Groundwater levels measured in the shallow bores constructed within the alluvium range from 290 mAHD to 605 mAHD.

4.3 Groundwater Levels

The relatively long period of groundwater development within the Surat Basin (pre 1900 to 2010) has seen a large scale decline in groundwater pressure or levels (i.e. head) within the primary sandstone aquifers such that the majority of once artesian bores have ceased to flow with sub-artesian levels prevailing (Henning, 2005). However, the recent government initiative of capping freely flowing artesian bores (typically located at significant distances from the project development area) has restored some of this pressure decline within certain areas. In addition, analysis of records and hydrographs show that the watertable within the Condamine Alluvium has also been trending downwards over the past 40 years due to groundwater extraction exceeding recharge (Hillier 2010).

Available groundwater monitoring data (primarily sourced from the DERM database) indicates that significant perturbation (marked by the initiation of mining projects and coal seam gas projects in the area) of the groundwater levels measured in the Walloon Subgroup and adjacent strata is observed from approximately 1995. This date was therefore used to define the two datasets, a pre 1995 group and a post 1995 group. Each dataset is described briefly below and is considered representative of the groundwater level conditions in the project development area.

4.3.1 Groundwater Levels: Pre 1995

Figures 2.22 to 2.31 in Appendix B present the distribution of data points and the contoured groundwater levels for the key resource aquifers with the study area.

Shallow Aquifers

Groundwater data in the Condamine Alluvium show a roughly westerly to south-westerly gradient, with lower groundwater levels (300 mAHD) to the northwest and higher levels in the southeast (400 mAHD) indicating that groundwater flow is generally to the northwest (Figure 2.22, Appendix B).

Intermediate Aquifers

The Kumbarilla Beds are restricted to the project development area and in the vicinity immediately to the west. The groundwater elevations are more uniform than observed in other units, but peak at about 400 mAHD around the Dalby and Millmerran resource areas and reduce to around 250 mAHD to the south and 300+ mAHD to the north. The dominant groundwater flow direction appears to be to the southwest (Figure 2.23, Appendix B).

The major regional flow direction in the Gubberamunda Sandstone appears to be from the north to south with potential localised flow system in the vicinity of the most northerly Arrow project development area where the flow is from south to north. The groundwater levels in the majority of the basin are between 350 and 250 mAHD (Figure 2.25, Appendix B).

The contoured groundwater levels in the Springbok Sandstone show a general flow direction from northwest to southeast (Figure 2.27, Appendix B). As with the Gubberamunda Sandstone a localised flow system is defined to the west of the most northerly portion of the project development area. In this region the primary groundwater flow direction is from the west and south to the north. The highest groundwater levels are found in the northwest (over 400 mAHD) and the lowest to the north east (less than 250 mAHD).

Walloon Coal Measures (Walloon Subgroup)

The Walloon Coal Measure contours indicate high groundwater levels where recharge areas outcrop (over 500 mAHD) in the vicinity of the eastern highlands (Figure 2.28, Appendix B). The contours indicate two flow directions moving away from the recharge area. One groundwater flow direction is to the east (Lockyer Valley), reaching approximately 50 mAHD, and the other to the west, reaching about 300 mAHD.

Deep Aquifers

The Hutton Sandstone and Marburg Subgroup pressures are similar to the Walloon Coal Measures in the vicinity of the Arrow project development area and to the east (Figure 2.29, Appendix B). To the north and northwest the Hutton Sandstone and Marburg Subgroup trends are similar to the shallower Gubberamunda and Springbok Sandstones. Two main flow components are evident: one from north to south and another from northwest to northeast.

The Precipice Sandstone displays higher groundwater levels to the north which are associated with outcrop at Carnarvon Gorge (above 550 mAHD) and a steep gradient from that area to the southwest into the Dawson River catchment (below 250 mAHD). In the southeast there is a substantial gradient to the east and northwest (Figure 2.31, Appendix B).

4.3.2 Groundwater Levels: 1995 – 2009

Schlumberger 2010 (see references) presented the distribution of data points and the contoured groundwater levels for the period 1995 to 2009. The discussion below provides references to specific figures from that report. Note that these figures are not presented in Schlumberger 2011 in Appendix B.

Shallow Aquifers

The Condamine Alluvium groundwater levels show a reduction in groundwater level from 1995 onwards (Figure 2.29 in Schlumberger, 2010). The drawdown ranges from a few centimetres to 10 m. This variation is likely to relate to abstraction of water for irrigation and other purposes, as well as long-term low residual recharge due to low rainfalls.

Intermediate Aquifers

There are two bores completed in the Orallo Formation and both are located on the western edge of the Wandoan resource area, otherwise this formation is not generally present across the project development area. Although only a few groundwater levels have been recorded since 2001, they show no significant variation over time. Also, relatively stable groundwater levels have been recorded in the Kumbarilla Beds in the Wandoan resource area between 2001 and 2006 (Figure 2.30 in Schlumberger, 2010).

Two bores assigned to the Westbourne Formation show no significant groundwater level reductions with time. One is located in the Dalby resource area and provides a long time series with levels at about 330 mAHD. The other is to the south, within Millmerran resource area and returns a level of about 410 mAHD (Figure 2.31 in Schlumberger, 2010).

East of the Millmerran resource area, hydrographs for two bores completed in the Springbok Sandstone, both describe a general decline in groundwater elevation over most of the data record, with a small recovery in recent years (2006 to 2009) (Figure 2.32 in Schlumberger, 2010).

Walloon Coal Measures

Seven time series datasets have been identified as being within the Walloon Coal Measures. They are concentrated around the Dalby and Millmerran resource areas and most show little variation in observed groundwater level from 1995. However two bores in the east do show significant variation in hydraulic head over time (Figure 2.33 in Schlumberger, 2010).

Data from one bore (Daandine 2) provides a time series from 2005 to 2007 and captures the effects of the initial Arrow coal seam gas operations in the area (i.e. drawdown in groundwater levels). Daandine 2 records show nearly 30 m of drawdown. At this location from 2005 to 2006 drawdown increases quite slowly (at a rate of about 2.5 metres per year (m/year)). In the following two years observed drawdown increases at a rate of about 12.5 m/year.

Deep Aquifers

Four bores are located within the Hutton and Marburg Sandstones. None show any significant change in groundwater level over the observation time period. The two locations to the east return higher groundwater level observations than those to the south. This is comparable with the pre-1995 observations.

4.3.3 Inter-aquifer Flows

Groundwater movement (prior to commencement of coal seam gas abstraction activities) within the major confined aquifers of the Surat Basin is dominated by horizontal flow through permeable aquifers. The low-permeability confining layers (aquitards) that separate aquifer formations (and vertical anisotropy) restrict interconnection and hence flow between aquifers. However, inter-aquifer flows may occur where there is direct aquifer connectivity – and this may occur where confining layers are thinner, or eroded prior to subsequent deposition. In addition, if significant head differences exist between aquifers, then inter-aquifer flows can occur. Where theses head differences are localised such flows may be insignificant. However large head differences over large areas can lead to significant inter-aquifer flow.

4.3.4 Groundwater Recharge and Discharge

Indicative groundwater flow within the GAB is shown in Figure 4.1. Most recharge occurs along the elevated eastern margin of the basin where the sandstones are exposed and average rainfall is relatively high (Habermehl, 2002). The ‘intake beds’ extend in a continuous arc from east of Goondiwindi to the top of Cape York Peninsula. Hydraulic gradients are steep in the higher rainfall recharge areas, and recharge rejection is known to occur, where infiltration potential exceeds aquifer recharge needs. Recharge to the shallow alluvium aquifer occurs from river recharge, and direct infiltration of precipitation from the ground surface.

Groundwater losses occur by means of natural discharge in the form of springs along distal GAB margins, and as artificial discharge by way of pumped extraction from groundwater bores.

4.3.5 Surface Water/Groundwater Interaction

Within the project development area, groundwater tables are generally well below stream bed levels and groundwater baseflow to streams is limited. Water balances for the Condamine Alluvium aquifer indicate significant aquifer recharge from river bed leakage, but little or no baseflow discharge to streams (Barnett and Muller 2008; Hillier 2010).

4.4 Hydrogeological Parameters of Aquifers within the Surat Gas Project Development Area

Based on a literature review focussed on the hydraulic characteristics of the geological formation of the Surat and Clarence Moreton Basins a set of hydraulic parameters have been derived. These are shown in Table 4.1

Table 4.1 – Aquifer characteristics in the project development area

Hydrogeological Unit	Horizontal Hydraulic Conductivity (m/day)	Kv:Kh Ratio	Specific Storage (m^{-1})
Condamine River Alluvium	5 **(0.01 – >30)**	1:10	0.05 **(0.04 – $5x10^{-6}$)**
Gubberamunda Sandstone	0.5 **(0.1 – 5)**	1:10	$5x10^{-6}$ **($1x10^{-4}$ – 10^{-7})**
Kumbarilla Beds	0.1	1:50	$5x10^{-6}$
Westbourne Formation	0.001	1:100	$5x10^{-6}$
Springbok Sandstone	0.5	1:10	$5x10^{-6}$
Juandah Coal Measures	0.001 **(0.0001 – 1)**	1:100	$5x10^{-6}$ **($6x10^{-5}$ – $6x10^{-7}$)**
Tangalooma Sandstone	0.1	1:50	$5x10^{-6}$
Taroom Coal Measures	0.001 **(0.0001 – 1)**	1:100	$5x10^{-6}$
Durabilla/Eurombah Formation	0.05 **(0.03 – 0.14)**	1:50	$5x10^{-6}$
Hutton Sandstone	0.1 **(0.05 – 1.25)**	1:50	$5x10^{-6}$ **($3x10^{-5}$ – $1x10^{-6}$)**
Evergreen Formation	0.001 **(0.008)**	1:100	$5x10^{-6}$
Precipice Sandstone	1 **(0.1 – 4)**	1:10	$5x10^{-6}$ **($5x10^{-6}$ – $1x10^{-7}$)**
Triassic (upper 200m)	0.0001	1:50	$5x10^{-6}$

Documented range in brackets. Documented range determined from literature values (Schlumberger 2011).

4.5 Groundwater Quality and Resource Development

4.5.1 Great Artesian Basin Groundwater Quality

As discussed above, recharge to the GAB aquifers takes place in outcrop areas along the eastern margins of the Surat Basin. As fresh water migrates along the flow path through different aquifers it dissolves and interacts with minerals. These processes, amongst others, account for the variability in groundwater quality throughout the basin.

In general, GAB groundwater is dominated by sodium-bicarbonate (Na-HCO_3) type water in the eastern and central part of the basin. In the western areas of the GAB, chloride and sulphate dominate the chemistry. Sodium and bicarbonate increase in concentration from the north-eastern margins to the south-western discharge areas along the regional flow path (Herczeg et al., 1991). These chemical trends are caused by mass transfer reactions involving cation exchange of Na for Ca-Mg, carbonate dissolution and reactions between Na and kaolinite to form Na-smectite.

Herczeg et al. (1991) explored several processes to explain the increasing TDS content down-gradient including:

- Mixing of dilute recharge waters with saline waters present within deeper parts of the basin;
- Ion-filtration through shale membranes;
- Dissolution of evaporites, carbonate minerals or incongruent dissolution of feldspars, micase or clay minerals.

However it was concluded that a combination of evapotranspiration within the recharge areas and mineral dissolution provided the most plausible mechanisms for the chemical trends observed (Herczeg et al. 1991).

4.5.2 Groundwater Quality in the Surat Gas Project Development Area

Groundwater quality from aquifers in the project development area was assessed by analysing available groundwater quality data in the DERM database. It should be noted that groundwater quality data included in the following sections dates as far back as the 1960s. It is considered that this data is generally representative of current groundwater quality in the relevant formations, and that the data set considers a timeframe relevant to the study. The formation names below are as noted in the DERM database.

4.5.2.1 Undifferentiated Alluvium Unit

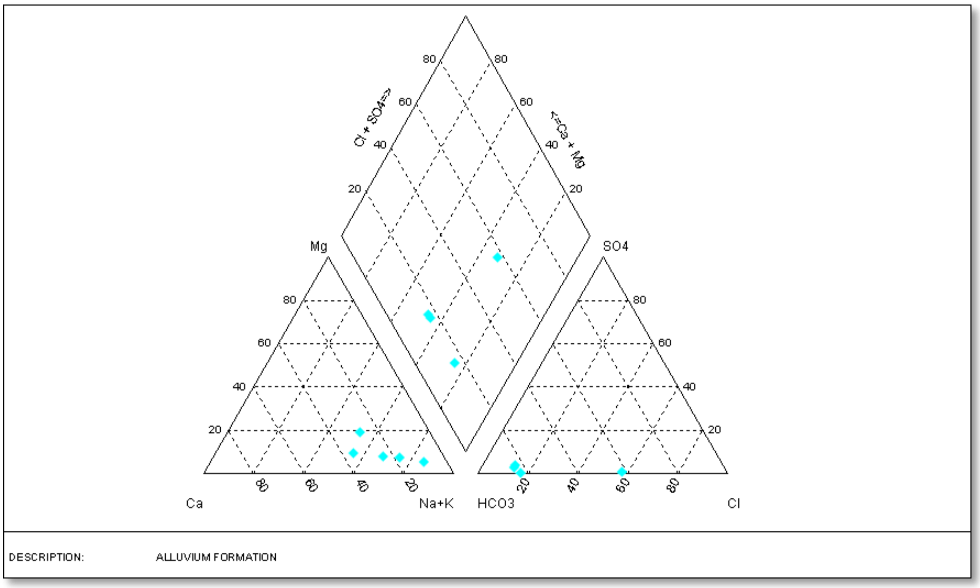


Table 4.2 – Summary of groundwater quality in the undifferentiated alluvium aquifers

Parameter	Unit	Min	Max	Average	No. Samples
pH		7.1	8.2	7.8	5
Conductivity	µS/cm	410	1700	896	5
TDS	mg/L	266	1105	582	5
Ca	mg/L	25	57	36	5
Mg	mg/L	5	12	9	5
Na	mg/L	57	355	156	5
Cl	mg/L	25	248	114	5
HCO_3	mg/L	229	664	367	5
SO_4	mg/L	2.4	9.5	6.9	3

Note: Ca = Calcium, Mg = Magnesium, Na = Sodium, Cl = Chloride, HCO_3 = Bicarbonate, SO_4 = Sulphate

There is limited data (5 samples in total) for the undifferentiated alluvium but the available hydrochemical results indicate variable groundwater quality, which is alkaline and sodium bicarbonate dominant. The pH varied from 7.1 to 8.2 and conductivity from 410 to 1,700 microSiemens per centimetres (µS/cm) (typical of freshwater). The average concentration of sodium is 156 milligrams per litre (mg/L), ranging from 57 to 355 mg/L. Bicarbonate concentrations range from 229 to 664 mg/L.

4.5.2.2 Condamine River Alluvium

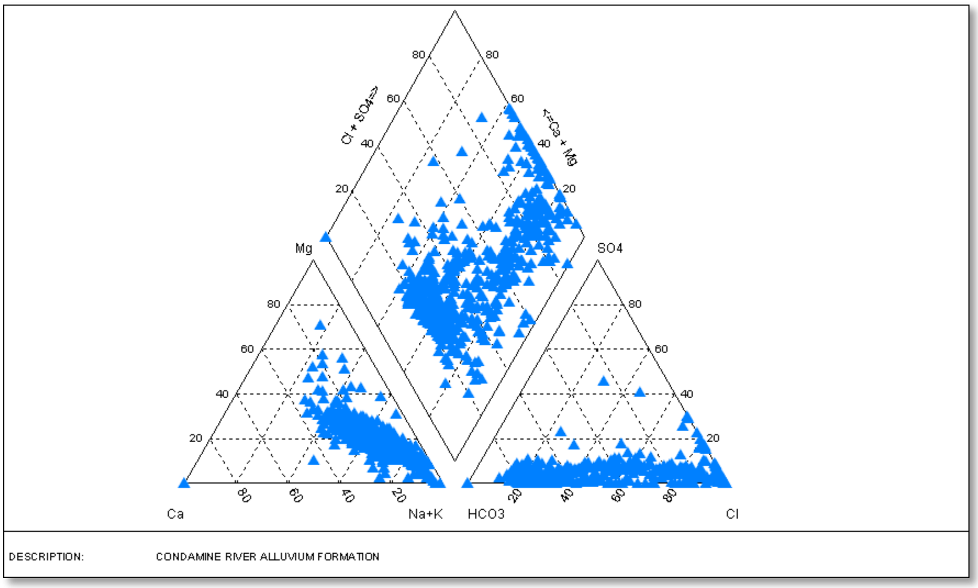


Table 4.3 – Summary of groundwater quality in the Condamine Alluvium aquifer

Parameter	Unit	Min	Max	Average	No. Samples
pH		5.6	9.7	7.9	534
Conductivity	µS/cm	225	32,790	2,095	531
TDS	mg/L	146	21,313	1,361	531
Ca	mg/L	0.2	1,426	56	574
Mg	mg/L	0.1	1,020	49	565
Na	mg/L	7.1	5,775	353	572
Cl	mg/L	7	12,642	526	575
HCO_3	mg/L	0.4	1,179	372	546
SO_4	mg/L	0.3	826	56	513

Note: Ca = Calcium, Mg = Magnesium, Na = Sodium, Cl = Chloride, HCO_3 = Bicarbonate, SO_4 = Sulphate

The hydrochemistry data indicate a range in groundwater quality within the Condamine Alluvium. The chemistry is dominated by sodium cations, with some magnesium but in general this variability is associated with the evolution of water chemistry and the influences of recharge processes involving surface water and deeper groundwater sources. The water types within this aquifer are classified from sodium-chloride (predominant) to sodium-bicarbonate and magnesium-bicarbonate. The groundwater within this aquifer is generally slightly alkaline with a pH average of 7.9 and ranges from pH 5.6 to 9.7. The conductivity ranges from 225 to 32,790 µS/cm, indicating that groundwater in this unit ranges from fresh to very saline. The average concentration of sodium is 353 mg/L and ranges from 7.1 to 5775 mg/L. The average chloride and bicarbonate concentrations are 526 and 372 mg/L respectively.

Dissolved metal concentrations vary and elevated iron and manganese are recorded (DERM database information). These results indicate that the groundwater associated with the alluvium is typically not potable and in some cases has limited suitability for use.

4.5.2.3 Hutton Sandstone

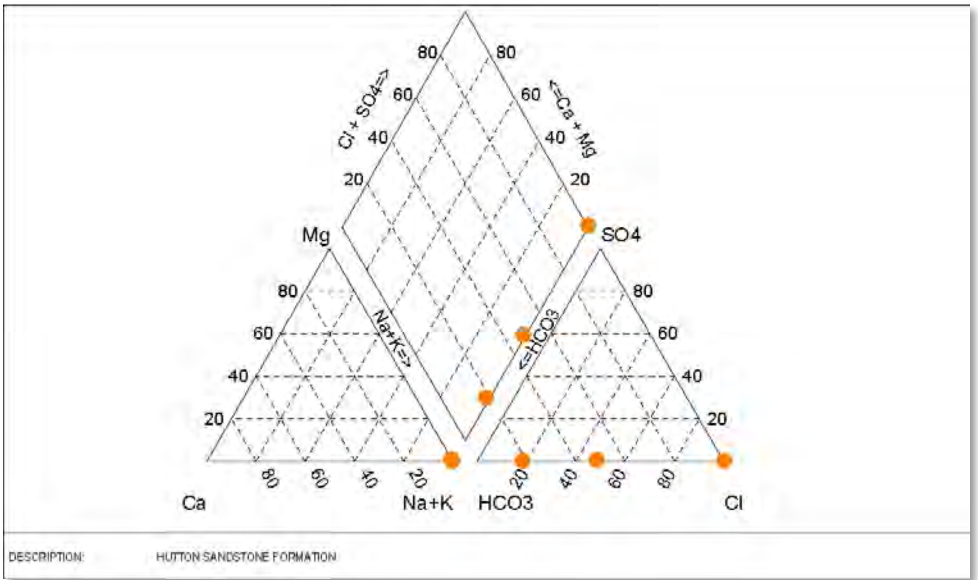


Table 4.4 – Summary of groundwater quality in the Hutton Sandstone aquifer

Parameter	Unit	Min	Max	Average	No. Samples
pH		7.9	8.6	8.4	3
Conductivity	µS/cm	2,900	3,100	2,000	2
TDS	mg/L	1,885	2,015	1,950	2
Ca	mg/L	4.2	5.7	4.8	3
Mg	mg/L	1.4	4.4	2.5	3
Na	mg/L	700	915	795	3
Cl	mg/L	210	735	488	3
HCO_3	mg/L	980	1,650	1315	2
SO_4	mg/L	0	7.6	2.5	3

Note: Ca = Calcium, Mg = Magnesium, Na = Sodium, Cl = Chloride, HCO_3 = Bicarbonate, SO_4 = Sulphate

There is limited data (3 samples in total) for the Hutton Sandstone but the available hydrochemistry data indicate variable groundwater quality. The groundwater is alkaline (ranging from pH 7.9 to 8.6) and is classified as sodium, chloride and bicarbonate type water. The conductivity ranges from 2,900 to 3,100 µS/cm indicating groundwater in this unit is fresh to brackish. Sodium concentrations range from 700 to 915 mg/L. Concentrations of chloride and bicarbonate range from 210 to 735 mg/L and 980 to 1,650 mg/L respectively.

4.5.2.4 Kumbarilla Formation / Beds

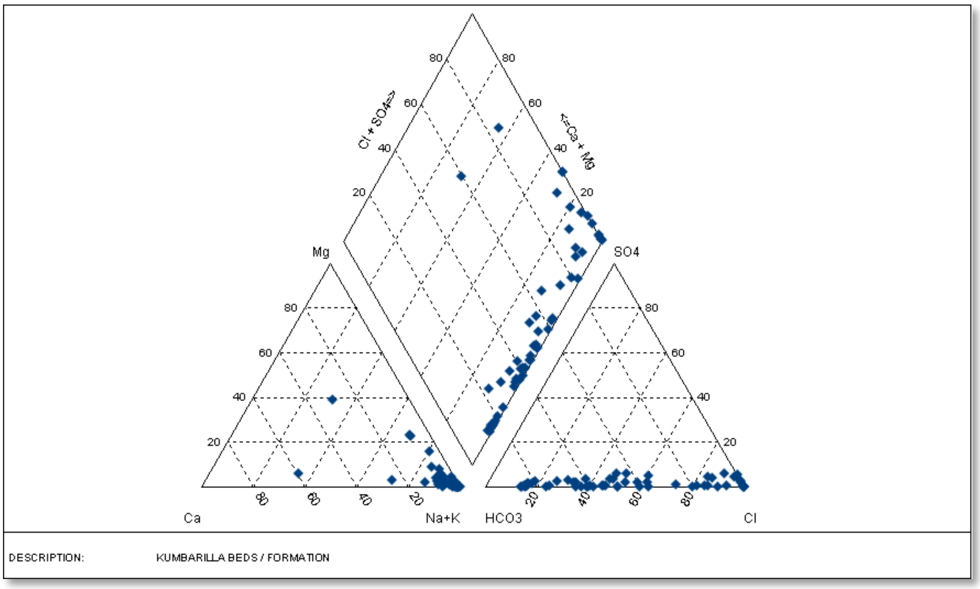


Table 4.5 – Summary of groundwater quality in the Kumbarilla Formation aquifer

Parameter	Unit	Min	Max	Average	No. Samples
pH		6.5	11	8.2	63
Conductivity	µS/cm	560	10,300	2,141	58
TDS	mg/L	364	6,695	1,391	58
Ca	mg/L	0	800	50	67
Mg	mg/L	0	1,029	39	67
Na	mg/L	92	5,893	676	68
Cl	mg/L	61.8	12,804	918	68
HCO_3	mg/L	0	1,830	405	67
SO_4	mg/L	0	350	24	64

Note: Ca = Calcium, Mg = Magnesium, Na = Sodium, Cl = Chloride, HCO_3 = Bicarbonate, SO_4 = Sulphate

The hydrochemistry data available for this aquifer indicate variable groundwater quality, and is classified as sodium-chloride and sodium-bicarbonate type water. Groundwater variability is likely to indicate chemical evolution and mineral dissolution within the aquifer, and evapotranspiration within recharge areas (Herczeg 1991). The groundwater is slightly alkaline with an average pH of 8.2. Conductivity ranges from 560 to 10,300 µS/cm (with an average of 2,141 µS/cm) which indicates groundwater in this unit varies from fresh to moderately saline. The average concentration of sodium is 676 mg/L and ranges from 92 to 5,893 mg/L. The average chloride and bicarbonate concentrations are 918 mg/L (ranging from 62 to 12,804 mg/L) and 405 mg/L (ranging from 0 to 1,830 mg/L) respectively.

4.5.2.5 Tertiary Main Range Volcanics

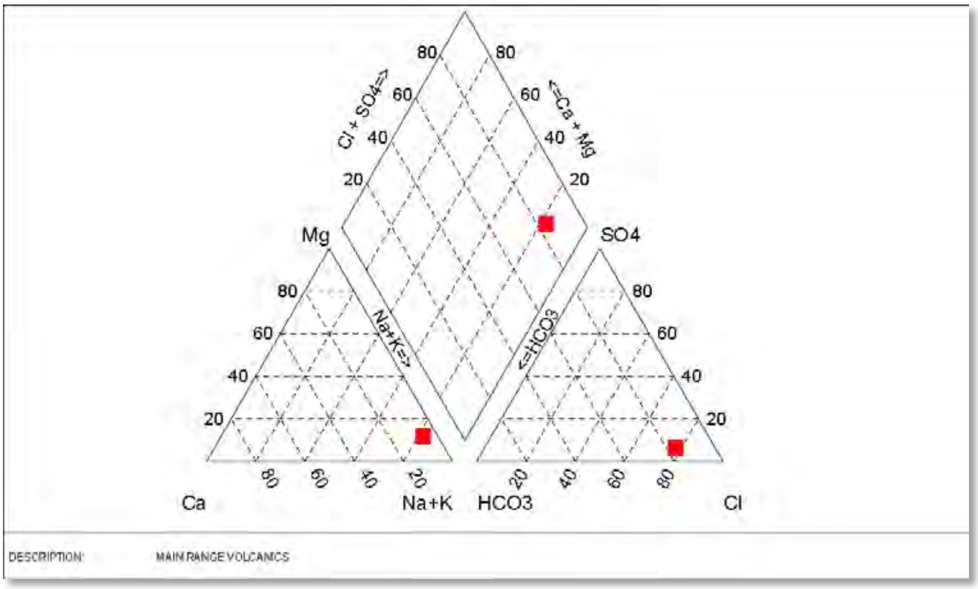


Table 4.6 – Summary of groundwater quality in the Tertiary Main Range Volcanics aquifer

Parameter	Unit	Min	Max	Average	No. Samples
pH		8.3	8.3	8.3	1
Conductivity	µS/cm	5,500	5,500	5,500	1
TDS	mg/L	3,575	3,575	3,575	1
Ca	mg/L	74	74	74	1
Mg	mg/L	82	82	82	1
Na	mg/L	1,103	1,103	1,103	1
Cl	mg/L	1,540	1,540	1,540	1
HCO_3	mg/L	555	555	555	1
SO_4	mg/L	166	166	166	1

Note: Ca = Calcium, Mg = Magnesium, Na = Sodium, Cl = Chloride, HCO_3 = Bicarbonate, SO_4 = Sulphate

Only one data entry was available for the Tertiary Main Range Volcanics. The hydrochemistry indicates that the groundwater is classified as sodium-chloride type, and slightly alkaline (pH of 8.3). The conductivity value is 5,500 µS/cm indicating that groundwater in this unit is brackish; however one data point is not sufficient for characterising the beneficial use. The concentration of sodium is 1,103 mg/L and chloride concentration is 1,540 mg/L.

4.5.2.6 Marburg Sandstone (Marburg Subgroup)

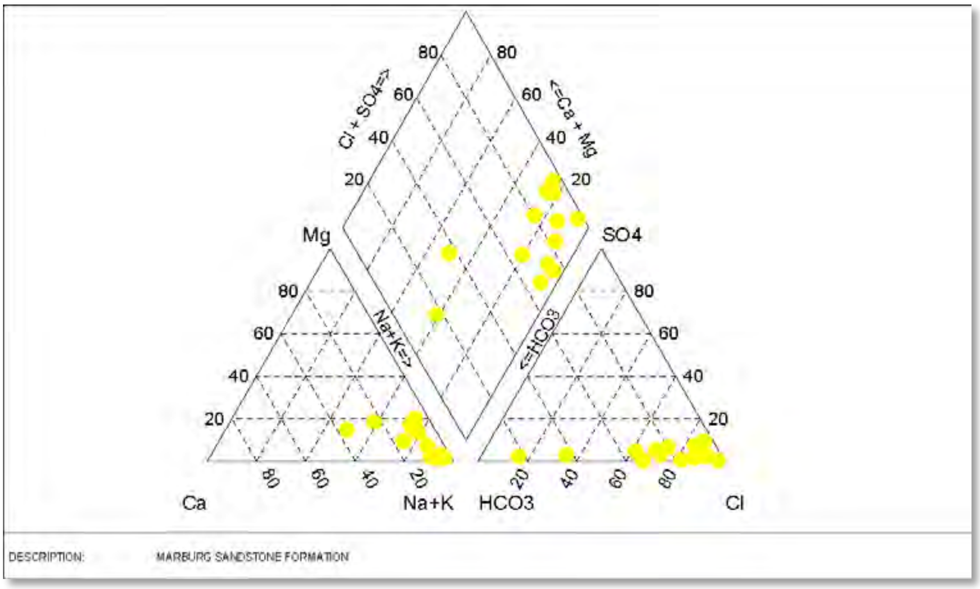


Table 4.7 – Summary of groundwater quality in the Marburg Sandstone aquifer

Parameter	Unit	Min	Max	Average	No. Samples
pH		7.2	8.3	7.8	14
Conductivity	µS/cm	250	15,550	5,134	14
TDS	mg/L	162	10,108	5,134	14
Ca	mg/L	12	208	86	14
Mg	mg/L	4	224	67	14
Na	mg/L	30	3,595	1002	14
Cl	mg/L	13	5,780	1,621	14
HCO_3	mg/L	120	567	363	14
SO_4	mg/L	0	300	82	14

Note: Ca = Calcium, Mg = Magnesium, Na = Sodium, Cl = Chloride, HCO_3 = Bicarbonate, SO_4 = Sulphate

The hydrochemistry data indicate variable groundwater quality. Groundwater variability is likely to indicate chemical evolution and mineral dissolution within the aquifer, and evapotranspiration within recharge areas (Herczeg 1991). Sodium-chloride and sodium-bicarbonate type waters are typical. Groundwater is slightly alkaline with an average pH of 7.8. Conductivity ranges from 250 to 15,550 µS/cm (with an average of 5,134 µS/cm) which indicates groundwater in this unit varies from fresh to moderate salinity. The average concentration of sodium is 1002 mg/L and ranges from 30 to 3,595 mg/L. The average chloride and bicarbonate concentrations are 1,621 mg/L (ranging from 13 to 5,780 mg/L) and 363mg/L (ranging from 120 to 567 mg/L) respectively.

4.5.2.7 Mooga Sandstone

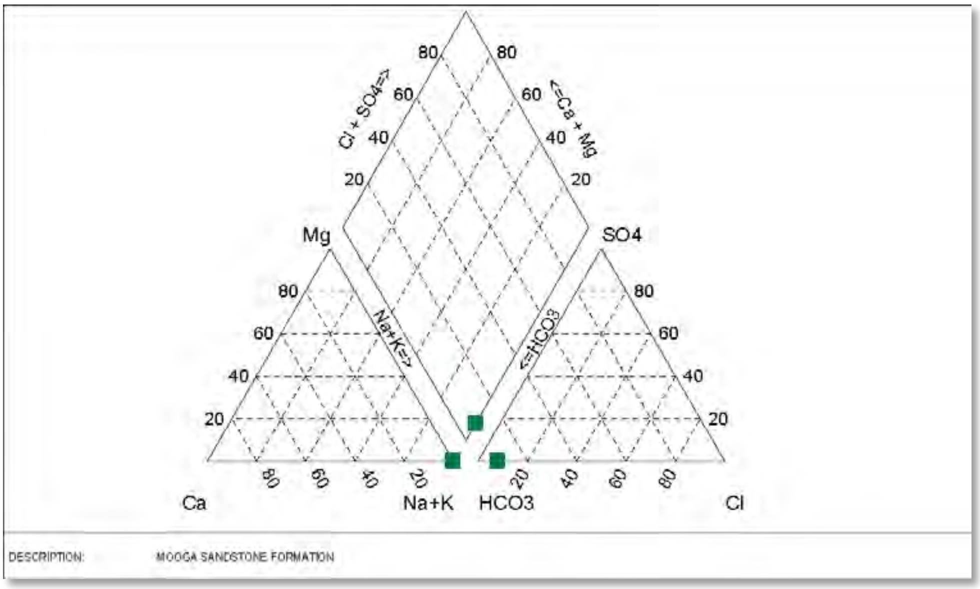


Table 4.8 – Summary of groundwater quality in the Mooga Sandstone aquifer

Parameter	Unit	Min	Max	Average	No. Samples
pH		8.6	8.6	8.6	1
Conductivity	µS/cm	1,500	1,500	1,500	1
TDS	mg/L	975	975	975	1
Ca	mg/L	1.5	1.5	1.5	1
Mg	mg/L	0.2	0.2	0.2	1
Na	mg/L	390	390	390	1
Cl	mg/L	44	44	44	1
HCO_3	mg/L	940	940	940	1
SO_4	mg/L	0.1	0.1	0.1	1

Note: Ca = Calcium, Mg = Magnesium, Na = Sodium, Cl = Chloride, HCO_3 = Bicarbonate, SO_4 = Sulphate

Only one data entry was able to be obtained for the Mooga Sandstone. The hydrochemistry data indicates a sodium-bicarbonate classification. It also indicates that the groundwater is slightly alkaline (pH of 8.6). Conductivity is reported at 1,500 µS/cm, indicating that groundwater in this unit is fresh. The concentration of sodium and bicarbonate is 390 mg/L and 940 mg/L, respectively.

4.5.2.8 Springbok Sandstone

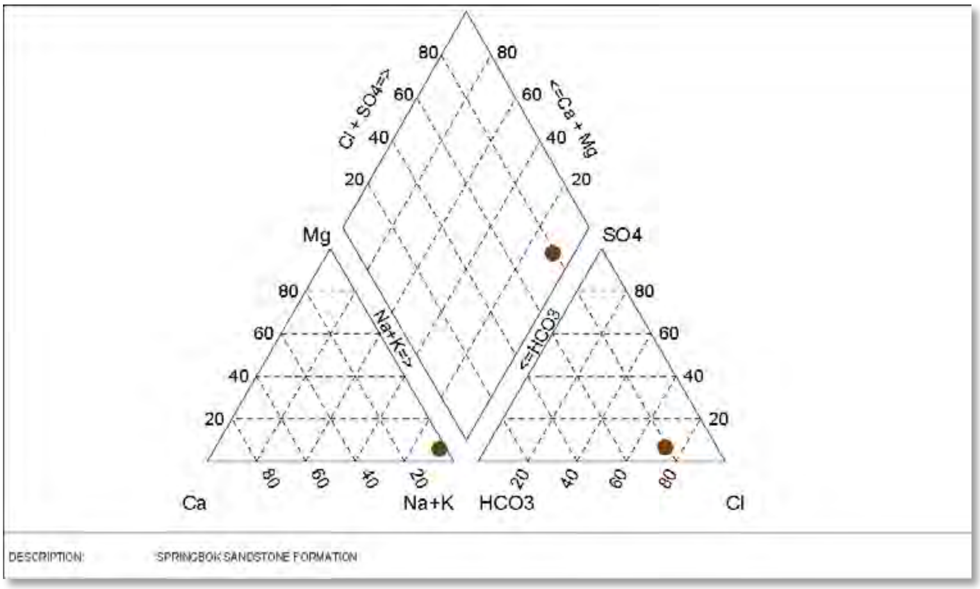


Table 4.9 – Summary of groundwater quality in the Springbok Sandstone aquifer

Parameter	Unit	Min	Max	Average	No. Samples
pH		7.8	7.8	7.8	1
Conductivity	µS/cm	5,300	5,300	5,300	1
TDS	mg/L	3,445	3,445	3,445	1
Ca	mg/L	35	35	35	1
Mg	mg/L	35	35	35	1
Na	mg/L	1,050	1,050	1,050	1
Cl	mg/L	1,310	1,310	1,310	1
HCO_3	mg/L	671	671	671	1
SO_4	mg/L	160	160	160	1

Note: Ca = Calcium, Mg = Magnesium, Na = Sodium, Cl = Chloride, HCO_3 = Bicarbonate, SO_4 = Sulphate

Only one data entry was available for the Springbok Sandstone. The hydrochemistry indicates groundwater is sodium-chloride type with a pH of 7.8. Conductivity is reported at 5,300 µS/cm, indicating that groundwater in this unit is brackish. The concentration of sodium and chloride is 1,050 mg/L and 1,310 mg/L, respectively.

4.5.2.9 Walloon Coal Measures

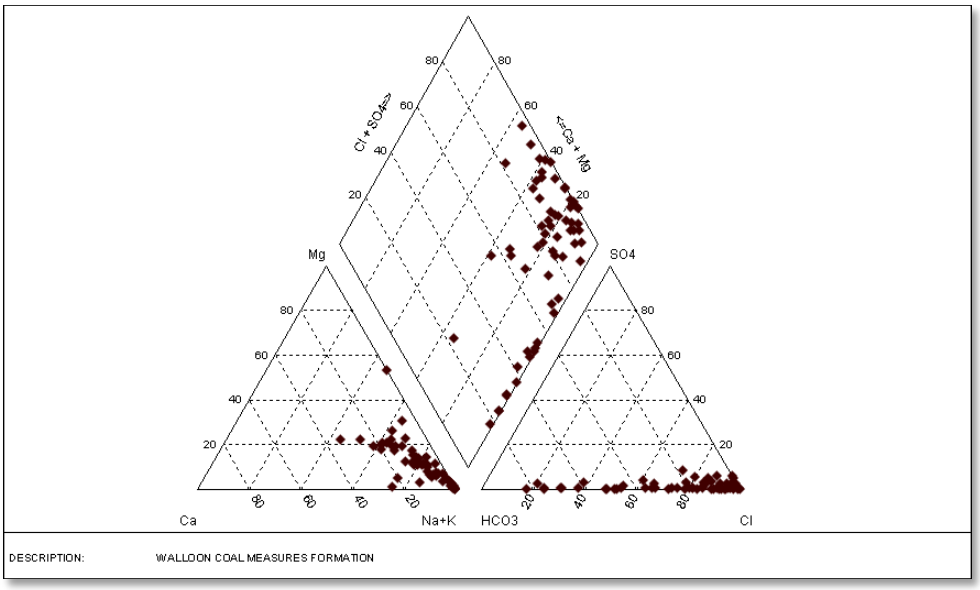


Table 4.10 – Summary of groundwater quality in the Walloon Coal Measures

Parameter	Unit	Min	Max	Average	No. Samples
pH		7.1	11.4	8.1	63
Conductivity	µS/cm	830	31,000	7,223	61
TDS	mg/L	534	20,150	4,694	61
Ca	mg/L	4	1,160	136	67
Mg	mg/L	2	850	113	66
Na	mg/L	135	6,950	1,420	67
Cl	mg/L	65	12,770	2,280	67
HCO_3	mg/L	5.2	1,980	561	65
SO_4	mg/L	0	355	43	63

Note: Ca = Calcium, Mg = Magnesium, Na = Sodium, Cl = Chloride, HCO_3 = Bicarbonate, SO_4 = Sulphate

The hydrochemistry data indicate variable groundwater quality within the Walloon Coal Measures. Groundwater chemistry variability is likely to indicate chemical evolution and mineral dissolution within the aquifer, and evapotranspiration within recharge areas (Herczeg 1991). In addition the heterogeneity of this formation is likely to influence groundwater chemistry spatially.

Sodium-chloride and sodium-bicarbonate type waters are present. Groundwater is generally slightly alkaline with a pH average of 8.1 and ranges from pH 7.1 to 11.4. Conductivity ranges from 830 to 31,000 µS/cm which indicates groundwater in this unit ranges from fresh to very saline with some concentrations approaching sea-water salinity (average concentration 7,223 µS/cm). The average concentration of sodium is 1,420 mg/L and ranges from 135 to 6,950 mg/L. The average chloride and bicarbonate concentrations are 2,280 and 561 mg/L respectively.

4.6 Groundwater Resource Development

4.6.1 Registered Groundwater Bores in the Project Development Area

Table 4.11 provides a summary of registered bores tapping each aquifer in the study area, extracted from the Queensland Groundwater Resource Information Database (DERM database). This information is limited to registered bore users and may exclude a significant number of other bore users within the region that are unregistered.

The majority of groundwater bores within the project development area utilise the Condamine Alluvium aquifer. It is noted that groundwater is also used from the Walloon coal measures by some abstractors, even though the quality may be poor and the yield generally low in comparison with the Condamine Alluvium.

A small proportion of bores identified are annotated from formations unlikely to be present in the project development area. In some of these cases, the bore co-ordinates may be erroneous. In other cases, the formation names may be misapplied.

Table 4.11 – Registered bores in the project development area

Hydrogeological Unit	Aquifer Name*	Number of Registered Bores*
Shallow Aquifers	Alluvium (Undifferentiated)	8
	Charleys Creek Alluvium	5
	Condamine River Alluvium	1489
	Other Creek and Alluvium Formations	13
	Wallumbilla Formation	0
	Bungil Formation	0
	Tertiary Main Range Volcanics	5
	TOTAL SHALLOW	**1520**
Intermediate Aquifers	Kumbarilla Beds	136
	Mooga Sandstone	2
	Orallo Aquifer	0
	Gubberamunda Sandstone	1
	Westbourne Formation	1
	Springbok Sandstone Aquifer	1
	TOTAL INTERMEDIATE	**141**
Walloon Unit	Walloon Aquifer	150
	Eurombah	0
	Injune	16
	TOTAL WALLOON	**166**
Lower Aquifers	Hutton Sandstone	13
	Marburg Subgroup	35
	Evergreen Formation	2

Hydrogeological Unit	Aquifer Name*	Number of Registered Bores*
	Precipice Sandstone	2
	TOTAL LOWER	**52**
Basement	Permian Granite	1
Other/ Not labelled		12
TOTAL		**1892**

** From DERM Database (data extracted 6 October 2009)*

4.6.2 Existing Use of Groundwater within the Project Development Area

The majority of the project development area is contained within the areal boundaries of the following groundwater management areas (GMAs): GMA 19 (Surat), GMA 20 (Surat North), GMA 21 (Surat East) and GMA 24 (Eastern Downs) (Figure 4.4). These GAB GMAs represent the hydrogeological data capture areas for this study. Groundwater bores in Queensland are registered within the DERM database, the licence information being consigned in the Water Entitlements Registration Database (WERD). The WERD database was extracted in February 2010 and is considered to be representative of the project area.

Based on the number of registered users, the majority of groundwater use in the project development area is for irrigation and stock purposes. Other significant uses include town supply, industrial uses, domestic supply and aquaculture. It is likely that demands for water for these uses will increase over time. Table 4.12 presents a range of licensed bore use within the project development area.

Table 4.12 – Licensed bore users in the project development area

Bore Use Category	Approximate Number of Registered Users
Agriculture	6
Amenities	3
ANY	1
Aquaculture, Irrigation	4
Aquaculture, Irrigation, Water harvesting	2
Commercial	3
Commercial, Industrial	1
Commercial, Irrigation	12
Commercial, Irrigation, Stock Intensive	1
Dairying, Domestic Supply, Irrigation, Stock	1
Dairying, Irrigation	14
Divert the course of flow	1
Domestic Supply, Irrigation	6
Domestic Supply, Irrigation, Stock	11
Domestic Supply, Irrigation, Water harvesting	1

Bore Use Category	Approximate Number of Registered Users
Domestic Supply, Stock	1
Educational Facility	1
Educational Facility, Irrigation	10
Educational Facility, Test Purposes	3
Gardens Only	1
Industrial	20
Industrial, Irrigation	8
Irrigation	1652
Irrigation, School	8
Irrigation, Stock	21
Irrigation, Stock Intensive	86
Irrigation, Urban	1
Irrigation, Water harvesting	4
Relift Water	12
Repumping	1
School	3
Stock	1
Stock Intensive	7
Town Supply	21
Urban	13
Water harvesting	44
TOTAL	**1990**

Includes issued licences and those under amendment, renewal, transfer and variation.

4.6.3 Water Allocation, Entitlement, and Extraction

The documented 'nominal entitlement' of the 1990 groundwater bores within the project development area is 331,545 ML and may be a significant under-estimate. It should be noted that only 51% of licenses had a nominal extraction referenced. It is also noted that 191 bores are either not metered or historical and current groundwater usage data has not been incorporated into the WERD database.

4.7 Groundwater Dependent Ecosystems

4.7.1 Springs

Recharge to the GAB occurs through areas where sandstone formations are exposed or buried beneath porous sand-sheets on the margins of the Basin (Habermehl 1980, 2001, Welsh 2000). In Queensland these formations are: Adori, Boxvale, Clematis, Expedition, Gilbert River, Gubberamunda, Hampstead, Hooray, Hutton and Precipice Sandstones, the Bulimba, Glenidal, Moolayember, Rewan and Westbourne Formations, and the Helby and Ronlow Beds (Fensham & Fairfax, 2005).

Springs occurring in locations where these outcrops are exposed or in recharge areas are defined here as ‘recharge springs’. The major recharge areas occur around the northern and eastern margins of the GAB, where mean annual rainfall is around 500 – 600 mm/yr. When in-flow exceeds through-flow groundwater can discharge from the spring. Recharge springs are commonly an ephemeral feature in a local aquifer and not necessarily connected to the watertable. In this case, groundwater drawdown in GAB aquifers should not affect recharge spring flows.

Other springs that derive their groundwater source from the GAB, but with a surface geology other than those units defined above are defined as ‘discharge area springs’.

Discharge area springs occur under a range of circumstances including:

- Where the water-bearing formations approach the ground surface near the downgradient margins of the Basin.
- Where water flows through faults or unconformities in the overlying formations.
- Where a conduit is provided at the contact between the confining formations and the outcropping bedrock.

The discharge springs of the GAB are commonly referred to as mound springs. Mounds can develop by a number of processes including upward sub-soil transport by artesian water, by accretion of calcium carbonate as travertine, by the accumulation of aeolian sand, by the expansion of reactive surface clays, and through the development of peat from spring wetland vegetation. Faunal communities endemic to these locations may be considered as groundwater dependent.

Artesian fed mound springs are common in many GAB areas in the southern and western basin margins, and also where structural controls such as faults have provided pathways for artesian groundwater to the surface. However mound springs are not known within the Surat Basin and Clarence-Moreton Basin project development area (Fensham et al, 2005).

Springs have been identified within the groundwater model extent, as shown on Figure 4.5. (Source data for spring locations is Fensham et al, 2005). A summary of these spring complexes is provided in Appendix C.

The identified springs are located between 50 km and 300 km to the north and northwest of Wandoan, the northern most extent of the project development area.

In April 2010 the Queensland Government delegated to the QWC the responsibility for management of cumulative impacts from all petroleum operations, including spring impact management. The QWC has prepared Terms of Reference for assessment of identified priority springs and will prepare a Springs Impact Management Strategy (SIMS).

The SIMS will include:

- An inventory of springs in the Surat cumulative management area;
- An assessment of the source aquifer of the springs;
- Assessment of the likelihood of impacts from petroleum, development on springs; and
- Monitoring and mitigation strategies for priority springs.

Key objectives of the SIMS project include:

- Developing a conceptual understanding of springs in priority areas;
- Source aquifer investigations at high priority springs;
- Providing a dataset of hydrogeological parameters at priority springs; and
- Providing a basis for coal seam gas proponents (including Arrow Energy) to meet their obligations under the EPBC Act 1999.

The outcomes of this will enable Arrow Energy to refine their monitoring, mitigation and management strategies to minimise impacts to groundwater dependent ecosystems associated with springs.

5 ENVIRONMENTAL VALUES

This section discusses the groundwater environmental values of the study area and their characteristics. The sensitivity or susceptibility of these values to change in response to disturbance is discussed in section 9.

In many cases, the attributes of a groundwater system are such that it is relied upon to provide groundwater for a variety of extractive uses, to support areas of biological importance, or for human interest. The enhancement and protection of these aspects of groundwater reliance are required in the Environmental Protection (Water) Policy 2009 (EPP (Water) Policy) and are discussed further below.

There are broadly similar geological, hydrological and water chemistry characteristics for each aquifer system, and the environmental values to be protected are categorised under these defined systems:

- Shallow groundwater system.
- Intermediate groundwater system.
- Coal seam gas groundwater system.
- Deep groundwater system.

The attributes of these groundwater systems represent the groundwater environmental values, and determine how groundwater responds to disturbance, i.e. the sensitivity of each groundwater system.

How a groundwater system responds to disturbance is controlled by a combination of the fundamental characteristics of the groundwater system (e.g. water chemistry, transmissivity, storativity, extent) and the hydrogeologic processes acting on the groundwater systems (e.g. recharge and discharge).

5.1 Environment Protection Policy

The EPP (Water) Policy provides a framework for identifying the environmental values, and establishing water quality guidelines and objectives to enhance or protect Queensland waters. For the purposes of this assessment, the “values” as defined in the EPP (Water) Policy are used to define those attributes of the groundwater systems within the project development area that are important.

The groundwater systems and their environmental values will be discussed in section 9 in terms of their sensitivity to impact.

This section of the assessment presents the environmental values (as summarised from the EPP (Water) Policy) that govern how the groundwater systems within the project development area are to be protected or enhanced.

5.2 Groundwater Environmental Values

Although no grouping is provided in the EPP (water) policy, for discussion purposes it is convenient to characterise groundwater systems in a way that indicate their suitability to:

- Support biological ecosystems;
- Allow consumptive or productive uses; and
- Support areas of anthropomorphic importance.

The identified groundwater uses listed above are presented in the following sub-sections, identifying environmental values, and with comments and notes of relevance for application to groundwater systems in the project development area.

5.2.1 Biological Areas

As defined in the EPP (Water) Policy, for groundwater systems that support biological areas the biological environmental values to be protected are:

1) Biological integrity of a pristine or modified aquatic ecosystem that is effectively unmodified or highly valued. (For high ecological value waters).
2) Biological integrity of an aquatic ecosystem that is affected adversely to a relatively small but measureable degree by human activity. (For slightly to moderately disturbed waters).
3) Biological integrity of an aquatic ecosystem that is measurably degraded and of lower ecological value that waters mentioned in 1) and 2) above. (For highly disturbed waters).

Groundwater systems may be considered to support biological areas where the groundwater supports an aquatic ecosystem either directly or indirectly. For example, where an aquifer discharges to a spring system (e.g. a discharge spring) then the groundwater system may be directly supporting an ecosystem. Where an aquifer discharges to a wetland, lake or stream, then the groundwater system may be indirectly supporting an ecosystem.

The biological integrity of such ecosystems would require protection at levels dependent on the ecological value of the groundwater.

Ecological Value of Groundwater. For the purpose of assessing environment values, and assessing the ecological value of waters (as relevant to groundwater) the following aspects have been considered:

> **Chemistry**. Aspects of the water chemistry (for instance high salinity) would reduce the ecological value of groundwater if it were discharging to a low salinity surface feature (e.g. fresh wetland, stream, etc). However the same groundwater might have high ecological value where discharging to a naturally saline wetland system.
>
> **Discharge to surface water**. Groundwater systems that interact with surface ecosystems potentially have high ecological value. Deeper confined and isolated groundwater systems that do not interact with surface water may have lower intrinsic ecological value.
>
> **Isolation from human processes**. Groundwater systems in remote, forested or undeveloped areas are less likely to be disturbed or impacted by human processes, and may have higher ecological values.
>
> **Wetlands, Lakes and Streams**. Within the study area a range of groundwater/surface-water interaction is expected to occur. In some cases this will result in groundwater discharge (baseflow) to surface water features, and biological features will require protection, depending on the ecological value of the groundwater systems. In most cases, the discharging groundwater will be from the surface (watertable) aquifer. Within agricultural and urban areas, the water quality from unconfined aquifers is in general expected to be ‘slightly to moderately disturbed’. Within some areas, for instance state forest, the shallow groundwater may be of high ecological value.

Springs. Recharge and discharge springs are common in many GAB areas in the southern and western basin margins, and also where structural controls such as faults have provided pathways for artesian groundwater to the surface. Recharge and discharge springs are not located within the project development area, however may be located within 50 km of the nearest Arrow tenure (refer Section 4.7.1).

5.2.2 Human Interaction and Aesthetic Qualities

As defined in the EPP (Water) Policy, water systems that support human interaction through recreation or aesthetic uses can be further characterised as displaying attributes that support the following environmental values:

4) Primary recreational use.

5) Secondary recreational use.

6) Visual recreational use.

This category of water use and reliance apply to surface water features which are either accessible for recreational use or visual interaction. They are not considered applicable to groundwaters of the project development area. Surface waters and their environmental values are discussed in Alluvium (2011) 'Surface Water Assessment, Part A: Fluvial Geomorphology and Hydrology, Part B: Surface Water Quality'.

5.2.3 Consumptive or Productive Use of Groundwater

As defined in the EPP (Water) Policy, groundwater systems that support consumptive or productive uses can be further characterised as displaying attributes that support the following environmental values:

7) Minimal treatment before supply as drinking water.

8) Use in agriculture.

9) Use in aquaculture, and producing aquatic food for human consumption.

10) Suitability for industrial uses.

Potable Uses. The GAB aquifers are recognised as having areas and strata which contain groundwater ranging from potable, to brackish, and to saline quality, often varying widely within a given formation. For assessing the suitability for drinking water supply it is appropriate to apply the Australian Drinking Water Guidelines (National Health and Medical Research Council & Natural Resource Management Ministerial Council (NHMRC & NRMMC), 2004). The spatial variability of water quality means that the suitability of groundwater for these purposes will be, in many cases, location specific.

Non-Potable Uses. A significant portion of the non-potable groundwater in the region is suitable for (and used for) irrigation and stock purposes. In some cases, such as typical coal seam gas water, the high sodium adsorption ratio (SAR) rather than salinity (TDS) limits irrigation uses due to potential soil structural impacts.

Aquaculture and the production of aquatic food for human consumption are viable uses for brackish and saline waters although the water quality parameters for these uses are often highly process specific. Aquaculture uses have not been identified in the project development area, but are feasible.

The groundwater quality is generally suitable for a large number of industrial processes including cooling water, process water, utility water and wash water. As industrial processes require particular water quality, specific hydrochemical data is normally required to evaluate suitability for a specific industrial use.

5.2.4 Anthropomorphic Areas

As defined in the EPP (Water) Policy, groundwater systems that support areas of anthropomorphic importance can be further characterised as displaying attributes that support:

11) Cultural and spiritual values.

The characteristics of groundwater systems that support areas of anthropomorphic importance would relate to physical features where groundwater interaction can occur, such as wells and springs having indigenous and non-indigenous anthropological, archaeological, historic, sacred or scientific significance.

Although discharge springs (mound springs) are unknown in the project development area, springs are identified within the groundwater model extent, located between 50 km and 300 km to the north and northwest of Wandoan (refer to section 4.7.1 and Figure 4.5). The reader is referred to the Indigenous Cultural Heritage Impact Assessment (Central Queensland Cultural Heritage Management, 2011). It is noted that specific springs of cultural heritage significance have not been identified within the Indigenous Cultural Heritage Impact Assessment report.

5.3 Identified Environmental Values

A diverse range of groundwater systems containing accessible water is present across the project development area due to the geographical size and the complex basin stratigraphy. Because of this, a structured consideration of environmental values is appropriate, and this should include all the main water-bearing formations within the basin that are potentially influenced either directly or indirectly by the proposed development activities. Attributes will vary across different aquifers; therefore the values have been defined across similar aquifer systems as described in sections 3 and 4.

Accordingly, the approach taken is to present a tabulated assessment of environmental values together with supporting comments where required (Table 5.1).

Table 5.1 – Environmental Values of the study area: Groundwater system characteristics, properties and processes

GROUNDWATER SYSTEM / AQUIFER	ENVIRONMENTAL VALUES											Intrinsic Groundwater Properties
	[1]BIOLOGICAL AREAS				SUITABILITY FOR CONSUMPTIVE AND PRODUCTIVE USES						ANTHROPOMORPHIC	
	[6]Ecological Importance	Ground water supports biological integrity of pristine biological systems	Ground water supports biological integrity of slightly to moderately disturbed biological systems	Ground water supports biological integrity of slightly to highly disturbed biological systems	[2]Potable Supply	[3]Agricultural Use	[4]Stock Watering	[5]Aqua-culture	[5]Producing Aquatic Food for Human Consumption	[5]Industrial Use	Cultural & Spiritual Values of the Water	
SHALLOW GROUNDWATER SYSTEMS (Unconfined or watertable aquifers)												
Quaternary Alluvium Aquifers (including Condamine Alluvium)	MODERATE to HIGH	In remote or isolated areas	Most areas	Some areas	√	√	√	√	√	√	Not identified within project development area	Groundwater quality across the basins can vary spatially within the same aquifer. In general, most environmental values must be protected, unless site-specific data shows otherwise. **Biological Values** The shallow aquifers are generally considered to be slightly to moderately disturbed due to anthropogenic processes caused by land development, settlement, and urbanisation, such as infiltration of pollutants, nutrients, and agricultural chemicals, such as fertilisers, herbicides and pesticides. **Consumptive and Productive Use Values** Generally low to moderate TDS waters having a wide range of beneficial uses however is predominately suitable for agricultural use within the project development area. **Anthropomorphic Values** No specific groundwater sites with cultural or spiritual values identified.
Other Aquifer Formations where Unconfined	MODERATE to HIGH	In remote or isolated areas	Most areas	Some areas	√	√	√	√	√	√	Not identified within project development area	

1. The biological environmental values of water to be protected under the Environmental Protection (Water) Policy 1997 include:
   - For high ecological value waters –***The biological integrity of an aquatic ecosystem that is effectively unmodified or highly valued***; and
   - For slightly modified disturbed waters – ***The biological integrity of an aquatic ecosystem that is affected adversely to a relatively small but measurable degree by human activity***; and
   - For highly disturbed waters – ***The biological integrity of an aquatic ecosystem that is measurably degraded and of lower ecological value than waters mentioned above***.
   - Spring complexes (although not identified) could be considered under biological and anthropomorphic values.

Relevant assessment guidelines for the consumptive and productive use environmental values to be protected include:

2. Australian Drinking Water Guidelines 2004 (National Health and Medical Research Council & Natural Resource Management Ministerial Council).
3. ANZECC 1992 - Australian Water Quality Guidelines for Irrigation Water Quality.
4. ANZECC 1992 - Australian Water Quality Guidelines for Fresh and Marine Waters – Guidelines for Livestock Watering.
5. Groundwater quality criteria is specific to application.
6. Unconfined groundwater systems can have high quality groundwater, and could support ecosystems such as streams and wetlands, and thereby have moderate to high ecological importance.

Table 5.1 – Environmental Values of the study area: Groundwater system characteristics, properties and processes

GROUNDWATER SYSTEM / AQUIFER	ENVIRONMENTAL VALUES											Intrinsic Groundwater Properties
	[1]BIOLOGICAL AREAS				SUITABILITY FOR CONSUMPTIVE AND PRODUCTIVE USES						ANTHROPOMORPHIC	
	[6]Ecological Importance	Ground water supports biological integrity of pristine biological systems	Ground water supports biological integrity of slightly to moderately disturbed biological systems	Ground water supports biological integrity of slightly to highly disturbed biological systems	[2]Potable Supply	[3]Agricultural Use	[4]Stock Watering	[5]Aqua-culture	[5]Producing Aquatic Food for Human Consumption	[5]Industrial Use	Cultural & Spiritual Values of the Water	
INTERMEDIATE GROUNDWATER SYSTEMS (confined aquifers located above coal seam gas formations)												
Mooga Sandstone	MODERATE to HIGH	Some areas	Some areas	Not expected	Most areas	Most areas	√	√	√	√	Not identified within project development area	Groundwater quality across the basins can vary spatially within the same aquifer. In general, most environmental values must be protected, unless site-specific data shows otherwise. **Biological Values** The intermediate aquifers are generally considered to be of higher value (where at depth) to only slightly disturbed (where sub-cropping or near recharge areas) by anthropogenic processes **Consumptive and Productive Use Values** Based on variable TDS, water has a range of uses, however is predominately suitable for agricultural use within the project development area. **Anthropomorphic Values** No specific groundwater sites with cultural or spiritual values identified
Gubberamunda Sandstone	MODERATE to HIGH	Some areas	Some areas	Not expected	Most areas	Most areas	√	√	√	√	Not identified within project development area	
Springbok Sandstone	MODERATE to HIGH	Some areas	Some areas	Not expected	Most areas	Most areas	√	√	√	√	Not identified within project development area	

1. The biological environmental values of water to be protected under the Environmental Protection (Water) Policy 1997 include:
   - For high ecological value waters –***The biological integrity of an aquatic ecosystem that is effectively unmodified or highly valued***; and
   - For slightly modified disturbed waters – ***The biological integrity of an aquatic ecosystem that is affected adversely to a relatively small but measurable degree by human activity***; and
   - For highly disturbed waters – ***The biological integrity of an aquatic ecosystem that is measurably degraded and of lower ecological value than waters mentioned above***.
   - Spring complexes (although not identified) could be considered under biological and anthropomorphic values.

Relevant assessment guidelines for the consumptive and productive use environmental values to be protected include:
2. Australian Drinking Water Guidelines 2004 (National Health and Medical Research Council & Natural Resource Management Ministerial Council).
3. ANZECC 1992 - Australian Water Quality Guidelines for Irrigation Water Quality.
4. ANZECC 1992 - Australian Water Quality Guidelines for Fresh and Marine Waters – Guidelines for Livestock Watering.
5. Groundwater quality criteria is specific to application.
6. Deeper confined groundwater systems can have high quality groundwater, and could support ecosystems such as fault fed springs (although none identified), and thereby have moderate to high ecological importance.

Table 5.1 – Environmental Values of the study area: Groundwater system characteristics, properties and processes

GROUNDWATER SYSTEM / AQUIFER	ENVIRONMENTAL VALUES											Intrinsic Groundwater Properties
	[1]BIOLOGICAL AREAS				SUITABILITY FOR CONSUMPTIVE AND PRODUCTIVE USES						ANTHROPOMORPHIC	
	Ecological Importance	Ground water supports biological integrity of pristine biological systems	Ground water supports biological integrity of slightly to moderately disturbed biological systems	Ground water supports biological integrity of slightly to highly disturbed biological systems	[2]Potable Supply	[3]Agricultural Use	[4]Stock Watering	[5]Aqua-culture	[5]Producing Aquatic Food for Human Consumption	[5]Industrial Use	Cultural & Spiritual Values of the Water	
COAL SEAM GROUNDWATER SYSTEMS (confined aquifers associated with coal seam gas formations, including Walloon Coal Measures and adjacent formations												
Walloon Coal Measures	LOW	Not expected	Not expected	Not expected	Some areas	Some areas	Some areas	√	Some areas	√	Not identified within project development area	Groundwater quality across the basins can vary spatially within the same aquifer. In general, most environmental values must be protected, unless site-specific data shows otherwise. **Biological Values** The coal seam formation aquifers are generally considered to be of lower ecological value due to higher salinity, high SAR, and coal formation chemistry. **Consumptive and Productive Use Values** The coal seam formation aquifers are generally considered to be of lower quality due to higher salinity, high SAR, and coal formation chemistry. The groundwater is generally suitable for stockwatering and production of aquatic food for human consumption. **Anthropomorphic Values** No specific groundwater sites with cultural or spiritual values identified
Tangalooma Sandstone	LOW	Not expected	Not expected	Not expected	Some areas	Some areas	√	√	Some areas	√	Not identified within project development area	

1. The biological environmental values of water to be protected under the Environmental Protection (Water) Policy 1997 include:
   - For high ecological value waters –***The biological integrity of an aquatic ecosystem that is effectively unmodified or highly valued***; and
   - For slightly modified disturbed waters – ***The biological integrity of an aquatic ecosystem that is affected adversely to a relatively small but measurable degree by human activity***; and
   - For highly disturbed waters – ***The biological integrity of an aquatic ecosystem that is measurably degraded and of lower ecological value than waters mentioned above***.
   - Spring complexes (although not identified) could be considered under biological and anthropomorphic values.

Relevant assessment guidelines for the consumptive and productive use environmental values to be protected include:

2. Australian Drinking Water Guidelines 2004 (National Health and Medical Research Council & Natural Resource Management Ministerial Council).
3. ANZECC 1992 - Australian Water Quality Guidelines for Irrigation Water Quality.
4. ANZECC 1992 - Australian Water Quality Guidelines for Fresh and Marine Waters – Guidelines for Livestock Watering.
5. Groundwater quality criteria is specific to application.

Table 5.1 – Environmental Values of the study area: Groundwater system characteristics, properties and processes

AQUIFER SYSTEM	ENVIRONMENTAL VALUES											Intrinsic Groundwater Properties
	[1]BIOLOGICAL AREAS				SUITABILITY FOR CONSUMPTIVE AND PRODUCTIVE USES					ANTHROPOMORPHIC		
	[6]Ecological Importance	Ground water supports biological integrity of pristine biological systems	Ground water supports biological integrity of slightly to moderately disturbed biological systems	Ground water supports biological integrity of slightly to highly disturbed biological systems	[2]Potable Supply	[3]Agricultural Use	[4]Stock Watering	[5]Aqua-culture	[5]Producing Aquatic Food for Human Consumption	[5]Industrial Use	Cultural & Spiritual Values of the Water	
DEEPER GROUNDWATER SYSTEMS (confined aquifers located below Coal Seam Gas formations)												
Hutton/Marburg Sandstone	HIGH	Most areas	Some areas	Not expected	Some areas	√	√	√	√	√	Not identified within project development area	Groundwater quality across the basins can vary spatially within the same aquifer. In general, most environmental values must be protected, unless site-specific data shows otherwise. **Biological Values** The deeper confined formation (artesian) aquifers are generally considered to be of high ecological value due to lower salinity, although interaction with surface waters is not encountered in the project development area. **Consumptive and Productive Use Values** Low TDS means a wide range of uses available, however, is predominately suitable for agricultural uses. **Anthropomorphic Values** No specific groundwater sites with cultural or spiritual values identified, although the aquifer may have historical cultural importance.
Precipice Sandstone	MODERATE	Most areas	Some areas	Not expected	Some areas	√	√	√	√	√	Not identified within project development area	

1. The biological environmental values of water to be protected under the Environmental Protection (Water) Policy 1997 include:
   - For high ecological value waters –***The biological integrity of an aquatic ecosystem that is effectively unmodified or highly valued***; and
   - For slightly modified disturbed waters – ***The biological integrity of an aquatic ecosystem that is affected adversely to a relatively small but measurable degree by human activity***; and
   - For highly disturbed waters – ***The biological integrity of an aquatic ecosystem that is measurably degraded and of lower ecological value than waters mentioned above***.
   - Spring complexes (although not identified) could be considered under biological and anthropomorphic values.

Relevant assessment guidelines for the consumptive and productive use environmental values to be protected include:

2. Australian Drinking Water Guidelines 2004 (National Health and Medical Research Council & Natural Resource Management Ministerial Council).
3. ANZECC 1992 - Australian Water Quality Guidelines for Irrigation Water Quality.
4. ANZECC 1992 - Australian Water Quality Guidelines for Fresh and Marine Waters – Guidelines for Livestock Watering.
5. Groundwater quality criteria is specific to application.
6. Deeper confined groundwater systems can have high quality groundwater, and could support ecosystems such as fault fed springs (although none identified), and thereby have moderate to high ecological importance.

5.4 Spatial and Non-Spatial Environmental Values

The identified groundwater values include those having a spatial component and also those that are unconstrained spatially.

Groundwater attributes that support biological areas are an example of environmental values that can be spatially constrained. For example, high ecological value groundwater systems (i.e. undisturbed waters) could be mapped if sufficient data were available and constraints applied to development in key areas, such as areas of high ecological importance.

Anthropomorphic areas are also constrainable by mapping those sites or areas of cultural and spiritual value.

The groundwater attributes that define consumptive and productive uses, are widely applicable to groundwater. Hence it is not practical to constrain these based on spatial factors, because the requirement to protect these uses as they relate to groundwater at any location is independent of the identified value. Because these values are site specific, controls may also be site specific.

5.5 Summary

As defined in Table 5.1 and in conjunction with the EPP (Water) Policy, groundwater systems present within the project development area are characterised by attributes that support:

- Biological integrity of:
    - a pristine or modified aquatic ecosystem that is effectively unmodified or highly valued. (For high ecological value waters).
    - an aquatic ecosystem that is affected adversely to a relatively small but measureable degree by human activity. (For slightly to moderately disturbed waters).
    - an aquatic ecosystem that is measurably degraded and of lower ecological value that waters mentioned in 1) and 2) above. (For highly disturbed waters).
- Minimal treatment before supply as drinking water.
- Use in agriculture.
- Use in aquaculture, and producing aquatic food for human consumption.
- Suitability for industrial uses.
- Cultural and spiritual values.

Therefore, the sustainable function, use of, and dependence upon, groundwater resources within the project development area will require protection of the attributes of the groundwater systems that support/enable these uses.

6 PROJECT DESCRIPTION AND ACTIVITIES

This section provides a description of the indicative schedule of gas field development and expected quantity of coal seam gas water produced during the project between 2011 and 2050. Due to the limited amount of data available to support these estimates and the early stage of the project, it is likely that the estimated quantities of coal seam gas water will change as the project progresses and more field information becomes available.

6.1 Project Development Area

The project development area is located approximately 160 km west of Brisbane in Queensland's Surat Basin. It covers an area of approximately 8,600 km^2 and extends from the township of Wandoan in the north towards Goondiwindi in the south, in arc through Dalby. The project development area comprises petroleum leases (PLs) 194, 198, 230, 238, 252, 258, 260; petroleum lease applications (PL(A)s) 185, 253; authority to prospect (ATPs) 676, 683, 689, 810, part of ATP747; and parts of authority to prospect applications (ATP(A)s) 746.

Figure 1.2 shows the petroleum tenures that form the project development area. Tenures indicated as ATP(A) or PL(A) indicates that at the time this assessment was prepared, an application had been submitted for these tenures.

6.1.1 Current Arrow Coal Seam Gas Development

Arrow has existing facilities in the Surat Basin that have provided gas since 2006 to local power stations, and to domestic and industrial markets. This production currently comes from Tipton West, Daandine, Kogan North and recently Stratheden gas fields (Figure 1.3).

Figure 1.3 shows the locations of existing production wells, gas compression and processing facilities, and gas-fired power stations.

6.2 Overview of Gas Field Development

Approximately 7,500 production wells and associated gas and water gathering and management infrastructure will be installed. The development area (Figure 6.1) has been divided into parcels that each contains a nominal 100 production wells. The final number of production wells in each parcel will ultimately depend on how prospective each parcel proves to be, what environmental constraints are present within the parcel and the outcomes of landowner negotiations. Wells will be physically arranged in ‘pods’. Pods comprise groups of approximately 10 wells, located in the same geographic area and associated with common access roadways and/or common gathering system ‘rights of way’.

Based on an 800 m grid spacing, the maximum number of wells per parcel could exceed 118. However environmental and physical constraints (areas where development cannot proceed such as towns or physical obstacles to development such as land holder activities, roads or rivers) will determine the number of wells that can physically be located in any parcel. Wells may be spaced between 700 m and 1,500 m apart, which provides flexibility in their placement. Production wells will be located greater than 200 m from any sensitive receptor.

A designated set of parcels of wells will feed associated facilities including field compression facilities (approximately six), central gas processing facilities (approximately six) and integrated processing facilities (approximately six). Coal seam gas water will bypass field compression facilities. Central gas processing facilities will incorporate water transfer facilities, and integrated processing facilities will incorporate water treatment, storage and offtake facilities.

The project development area is divided into five areas for field development planning: Dalby, Wandoan, Millmerran/Kogan, Chinchilla and Goondiwindi (Figure 6.1). Arrow expects to locate facilities to gather gas and water from production wells at approximately 25 km intervals throughout the project development area.

The project life will be influenced by a combination of the reserves determined to be available, an anticipated (average) well life of 15 to 20 years and the life of the Arrow LNG plant on Curtis Island. Development will involve the installation of approximately 400 wells per year and development of approximately 1 facility per year from 2014 (with 2 facilities being built in some years and none in others).

6.2.1 Gas Production

Arrow currently supplies up to 80 TJ/d of gas to the domestic gas market for power generation under existing gas sales agreements. These agreements will not expire until between 2020 and 2025. It is anticipated that the domestic gas production will be maintained through gas production from the project development area that is additional to the projected 970 TJ/d total for LNG production. Approximately 20 new production wells will be required annually to maintain domestic supply.

The Arrow LNG Plant will receive gas from Arrow's tenements in the Surat Basin (Surat Gas Project) and Bowen Basin (proposed Bowen Gas Project). For impact assessment purposes, the gas required for the initial two trains (1,350 TJ/d) is expected to be in the order of 65% from the Surat Gas Project and 35% from the Bowen Gas Project. The ultimate capacity of the LNG plant is subject to detailed design, as is the proportion of gas supplied from the Surat and Bowen Basins.

6.2.2 Future Arrow Development

For the purpose of this assessment and the associated groundwater modelling (conducted by Schlumberger, 2011), Arrow has provided a preliminary schedule for well field development as presented in Table 6.1, and the related coal seam gas water abstraction rates presented in Table 6.2.

The rate of development of the 5 development areas will be based on future demand in domestic gas contracts and LNG opportunities. Considerations that will affect the final rate and sequencing of development of these resource areas include:

- Results of the exploration and pilot well programs in the Wandoan, Millmerran/Kogan, Chinchilla and Goondiwindi development areas, and the proving of resources.
- Access to suitable land for installation of production wells and related infrastructure.
- Access to and most effective use of existing infrastructure, and the capital cost of new infrastructure.
- Resolution of any environmental issues, and mitigating potential for impacts.
- Identification of any significant opportunities that support the selective development of specific areas of high quality gas resources, in advance of the overall development of each development area.

Table 6.1 – Potential production wells (unconstrained by gas resources)

Timeline Year	Notional Year	Wandoan	Chinchilla	Dalby	Millmerran Kogan	Goondiwindi
Year 0	2010	0	0	0	0	0
Year 1	2011	0	0	0	0	0
Year 2	2012	0	0	0	0	0
Year 3	2013	0	0	0	0	0
Year 4	2014	174	0	0	0	0
Year 5	2015	20	0	203	0	0
Year 6	2016	260	0	105	0	0
Year 7	2017	100	0	286	0	0
Year 8	2018	276	0	221	0	0
Year 9	2019	0	0	196	0	0
Year 10	2020	201	0	170	85	0
Year 11	2021	249	0	27	188	0
Year 12	2022	0	289	0	93	0
Year 13	2023	0	166	0	0	0
Year 14	2024	60	291	0	0	0
Year 15	2025	70	127	0	114	0
Year 16	2026	0	0	0	305	0
Year 17	2027	0	0	0	152	0
Year 18	2028	0	0	0	440	0
Year 19	2029	47	81	0	233	0
Year 20	2030	0	40	60	213	420
Year 21	2031	0	0	11	17	280
Year 22	2032	0	0	0	0	0
Year 23	2033	0	0	0	0	0
Year 24	2034	0	0	0	0	0
Year 25	2035	0	0	0	0	0
Year 26	2036	0	00	0	0	0
Year 27	2037	0	0	0	0	0
Year 28	2038	0	0	0	0	0
Year 29	2039	-	-	-	-	-
Year 30	2040	-	-	-	-	-

Timeline Year	Notional Year	Wandoan	Chinchilla	Dalby	Millmerran Kogan	Goondiwindi
Year 31	2041	-	-	-	-	-
Year 32	2042	-	-	-	-	-
Year 33	2043	-	-	-	-	-
Year 34	2044	-	-	-	-	-
Year 35	2045	-	-	-	-	-
Year 36	2046	-	-	-	-	-
Year 37	2047	-	-	-	-	-
Year 38	2048	-	-	-	-	-
Year 39	2049	-	-	-	-	-
Year 40	2050	-	-	-	-	-
Year 41	2051	-	-	-	-	-
Year 42	2052	-	-	-	-	-

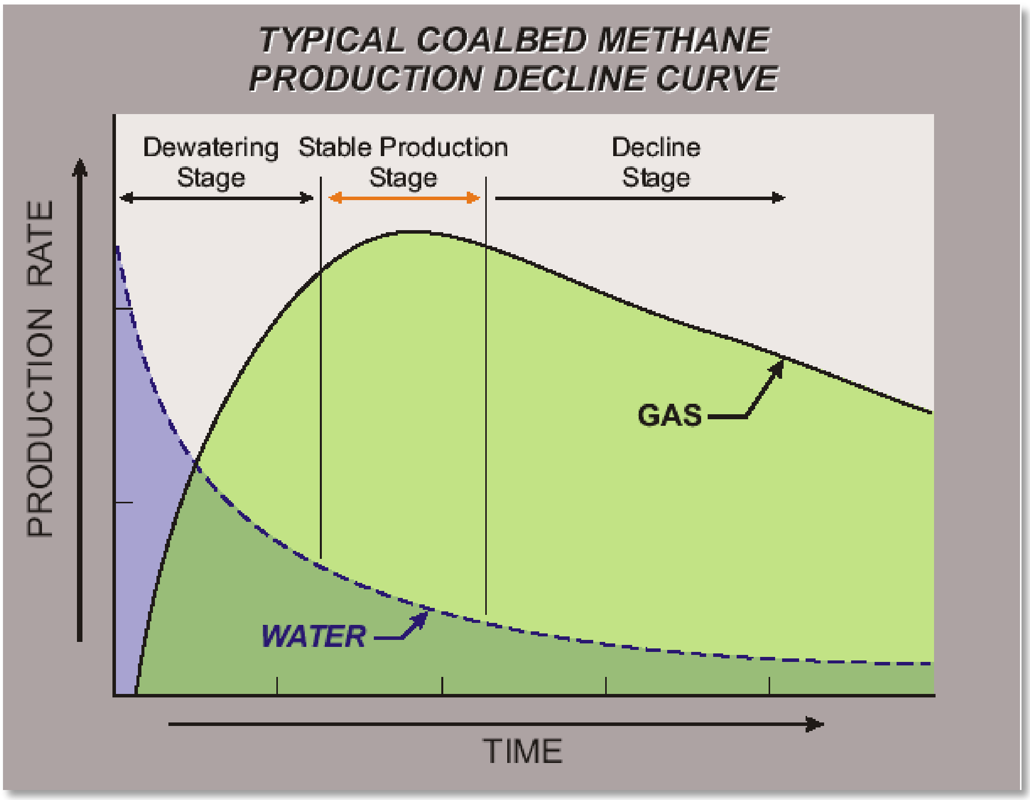
6.3 Coal Seam Gas Production Overview

Coal seam gas is primarily comprised of methane gas. Within a typical coal seam, the methane is bound (adsorbed) to the coal surface, and retained due to the hydrostatic pressure within the formation. When this pressure is released, for instance by pumping groundwater from the coal formation, the gas becomes liberated from the coal surfaces (desorbed) and can flow into the well. Because the coal formation is highly fractured (i.e. naturally by geological processes), there are usually large surface areas available for gas desorption, and the fracture network provides a means for the gas and water to flow to the well. Hence, gas production requires groundwater extraction alongside gas production, and the water is a by-product of the coal seam gas production. The P&G Act uses the term "associated water" to describe water produced in this manner. In this report it is referred to as coal seam gas water.

Arrow has committed that no hydraulic fracturing (‘fraccing’) of the coal will occur in the Surat Gas Project development area. The depth and permeability of the coal makes the process unnecessary.

Producers often have to remove large quantities of water to depressurise coal seams to allow gas to flow, and a key production objective is to minimise the quantity of water produced. If the ratio of water volume to gas produced is too high then a production well becomes uneconomical. Initially, large volumes of water can be produced with initially low gas production. As hydrostatic pressure reduces over time, the flowrate of water decreases and the gas production rate increases. Eventually, towards the end of the life of the production well gas flow rates also decline. Chart 6.1 illustrates this effect.

Chart 6.1 – Typical gas and water produced in a well



Coal seam gas water typically contains significant concentrations of salts, has a high sodium adsorption ratio (SAR) and may contain low concentrations of other dissolved components (e.g. metals). Both the quality and quantity of coal seam gas water varies from gas field to gas field.

6.4 Coal Seam Gas Water

6.4.1 Coal Seam Gas Water Production

Arrow's forecast of coal seam gas water production for the project development area is provided in Table 6.2. While the volume of produced water over the life of the project will vary, current rates of approximately 11 ML/day are expected to increase to a maximum peak of 120 ML/day.

Figure 2.34 (Appendix B) details the projected production of coal seam gas water by development area, and the total projected water production of all Surat Basin coal seam gas operators is shown in Figure 2.36 (Appendix B).

Table 6.2 – Water production rates

Timeline Year	Notional Year	Total LNG Export and Domestic Gas Supply per Annum (ML/year)	Cumulative Total LNG Export and Domestic Gas Supply (ML)
Year 0	2010	4276	4276
Year 1	2011	3839	8115
Year 2	2012	3120	11235
Year 3	2013	3997	15232
Year 4	2014	9801	25033
Year 5	2015	14695	39727
Year 6	2016	26849	66577
Year 7	2017	34198	100775
Year 8	2018	42893	143668
Year 9	2019	37340	181008
Year 10	2020	34759	215767
Year 11	2021	39656	255423
Year 12	2022	32471	287895
Year 13	2023	36134	324028
Year 14	2024	31752	355780
Year 15	2025	35181	390961
Year 16	2026	30917	421879
Year 17	2027	27574	449453
Year 18	2028	26547	476000
Year 19	2029	24091	500091
Year 20	2030	36645	536736
Year 21	2031	48811	585547
Year 22	2032	32241	617788
Year 23	2033	22285	640074
Year 24	2034	16655	656729
Year 25	2035	13106	669834
Year 26	2036	10551	680385
Year 27	2037	8631	689016
Year 28	2038	4196	693212
Year 29	2039	886	394098
Year 30	2040	866	694964

6.4.2 Coal Seam Gas Water Chemistry

Water currently treated at Arrow's existing Daandine and Tipton West facilities is characteristically brackish and containing 3,500 – 6,300 mg/L total dissolved solids (TDS) and Electrical Conductivity (EC) of 5,200 – 9,400 µS/cm (Appendix A). Arrow will continue to monitor coal seam gas water quality as development progresses but development is planned with the assumption that similar water quality and salt concentrations will be realised across the Surat Gas Project area.

The available monitoring data suggests that the key solutes of concern for the likely re-use options are TDS and SAR. These parameters are generally above trigger values for many beneficial use or disposal options. Accordingly, it is likely that some form of treatment will be required for the majority of the coal seam gas water.

6.4.3 Arrow's Water Management Strategy

Under the P&G Act and EP Act, Arrow is required to manage coal seam gas water produced during petroleum activities in accordance with a management plan that must be documented and submitted to DERM. Arrow has developed a coal seam gas water management strategy that identifies options for the management, use and disposal of coal seam gas water and residual salt.

The key challenges in developing a water management strategy include the following:

- Limited water quality characterisation data – at this early stage of the project, there is a minimum of groundwater quality monitoring data (for both coal seam and non-coal seam aquifers). As such, where appropriate, conservative assumptions have been made for the purposes of developing the strategy. Data from the Golders (2009c) Groundwater Impact Study was also utilised in the groundwater quality assessment.
- Uncertainty in water quantity predictions – there is uncertainty over the volumes and rates of coal seam gas water to be produced from each field. The numerical groundwater model (Appendix B) has provided estimates of groundwater abstraction over the life of the project.
- Balancing current operational needs with the longer term objectives of the strategy – current water management needs during current domestic production and ongoing field appraisal stage need to be compatible with the longer term strategy objectives.

With these key challenges in mind, the strategy has been developed so as to be adaptable to the prevailing physical, geographical, regulatory and socio-economic conditions.

6.4.4 Beneficial Uses of Coal Seam Gas Water

Beneficial use of associated water will reduce the potential impacts of the project, and provide added benefit by reducing demand on existing resource aquifers. It is Arrow's preference to supply coal seam gas water to substitute existing allocations of groundwater utilised for irrigation, agriculture, industrial or urban purposes.

The impact assessment assumes that the legislative framework to enable the substitution component of Arrow's water management strategy will be in place, and that Arrow will be able to deliver coal seam gas water (generally in treated form) to third party users, particularly irrigators, as a substitute for groundwater that would otherwise be drawn from aquifers and waterways.

Arrow plans for the majority of the coal seam gas water produced to be able to be used to substitute existing water allocations in the area - i.e. volumes of groundwater extracted for irrigation or other purposes in accordance with existing licences will be replaced with coal seam gas water provided by Arrow. The strategy assumes that substitution of water entitlements will continue until the production of coal seam gas water ceases.

During 2010, Arrow undertook an initial feasibility study into a deep injection trial targeting the Precipice Formation sandstone aquifer. The purpose of the trial is to identify the volume and rate that Arrow could sustainably inject water. The primary purpose of injecting coal seam gas water into shallow and deep aquifers is to mitigate any potential future impacts. The secondary purpose is to investigate the potential for recharge of depleted or stressed aquifers prior to the end of the coal seam gas development. A secondary study has commenced to evaluate the feasibility of shallow injection into the Condamine Alluvium.

The Surat Gas Project EIS assumes that the legislative framework to enable injection of coal seam gas water into shallow and deep aquifers will be in place.

7 GROUNDWATER NUMERICAL MODEL – GROUNDWATER DRAWDOWN PREDICTION

Numerical groundwater modelling was adopted to simulate impacts to the groundwater systems as a result of the project activities. The numerical model provides estimates of drawdown in groundwater levels in response to abstraction of coal seam gas water in an area of approximately 400 km by 300 km. Cumulative effects are considered, including groundwater extraction from four separate coal seam gas operations (i.e. Arrow, QGC, Origin Energy and Santos). The drawdown is simulated over a vertical stratigraphic sequence of over 2000 m extent, from the unconfined Condamine River Alluvium through to the base of the Jurassic sediments. The numerical modelling report (Schlumberger, 2011) is provided in Appendix B.

It is important to note that the modelling presents unmitigated potential drawdown – i.e. the potential drawdown that could occur if no steps were taken to reduce the impact. In practice, impact mitigation measures as detailed in section 9 are an integral component of the project development and will reduce actual impacts.

7.1 Approach

The MODFLOW numerical code (McDonald and Harbaugh, 1988) along with the user interface Groundwater Vistas, Version 5 (ESI, 2007) were used to develop the model and simulate groundwater flow. MODFLOW is an industry standard, widely used groundwater flow code and provides an appropriate platform for the simulation of abstraction of groundwater from the Walloon Coal Measures.

A total of 15 hydrogeological layers were incorporated into the model with the extent, top and base of each layer being sourced directly from a Petrel geological surface model (Schlumberger, 2011). The initial input hydrogeological parameters, including hydraulic conductivity and storage, as shown in Table 4.1, were determined through an extensive literature review. Boundary conditions including abstraction wells, boundary fluxes, drain cells and recharge are described in the modelling report.

7.2 Steady State and Time Variant Models

The steady state and time variant models were produced to simulate and reproduce the observed groundwater levels across the project development area. These models allowed for calibration of the parameters that were ultimately used in the predictive modelling. Various parameters were adjusted within the ranges described in Table 4.1 to provide the best fit between observed and simulated heads at monitoring points and the best representation of regional potentiometric heads.

7.3 Predictive Modelling

The predictive model was constructed using the calibrated parameters and starting conditions from the initial time variant model. The model was used to simulate different abstraction scenarios and then to investigate the sensitivity of predictions to changes in key hydraulic parameters. The hydraulic parameters producing the calibration form the ‘base case’ for use in the predictive modelling.

Three scenarios were considered that investigated the effects of groundwater abstraction from Arrow, QGC, Origin Energy and Santos coal seam gas developments on the regional groundwater system. They are:

- Scenario 1: Arrow only reference case. This scenario seeks to determine the unmitigated impacts on the groundwater system resulting from Arrow coal seam gas operations alone. Abstraction from Arrow coal seam gas wells based on the “reference case”.
- Scenario 2: Combined base case. This scenario seeks to determine the unmitigated impacts on the groundwater system resulting from a combination of Arrow coal seam gas operations and other coal seam gas projects that have taken Final Investment Decision (FID) prior to 31 January 2011. Abstraction from Arrow coal seam gas wells based on the “reference case” and abstraction from QGC and Santos coal seam gas wells. No abstraction from Origin is included in this scenario.
- Scenario 3: Cumulative case. This scenario seeks to determine the unmitigated impacts on the groundwater system resulting from all coal seam gas operations in the Surat Basin, whether they have taken FID or not. Abstraction from Arrow coal seam gas wells based on the “reference case” and abstraction from QGC, Santos and Origin coal seam gas wells.

The Scenario 1 predictive model simulates 30 years of Arrow coal seam gas water production followed by 20 years of recovery. This model simulates the period from 1 January 2011 to 1 January 2061. The Scenario 2 and 3 predictive models simulate 40 years of coal seam gas water production followed by 20 years of recovery. These models simulate the period from 1 January 2011 to 1 January 2071.

The results were considered in terms of the drawdown in groundwater levels from the predicted levels at the start of 2010. The results (drawdown contours) are provided for 2 model time steps; the time of maximum predicted drawdown for the layer in question and 31 December 2061 (20 years after Arrow abstraction ceases). However, as abstraction continues until 2051 in Scenario 2 and 3, in these cases this output time is 20 years after Arrow abstraction ceases but only 10 years after the cessation of all coal seam gas abstraction.

Results from the modelled scenarios are shown in Figures 4.9 to 4.26 in Appendix B and discussed in the impacts section (section 8). Impact mitigation is discussed in section 9.

7.4 Model Sensitivity

Sensitivity analyses were undertaken with the Scenario 1 predictive model (Figures 5.1 – 5.39, Appendix B). The analyses attempt to quantify the control that hydraulic parameters of key units have on model predictions of drawdown. The analyses focussed on the confined storage value used in all layers and the vertical hydraulic conductivity of some key lithological units, specifically the aquitards. This is an important aspect of the development of any numerical model.

Sensitivity simulations require incremental changes to the relevant parameters in the steady state, time variant historical and time variant predictive models and then running these in sequence. The projected coal seam gas abstraction used in Scenario 1 was applied to all sensitivity simulations. The results are detailed in Appendix B.

It is recommended that ongoing re-calibration of the model is performed as new data about aquifer properties and water level impact comes to hand. This will assist in refining the predicted impacts and ensure monitoring programs are appropriately designed.

8 POTENTIAL IMPACTS

The Surat Gas Project has the potential to cause impacts to the groundwater systems through activities associated with the project development, operation and decommissioning phases.

Impact assessment is used to determine the potential threat that project activities pose to the environmental values of the project development area and beyond. The environmental values relevant to the groundwater assessment of the EIS have previously been identified in section 5.

Potential groundwater related impacts associated with the proposed coal seam gas field development generally fall within the following categories:

1) Direct impacts caused by coal seam depressurisation;

2) Indirect impacts caused by coal seam depressurisation;

3) Impacts caused by field and infrastructure development, operation and decommissioning; and

4) Cumulative impacts caused by other developments.

The potential impacts associated with the project activities were assessed in order to enable impact mitigation measures to be developed. An assessment of the significance of impacts and mitigation measures is presented in section 9.

8.1 Depressurisation Impacts

Depressurisation of groundwater aquifers is a key activity of coal seam gas production. This activity produces significant volumes of coal seam gas water. This assessment considers both primary (direct) impacts which occur as a result of depressurisation of the Walloon Coal Measures, and secondary (indirect) impacts that could potentially occur as a result of the primary impact. The assumptions made in assessing the depressurisation impacts include:

Primary (direct) impacts that will occur (caused by coal seam gas abstraction from the Walloon Coal Measures) include:

- Potentiometric surface drawdown in the Walloon Coal Measures, potentially causing:
    - Reduced flows to any groundwater discharge features (e.g. streams, springs) that may be fed by the Walloon Coal Measures.
    - Reduced supply to existing or future groundwater users accessing groundwater from the Walloon Coal Measures.

Mitigation measures and residual impact significance related to depressurisation of the Walloon Coal Measures and related groundwater systems (direct impacts) are shown in Section 9, Table 9.6.

Secondary (indirect) impacts that have the potential to occur (caused by coal seam gas abstraction from the adjacent Walloon Coal Measures and depressurisation related flow through coal seam gas wells) include:

- Induced flow (leakage) between aquifers above and below the Walloon Coal Measures and between those adjacent groundwater systems, causing:

- Groundwater quality impacts from inter-aquifer flows across aquifers within all groundwater systems.

- Potentiometric surface drawdown in groundwater systems above or below the Walloon Coal Measures, causing:
  - Reduced supply to existing or future groundwater users accessing groundwater from aquifers above or below the Walloon Coal Measures.
  - Reduced flows to groundwater discharge features (e.g. streams, springs) fed from groundwater systems above or below the Walloon Coal Measures.
  - Impacts to cultural/spiritual values.
  - Land subsidence.

Mitigation measures and residual impact significance related to depressurisation of the shallow, intermediate and deep groundwater systems as a consequence of depressurisation of the Walloon Coal Measures (indirect impacts) are shown in Section 9, Table 9.7.

8.1.1 Drawdown Impact Modelling Results

Modelling has been used to predict unmitigated drawdown impacts on key resource aquifers, and understand groundwater system recovery modes upon cessation of production (section 7).

The groundwater modelling indicates that depressurisation may cause significant drawdown in the Walloon Coal Measure formation. In addition, vertical hydraulic gradient changes are expected to cause drawdown in adjacent formations and potential inter-aquifer transfer of groundwater. The results are discussed below, and summarised in Table 8.1.

Shallow Groundwater System

- **Scenario 1:** Outputs from the simulations from Scenario 1 predicted unmitigated drawdowns in the Condamine Alluvium ranging from just over 1 m to less than 0.1 m. The greatest drawdown is predicted to occur in the vicinity of the Dalby Development area, along the western extent of the Condamine Alluvium. In this area the peak predicted drawdown occurs in 2059 (Figure 4.9, Appendix B).
- **Scenario 2:** When abstraction from QGC and Santos fields are simulated (Scenario 2), the magnitude of unmitigated drawdown is greater peaking in 2060 at between 0.5 and 2 m along the western extent of the Condamine Alluvium (Figure 4.19, Appendix B).
- **Scenario 3:** Maximum unmitigated drawdown of about 2.5 m is predicted in the western extent of the Condamine Alluvium in 2065 in Scenario 3 (Figure 4.23, Appendix B).

Intermediate Groundwater System

- **Scenario 1:**
  - The Kumbarilla Beds outcrop within and to the west of the project development area and it is in this area that the maximum drawdown is predicted for the intermediate groundwater system (Figure 4.10, Appendix B). The greatest predicted unmitigated drawdown occurs in 2029, with between 20 and 30 m predicted to the northeast and 15 to 20 m to the southeast. However, this

level of drawdown is limited to relatively small areas and the average drawdown in the vicinity of the project development area is about 2.5 to 5.0 m at this time.

- The Mooga Sandstone shows a maximum predicted drawdown of 5 m by 2047 during abstraction from Arrow wells based on scenario 1 (Figure 4.11, Appendix B).
- The Gubberamunda Sandstone and Springbok Sandstone show a maximum drawdown of 15 m and 30 m in 2031 and 2024 respectively (Figures 4.12 and 4.13, Appendix B).

- **Scenario 2:** When abstraction from QGC and Santos fields are simulated (scenario 2), the maximum unmitigated predicted drawdown in the Springbok Sandstone is between 40 and 50 m and occurs between Miles and Chinchilla in 2036 (Figure 4.20, Appendix B). By 2061 water levels have recovered in most areas to within 10 m of the 2011 levels.
- **Scenario 3:** Predicted drawdown in the Springbok Sandstone in scenario 3 peaks at between 50 and 60 m between Miles and Chinchilla in 2039 (Figure 4.24, Appendix B). This reduces to between 20 and 30 m by 2061.

Coal Seam Gas Groundwater System - Walloon Coal Measures

- **Scenario 1:** Drawdown in the coal measures is predicted to be greatest in the Juandah Measures where it peaks for scenario 1 in 2024 at a value in excess of 75 m (Figure 4.14, Appendix B). The Taroom Coal Measures and the Tangalooma Sandstone experience a maximum unmitigated drawdown of between 50 m and 75 m in 2024 for scenario 1. This reduces to less than 10 m by 2067 (Figures 4.15 and 4.16, Appendix B).
- **Scenario 2:** Drawdown in the Juandah coal measures is predicted to peak in 2024, with drawdown averaging approximately 50 across the majority of the project development area. In the area west of Dalby, the drawdown is greatest, reaching approximately 150 m. By 2061, the predicted contours show areas of recovery in the region between Miles and Chinchilla, and to the southwest of Dalby. Drawdowns are predicted to recover to between 5 and 10 m across the majority of the project development area by 2061, with 10 to 20 m drawdown levels remaining in the central region of the project development area. Refer to Appendix D for model output figures.
- **Scenario 3:** Drawdown in the Junadah coal measures is predicted to peak in 2024, with drawdown averaging approximately 70m across the majority of the project development area. In the area west of the project development area, the drawdown is greatest, exceeding 150 m in places. By 2061, the predicted contours show areas of recovery in the region between Miles and Chinchilla, and to the southwest of Dalby. Drawdowns are predicted to recover to between 5 and 20 m across the majority of the project development area by 2061, with 20 to 30 m drawdown levels remaining to the west of the project development area. Refer to Appendix D for model output figures.

Deep Groundwater System

- **Scenario 1:** Simulations from scenario 1 predicted maximum unmitigated drawdowns in the Hutton Sandstone and Precipice Sandstone of 30 m and 20 m respectively (Figures 4.17 and 4.18, Appendix B). By 2062 drawdown had reduced to approximately 15 m in the Hutton Sandstone and 15 m in the Precipice Sandstone.
- **Scenario 2:** Significantly more drawdown is predicted in scenario 2 and peaks at approximately 40 m in 2029 in the Hutton Sandstone and 40 m in 2039 in the Precipice Sandstone (Figures 4.21 & 4.22, Appendix B).

- **Scenario 3:** In scenario 3, the maximum predicted unmitigated drawdown in the Hutton Sandstone (Figure 4.25, Appendix B) occurs in 2039 in an elongate zone just to the west of the Chinchilla, Millmerran/Kogan and Dalby Development areas. Drawdown in this area is between 50 and 70 m. Predicted drawdown in the Precipice Sandstone in scenario 3 is greatest to the southwest of Dalby, in the vicinity of the QGC Southern Development area and Arrow Dalby Development area (Figure 4.26, Appendix B).

Table 8.1 – Predicted typical maximum drawdowns in key aquifers within each groundwater system

Groundwater System and Aquifer(s)	Predicted Typical Maximum Drawdown (m) Scenario 1	Predicted Typical Maximum Drawdown (m) Scenario 2	Predicted Typical Maximum Drawdown (m) Scenario 3
Shallow Groundwater System (Condamine Alluvium)	1	2	2.5
Intermediate Groundwater System (Gubberamunda Sandstone and Springbok Sandstone)	30	50	60
Coal Seam Gas Groundwater system (Juandah Coal Measures)	75	100 - 150	>150
Deep Groundwater System (Hutton and Precipice Sandstones)Aquifers	30	60	75

8.2 Field Development and Operations Impact

The Surat Gas Project conceptual field development is summarised in section 6 of this report. Field development activities that have potential to impact on environmental values in the region include both wellfield development and infrastructure development.

Mitigation measures and residual impact significance related to field development and operations are shown in Section 9, Table 9.8.

8.2.1 Wellfield Development and other Sub-surface Activities

Coal seam gas production requires the drilling and installation of strategically located production wells across the development areas, and the installation of groundwater and gas monitoring and/or investigation wells. The installation process and installed wells have some potential to create environmental impacts. In addition, wells may require decommissioning when no longer required. Some of the potential impacts associated with the drilling and installation of production wells also apply to drilling of monitoring wells, and these are considered together in the impact assessment process.

Other sub-surface activities include the installation of gathering lines to transfer gas and water between wells and associated facilities.

8.2.2 Water Storage, Infrastructure, Processing and Distribution Impacts

Ancillary infrastructure associated with the coal seam gas development and expansion within the coal seam gas fields which may impact on groundwater includes; facilities (field compression facilities, central gas processing facilities and integrated processing facilities), gas and water gathering line networks, maintenance and lay down yards, electricity generation facilities, workers accommodation including sewage treatment plants, workshops, and storage facilities.

8.2.3 Assessment of Field Development Impacts

Table 8.2 provides a summary of the potential impacts associated with field development.

Table 8.2 – Potential impacts - field development

Impact	Potentially Affected Groundwater System(s)
Wellfield Development and Sub-surface Impacts	
Well installation – cross-contamination of aquifers	All groundwater systems *Production and monitoring wells will potentially intersect all groundwater systems.* *Sub-surface activities can potentially impact all groundwater systems.*
Well installation – contamination by drilling process	
Well installation – contamination by surface process	
Installation of sub-surface infrastructure – contamination from leaks and spills	
Water Storage, Infrastructure, Processing and Distribution Impacts	
Contamination of groundwater systems - storage of chemicals, fuels, oils	Shallow, Intermediate and Coal Seam Gas Groundwater Systems. *The Deep Groundwater System is excluded based on depth and isolation from these surface processes.*
Contamination of groundwater systems - waste generation and storage	
Contamination of groundwater systems - waste water and sanitation (effluent)	
Infrastructure Footprint Impacts	
Reduced aquifer recharge	Shallow, Intermediate and Coal Seam Gas Groundwater Systems. *The Deep Groundwater System is excluded based on depth and isolation from these surface processes.*
Installation of gas reticulation facilities and compressor stations	

8.3 Impacts from Coal Seam Gas Water

Managing coal seam gas water is challenging due to its variable quality and typically high volumes. Quality issues such as high concentrations of salts, high SAR commonly makes the water unsuitable for release to the environment or for many beneficial uses without treatment. Because of this, in the past a common management technique has been to dispose of the water through evaporation ponds. However changes to government policy have necessitated a change to using the water for beneficial purposes.

Details of Arrow's coal seam gas water management strategy are contained in section 6.4. Table 8.3 provides a summary of the potential impacts associated with coal seam gas water.

Table 8.3 – Potential impacts - coal seam gas water

Impact	**Potentially Affected Groundwater System(s)**
Impact to shallow groundwater systems caused by seepage of untreated coal seam gas water from storage facilities	Shallow Groundwater System. *The Intermediate, Coal Seam Gas and Deep Groundwater Systems are excluded based on depth and isolation from these surface processes.*
Altered groundwater flow direction	
Impact to shallow groundwater caused by seepage of brine concentrate from storage facilities	
Unplanned discharge of untreated coal seam gas water to the land surface	
Unplanned discharge of untreated water or brine to the land surface	

Mitigation measures and residual impact significance related to CSG water impacts are shown in Section 9, Table 9.8.

8.4 Land Subsidence Associated with Coal Seam Gas Production

Subsidence can be defined as the movement of the surface strata in response to the loss of underground support (Nagel, 2001). A loss of underground support can come from hydrocarbon removal from a reservoir, groundwater extraction from an aquifer and associated strata compaction (for water use or dewatering purposes) or from the creation of voids in the strata due to hard ore mining. Although the impact of subsidence may be more noticeable in the vertical direction, mediating the occurrence of subsidence can be equally important in the horizontal direction (Allen & Mayuga, 1970).

Documented cases of anthropogenic induced subsidence have been reported as early as 1918 in relation to hydrocarbon removal (Pratt & Johnson, 1929). The effects of subsidence include general land depression, shoreline and roadway subsidence, surface faulting, well failure, and disruption to surface structures. The phenomenon is not unique to hydrocarbon removal, subsidence effects have also been documented where groundwater extraction and underground and open-cut mining activities are occurring.

Although hydrocarbon industry related subsidence is well documented, some of the fundamental phenomena and mechanisms encountered in gas production from coal have not been studied in detail, and are unable to be explained by the current level of knowledge, such as long term consequence effects (Harpalani & Chen, 1997; Siriwardane, Raj, & Smith, 2009).

8.4.1 Subsidence in Coal Formations

One potential mechanism for subsidence occurring from the production of coal seam gas is volumetric changes in the coal formation and adjacent overburden (referred to as matrix volumetric strain). In some circumstances, a volumetric decrease can occur in a reservoir due to pore pressure reduction, which increases the stress applied to the rock matrix. Pore pressure reduction can occur during both dewatering and methane production stages (Myer, 2003).

Swelling of coal due to sorption of liquids has been reported by Gregg, (1961) and Green et al., (1985). Swelling of coal in the presence of an adsorptive gas (i.e. methane) has also been investigated in the past. Moffat and Weale (1955) reported studying the swelling and shrinkage of coal with adsorption or desorption of methane.

Documented literature estimating the magnitude of subsidence occurring with coal seam gas is limited.

8.4.2 Reservoir Compaction

Compaction of reservoir formations and overburden can occur from the thinning of the reservoir layers, and is a major cause of surface subsidence. The process is governed by 3 primary parameters; increasing effective stress, reservoir thickness and reservoir rock compressibility (Nagel, 2001). Reservoir compaction occurs when the underground system (initially in equilibrium) experiences a physical change (for example, gas extraction). During the removal of gas, hydrocarbon or groundwater, pore pressure declines and the effective stress (defined as the difference between the external stress and the pore pressure) increases (Nagel, 2001). This change to the effective stress acting upon a rock matrix will result in compaction until a new equilibrium is reached with the new effective stress state.

Reservoir thickness and reservoir rock compressibility are intrinsic characteristics of the reservoir, and are generally unalterable (Nagel, 2001). Thus these two parameters help define the potential extent of compaction. A greater thickness and higher compressibility will result in a larger potential for subsidence (Han, Sang, Cheng, & Huang, 2009) (Nagel, 2001). Compressibility is difficult to measure, itself being a function of rock mass constituent composition, the degree of sorting, the nature of mineral decomposition or alteration, cementation and the porosity of the rock (Nagel, 2001).

Permeability of coal formations is recognised as the most important parameter for coal seam gas production (Shi & Durucan, 2004) and a loss of permeability will result in a loss of gas production. Permeability of the coal seam is influenced in two ways; through phase-relative permeability effects and through a change in the effective stress within the seam (Harpalani & Chen, 1997). Methane desorption results in matrix shrinkage, which whilst significantly increasing coal permeability, may cause subsidence of the overburden (Myer, 2003).

8.4.3 Overburden Compaction

Pore pressure reduction can also occur in the overburden or confining layers due to dewatering. The magnitude of the volumetric decrease will depend on the compressibility and thickness of the affected strata. On the flanks of a structural controlled reservoir, bending of the overburden layers results in shear stress, potentially causing failure or slip on pre-existing discontinuities. If the pore pressure distribution, and hence, volumetric deformation, in the reservoir is not uniform, shear displacements in the overburden will be introduced at other places other than the flanks (Myer, 2003). It is possible that these secondary effects of subsidence may be more pronounced or have a greater impact on structures than regional subsidence due to the speed at which movement might occur.

In non-structural reservoirs, such as coal-seam gas formations in horizontal or sub-horizontal strata, such shear displacements may be less likely. Instead, matrix shrinkage may be more an issue.

In addition, matrix shrinkage may have an impact on long-term gas production from coal seam reservoirs (Harpalani & Chen, 1997)(Siriwardane, Raj, & Smith, 2009).

8.4.4 Risks Associated with Coal Seam Subsidence

The available literature on risks associated with coal seam subsidence focuses on the impact of coal seam shrinkage upon gas production; while limited data was found regarding the occurrence of subsidence from coal seam gas production or the impacts of coal seam gas induced subsidence. Although there is a lack of reported cases in the literature, the potential for subsidence to occur is still relevant to an impact assessment.

Land subsidence is a process that can occur over a wide range of temporal scales, from almost instantaneous settlement to very slow rates of ground level drop over long time-periods.

The occurrence of subsidence can cause changes to flood plain morphology (Zekster, Loaiciga, & Wolf, 2005). This could influence surface water runoff and may cause changes to flood regimes, and could precipitate a need to revise flood mapping if realised.

The most immediate impact of significant subsidence may involve surface structures (Nagel, 2001). However in cases of regional subsidence, the effects may not be as damaging to structures as localised subsidence. Subsidence and compaction can also affect gas and water production, and well casing deformation can occur due to axial buckling in the reservoir or horizontal shearing in the overburden.

Fissuring can be produced through differential settlement of subsiding lands (Zekster, Loaiciga, & Wolf, 2005). Fissures may be produced at pre-existing faults. Risks of failure or slip of pre-existing faults within the coal formation due to subsidence within the formation are dependent on the depth, in-situ stress state, pressure drawdown, coal strength and poro-elastic properties (Nagel, 2001). As a formation compacts, system changes may cause large principal stress differences increasing the potential for failure and slippage.

Although the permeability of coal increases with desorption of methane gas during production, the increase in effective stress due to a reduction in pressure also tends to cause a reduction in coal permeability. Results from Harpalani & Chen, 1997 suggest that the decrease in permeability due to increased effective stress is balanced by the overall increase in permeability from matrix shrinkage.

8.4.5 Conclusions

Based on the literature assessment, it is considered that the risk of land subsidence is not high but nevertheless cannot be entirely ruled out, and it is recognised that the major pressure reductions will occur in geological formations comprising consolidated rock. Because of the significant depth to the coal bearing formations, and the large areal extent of the depressurisation, the likely effects of any subsidence are considered unlikely to have significant impact on structures at the surface, and in particular any settlement that could occur is likely to be widespread and without differential movement.

9 SIGNIFICANCE ASSESSMENT AND IMPACT MITIGATION

9.1 Introduction

In section 8, potential impacts caused by the project to the groundwater systems were identified.

Assessment of the significance of these impacts is fundamental to environmental and social impact assessment, and provides stakeholders and decision makers with information about the importance of the environmental, social and cultural resources potentially affected by the development. Understanding the significance of potential impact enables an informed decision making framework.

In this study, the 'significance' of an impact is defined as *"An assessment of the sensitivity of an environmental value and the magnitude of potential impacts on that value."*

This section presents the significance approach methodology, and its application to the Surat Gas Project.

9.1.1 Significance Assessment Approach

An assessment approach based on sensitivity and magnitude has been adopted for this environmental impact assessment to determine the significance of impacts. In this approach, the significance of an impact is assessed by considering both the sensitivity of the environmental value and the magnitude of the impact, before and after the application of mitigation measures. This enables the effectiveness of the proposed mitigation measures in reducing the predicted impact to be assessed.

This approach assumes the identified impacts will occur, and focuses attention on the mitigation and management of potential impacts through the identification and development of effective design responses and environmental controls. This is a conservative method that enables a more comprehensive understanding and assessment of the likely impacts of the project.

9.1.2 Mitigation of Impacts

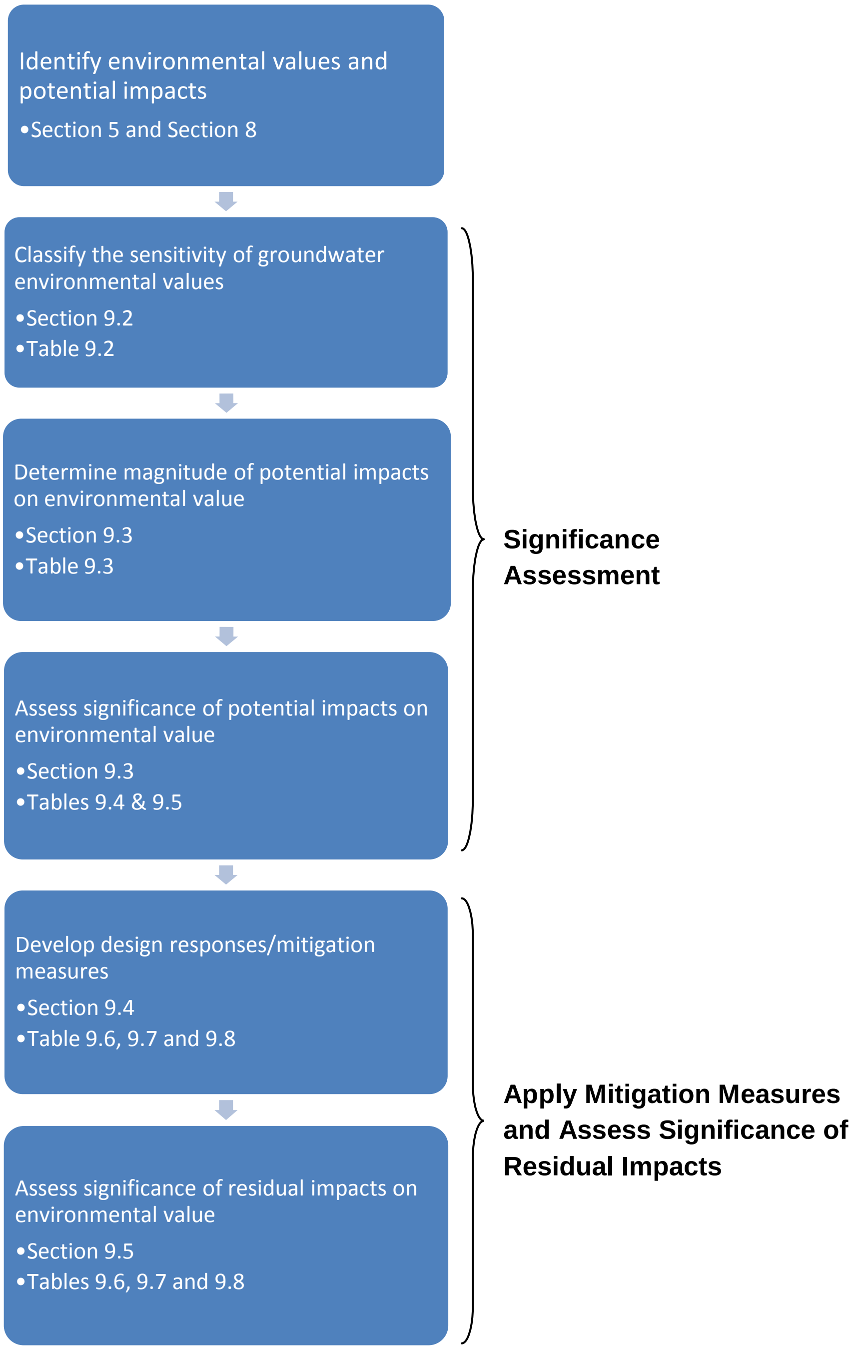
Section 8 identified potential impacts related to the project, and allows for the development of management and mitigation measures to ensure that impacts are addressed, and that environmental values are not adversely or irreversibly impacted. Application of appropriate management and mitigation measures will reduce the potential for adverse 'residual impacts' in the potential impact area of the project. Residual impacts are the potential impacts remaining after the application of mitigation measures or design responses.

The extent to which potential impacts have been reduced is also determined by undertaking an assessment of the significance of the residual impacts, giving a measure of the effectiveness of the mitigation measures or design responses in reducing the magnitude of the potential impacts. If proposed mitigation measures or design responses are ineffective in reducing the significance of the residual impacts, additional or new measures/responses may need to be developed.

Chart 9.1 provides a flow chart for the overall impact assessment process (with cross-references to relevant tables and sections of this report associated with the method) and identifies those steps that comprise the significance assessment.

Sections 9.2 and 9.3 describe the environmental values classification and significance assessment process. Sections 9.4 and 9.5 present the impact mitigation and summary tables.

Chart 9.1 – Impact assessment - process flow and cross reference



9.2 Environmental values – sensitivity classification

To assess the sensitivity of environmental values, a rating scheme must be applied to the values.

In the process adopted, the sensitivity of an environmental value is determined from its intrinsic characteristics, or susceptibility to threatening processes. This requires the establishment of a sensitivity classification scheme. While there are several aspects of a groundwater system that determine its sensitivity, the classification scheme provides a mechanism for determining an overall sensitivity rating. The following section discusses assumptions and constraints for the classification scheme. Table 9.1 presents the scheme, and shows the criteria adopted for classifying the sensitivity of the groundwater systems.

9.2.1 Assumptions and Constraints

The classification scheme used to assign sensitivity considers the following assumptions and constraints:

- The sensitivity criteria are assessed based on the potential impact area of the project, which can extend beyond the boundary of the project development area.
- Biological values are assessed with consideration of typical groundwater quality potentially available to support ecosystems, as well as the physical likelihood of supporting ecosystems (i.e. the ability of the groundwater system to discharge to surface features).
- Discharge springs or areas of cultural/spiritual importance are potentially located within the area that may be affected by drawdown of groundwater. DERM have assigned drawdown levels to trigger further investigation, and based on the modelled drawdowns and the DERM trigger levels, a number of specific springs located to the north and west of the project development area (and within the extent of the numerical groundwater model) have conservatively been included in the assessment as potentially subject to impact. The Injune Creek Group and the Evergreen Formation are identified as the potential source formations. The identified springs are located on the edge of the mapped extent of the formations within the Injune Creek Group, and the Evergreen Formation is not generally identified as an aquifer across the region. The specific aquifers that serve as a source for the identified springs remain unclear, and the identification and ground truthing of priority springs forms part of the responsibilities of the QWC. Given all of the above, the specific magnitude of potential impacts to the identified springs from drawdown in the Walloon Coal Measures aquifer is unknown at this time. The impact assessment below is based on known information and incorporates the future requirements for Arrow to develop monitoring programs and mitigation measures in association with the QWC and related SIMS.
- Consumptive and productive uses consider the general groundwater quality available.
- Although specific cultural and spiritual sites have not been identified that will be impacted by the project, it is feasible that isolated occurrences might exist and therefore have been considered in the impact assessment.
- Groundwater baseflow to the Condamine River has been considered to support cultural values of the River.
- The overall sensitivity rankings incorporate a variety of properties that respond in different ways.

- The context for resilience is with respect to drawdown recovery sensitivity, whereby high sensitivity equates to longer expected recovery times when the stress is removed, while low sensitivity equates to shorter expected recovery times when the stress is removed.
- Rehabilitation potential is considered with respect to impacts from depressurisation.

Table 9.1 – Groundwater system sensitivity classification criteria

Sensitivity Criteria		Very Low Sensitivity	Low Sensitivity	Moderate Sensitivity	High Sensitivity	Very High Sensitivity
Conservation status elements of the groundwater system as defined by statutory and regulatory authorities. This is related to the suitability of the water to support biological values, consumptive and productive values, and anthropomorphic values.	Biological values	Within the potential impact area of the project, groundwater does not support ecosystems.	Within the potential impact area of the project, groundwater can discharge to surface features and intrinsic properties support highly disturbed ecosystems.	Within the potential impact area of the project, groundwater can discharge to surface features and intrinsic properties support slightly to moderately disturbed ecosystems.	Within the potential impact area of the project, groundwater has the potential to discharge to surface features and intrinsic properties may support pristine ecosystems.	Within the potential impact area of the project, groundwater discharges to surface features and the intrinsic properties identified to support pristine ecosystems of national environmental significance.
	Consumptive and productive values	Within the majority of the potential impact area of the project, groundwater quality is unsuitable for any practical use.	Within the majority of the potential impact area of the project, groundwater quality is suitable for industrial use or aquaculture.	Within the majority of the potential impact area of the project, groundwater quality is suitable for production of aquatic food for human consumption or stock watering.	Within the majority of the potential impact area of the project, groundwater quality is suitable for agricultural use.	Within the majority of the potential impact area of the project, groundwater quality is suitable for potable supply.
	Anthropomorphic values	Intrinsic properties of groundwater do not support areas of spiritual or cultural significance within the potential impact area of the project.	Intrinsic properties of groundwater support isolated areas of spiritual or cultural significance within the potential impact area of the project.	Intrinsic properties of groundwater support numerous areas of spiritual and cultural significance within the potential impact area of the project.	Intrinsic properties of groundwater support areas of spiritual or cultural significance within the potential impact area of the project that are listed on the National Heritage register.	Intrinsic properties of groundwater support areas of spiritual or cultural significance within the potential impact area of the project that are inscribed on the World Heritage List.
Rarity of occurrence, abundance or distribution of groundwater system or aquifer type and availability of equivalent or representative alternatives		Attributes of the groundwater system are ubiquitous.	Attributes of the groundwater system are common on a local, regional and national basis, and therefore have local equivalents.	Attributes of the groundwater system are locally unique, but have regional equivalents.	Attributes of the groundwater system are locally unique, but with few regional equivalents.	Attributes of the groundwater system are unique. There are no regional equivalents.
Resilience to change (i.e. groundwater properties such as water level or pressure changes, porosity reduction)		Intrinsic properties of the groundwater system are completely resilient to change (as a result of depressurisation, for example).	Intrinsic properties of the groundwater system are highly resilient to change (as a result of depressurisation, for example).	Intrinsic properties of the groundwater system are moderately resilient to change, (as a result of depressurisation, for example) and the overall function of the groundwater system is relatively unchanged.	Intrinsic properties of the groundwater system are slightly resilient to change (as a result of depressurisation, for example) and the overall function of the groundwater system could be temporarily altered.	Intrinsic properties of the groundwater system are rigid to change (as a result of depressurisation, for example) and the overall function of the groundwater system could be permanently altered.
Dynamicism of existing environment (i.e. hydrogeologic processes)		Groundwater systems with high recharge rates and short recovery periods.	Groundwater systems with moderate recharge rates and medium term recovery periods.	Groundwater systems with low recharge rates and longer recovery periods.	Groundwater systems with very low recharge rates and very long recovery periods.	Groundwater systems isolated from recharge processes where pressure reduction would be permanent.
Rehabilitation potential		Rehabilitation can be successfully achieved in all cases.	Rehabilitation can be successfully achieved in the majority of cases.	Rehabilitation is likely to be slow or only partially successful.	Rehabilitation potential is limited or only successful in the minority of cases.	Extremely limited rehabilitation potential if impact on the value cannot be avoided.

A sensitivity weighting was assigned to each groundwater value, for each groundwater system, depending on its assessment of very high, high, moderate, low or very low sensitivity (5, 4, 3, 2 or 1 respectively).

The weightings assigned to each value were then summed to rank each groundwater system, and assign an overall sensitivity classification. The overall sensitivity rankings take into consideration the intrinsic properties and geologic/hydrogeologic processes that influence the way a groundwater system responds to an impact. This groundwater sensitivity classification underpins the significance assessment in the following sections.

The classification criteria in Table 9.1, together with the assumptions and constraints detailed above have been used to assess the sensitivity of the groundwater systems, as presented in Table 9.2. Specific characteristics that determine the overall sensitivity of each groundwater system are detailed below.

Overall sensitivity of the shallow groundwater system:

The shallow groundwater system is considered to have the following general characteristics for assessment of sensitivity:

- The Condamine Alluvium aquifer discharges to the Condamine River in some reaches, and is of moderate biological importance.
- Groundwater from this system is a supply generally suitable for agricultural uses in most places across the area of potential impact. It is suitable for potable use in some areas.
- Where baseflow discharge to the Condamine River occurs, the Condamine Alluvium aquifer may indirectly support cultural values associated with the Condamine River.
- The Condamine Alluvium aquifer is associated with the Condamine River valley. Although shallow aquifers are generally common, there are few regional equivalents and the aquifer is locally unique.
- The physical aspects of the aquifers within the shallow groundwater system make them highly resilient to depressurisation impacts.
- The shallow groundwater system is dynamic, with several recharge mechanisms. Shallow aquifers in the project development area are predominantly recharged from surface drainage, particularly from the main branch of the Condamine River (Huxley 1982, SKM 1999). However diffuse recharge and bedrock recharge can also occur. Recharge through surface soils of the Condamine River Valley can be limited due to low permeability soil types (i.e. black cracking-clay soils).
- The Condamine Alluvium directly overlies the Walloon Sub-Group in some parts of the project development area. Groundwater flow between these two units is possible.
- Shallow aquifers are recharged regularly through surface processes and bedrock leakage, and rapid groundwater level recovery is possible, compared with confined systems.
- Historical over abstraction by groundwater users and over allocation of the groundwater resource.
- Rehabilitation can be achieved when impacts are removed.

Overall sensitivity of the intermediate groundwater system:

The intermediate groundwater system is considered to have the following general characteristics for assessment of sensitivity:

- Groundwater from this system is of moderate biological importance due to generally better water quality than coal seam formations.
- The aquifers in this groundwater system provide a supply generally suitable for agricultural uses in most places across the area of potential impact. It is suitable for potable use in some areas.
- The aquifers in the intermediate groundwater system are not known to support areas of cultural or spiritual significance.
- The intermediate groundwater system forms a regional aquifer system across the GAB, and equivalent aquifers are common in many areas
- The physical aspects of the aquifers within the intermediate groundwater system make the system moderately resilient to depressurisation impacts.
- The intermediate groundwater system is more dynamic than deeper groundwater systems. The aquifers within the intermediate groundwater system are recharged through rainfall only where outcropping, and through inter-aquifer leakage, and can recover from groundwater drawdown over the medium term.
- Rehabilitation can be achieved when impacts are removed.

Overall sensitivity of the coal seam gas groundwater system:

- Groundwater from this system is of low biological importance, due to limited ability to discharge to surface water features and generally poorer water quality than other groundwater systems.
- The aquifers in the coal seam groundwater system provide a brackish to saline supply generally suitable for industrial uses or stock watering.
- The aquifers in the coal seam gas groundwater system are not known to support areas of cultural or spiritual significance.
- The coal seam gas groundwater system is a regional aquifer system across the GAB, and equivalent aquifers are common in many areas.
- The physical aspects of the aquifers within the coal seam gas groundwater system make the system moderately resilient to depressurisation impacts.
- The coal seam gas groundwater system is less dynamic than other shallower systems, with limited recharge mechanisms. The aquifers within the coal seam gas groundwater system are recharged through rainfall only where outcropping, and through inter-aquifer leakage, and can recover from groundwater drawdown slowly.
- Rehabilitation can be achieved when impacts are removed.

Overall sensitivity of the deep groundwater system:

- Aquifers in the deep groundwater system have the potential to discharge to surface features. They are of high biological importance due to the identified connection between them and mound spring complexes in more regional GAB groundwater discharge areas.
- The aquifers of the deep groundwater system provide a supply generally suitable for agricultural uses and stock watering in most places across the area of potential impact. Groundwater from this system is suitable for potable use in some areas.
- The aquifers in the deep groundwater system have historical cultural significance as artesian supply.
- The deep groundwater system is a locally unique aquifer system; however equivalent regional aquifers are common across the GAB.
- The physical aspects of the aquifers within the deep groundwater system provide some resilience to depressurisation impacts.
- The deep groundwater system is less dynamic than other shallower systems, with limited recharge mechanisms. The aquifers within the deep groundwater system are recharged through rainfall in distal areas where outcropping, and through inter-aquifer leakage, and can have long pressure recovery periods.
- Rehabilitation can be achieved when impacts are removed.

Table 9.2 – Assessment of groundwater sensitivity within the study area

GROUNDWATER SYSTEM	CONSERVATION STATUS			RARITY	RESILIENCE	DYNAMICISM	REHABILITATION POTENTIAL	SENSITIVITY RANKING	CLASSIFICATION
	BIOLOGICAL	CONSUMPTIVE AND PRODUCTIVE USE	ANTHROPOMORPHIC						
SHALLOW GROUNDWATER SYSTEMS (Unconfined or watertable aquifers)	**3**	**4**	**3**	**4**	**2**	**2**	**2**	**20**	**MODERATE**
INTERMEDIATE GROUNDWATER SYSTEMS (confined aquifers located above coal seam gas formations)	**3**	**4**	**1**	**2**	**3**	**3**	**2**	**18**	**MODERATE**
COAL SEAM GROUNDWATER SYSTEMS (confined aquifers associated with coal seam gas formations)	**1**	**3**	**1**	**2**	**3**	**3**	**2**	**15**	**LOW**
DEEP GROUNDWATER SYSTEMS (confined aquifers located below coal seam gas formations)	**4**	**4**	**3**	**3**	**4**	**4**	**2**	**24**	**HIGH**

Notes: Groundwater Sensitivity Weighting: Very High = 5, High = 4, Moderate = 3, Low = 2, Very Low = 1 **Sensitivity Classification**: Very Low = <10, Low = 10 - 15, Moderate = 16 - 20, High = 21 – 25, Very High = >25

9.3 Significance Assessment Methodology

9.3.1 Sensitivity Rating and Impact Magnitude Rating

The significance of potential impacts is determined by considering both the identified sensitivity of the impact on the environmental value based on the sensitivity classification in Table 9.2, and the magnitude of a potential impact on the environmental value.

Tables 9.2 presents the criteria used for sensitivity rating, and Table 9.3 presents the magnitude rating criteria.

Table 9.3 – Impact magnitude rating criteria

Magnitude Rating	Rank	Criteria
Very Low	1	Impact is restricted to within the area of activity or footprint. No short-term or long-term project impacts likely to environmental values.
Low	2	Some minor project impacts likely to environmental values, but such impacts likely for short duration only, with rapid recovery following end of impacting activity. Impact may extend beyond the area of activity or footprint, but is localised. Where impact is to an aquifer: • the impact is restricted to within that aquifer only; and • other aquifers or groundwater discharge features are not affected.
Moderate	3	Some minor project impacts likely to environmental values, but such impacts likely to persist over time. Or… Some moderate project impacts likely to environmental values, but such impacts likely short duration only, with rapid recovery following end of impacting activity. Impact extends beyond the area of activity or footprint. Where impact is to an aquifer: • the impact may occur across aquifers; or • groundwater discharge features may be affected.
High	4	Some moderate project impacts likely to environmental values, but such impacts likely to persist over time. Or… Some major project impacts likely to environmental values, but such impacts likely short duration only, with rapid recovery following end of impacting activity. Impact extends across significant areas.

Magnitude Rating	Rank	Criteria
		Where impact is to an aquifer: • the impact occurs across aquifers; and • groundwater discharge features are affected.
Very High	5	Some irreversible or persistent major project impacts likely to environmental values. No recovery from such impacts in the foreseeable future. Impact extends across regional areas. Where impact is to an aquifer: • the impact occurs across aquifers regionally; and • groundwater discharge features are affected at a regional scale or in multiple locations.

9.3.2 Impact Significance Interpretation

The significance of impacts to an environmental value is determined as follows:

1. Assess the sensitivity rating of the environmental value – Table 9.2
2. Assess the magnitude rating of the impact to environmental values – Table 9.3
3. Apply the sensitivity and magnitude ratings obtained to the assessment matrix - Table 9.4.
4. Interpret the significance of the impacts from the assessment matrix - Table 9.4

Five categories for interpreted significance for impacts and residual impacts are provided in Table 9.5 and range from very low to very high.

Table 9.4 – Matrix for the assessment of significance of groundwater related impact

Impact Magnitude Rating (refer Table 9.3)	**Sensitivity Rating** (refer Table 9.2)				
	Very Low	Low	Moderate	High	Very High
Very Low	1	2	3	4	5
Low	2	4	6	8	10
Moderate	3	6	9	12	15
High	4	8	12	16	20
Very High	5	10	15	20	25

Table 9.5 – Impact significance: assessment interpretation

Category	**Score**	**Legend Colour**
Very Low Significance	1-2	
Low Significance	3-4	
Moderate Significance	5-9	
High Significance	10-16	
Very High Significance	20-25	

9.4 Impact Mitigation

Potential impacts to environmental values by the project are detailed in section 8. This section provides a process for management and mitigation of the identified potential impacts. The fundamental process is to apply controls or design responses to project activities such as well-field development, water production and infrastructure that will ensure that impacts to the identified environmental values either do not arise from the activities, are minor, or where unavoidable are reversible over time and can be offset in the interim by make-good provisions.

All Arrow operations in the Surat Gas Project development area will be conducted in accordance with Arrow's Environmental Management System which will provide the minimum baseline standards for operational activities being undertaken. The Arrow Environmental Management System will present the level of mitigation to be applied to all locations. In areas characterised by higher environmental values, or with higher environmental constraints, schedules will be appended to the Environmental Management System that detail additional location specific mitigations as recommended in this section.

Monitoring associated with impact assessment, management and mitigation is detailed in Chapter 10.

9.4.1 Mitigation of Coal Seam Depressurisation Impacts

The extent of depressurisation, impacts on current groundwater users and future groundwater resources, and cumulative impacts need to be evaluated through the life of the project. The groundwater impact study and numerical modelling provides an indication of the extent of depressurisation within the coal seam groundwater system as well as predictions regarding possible impacts to other shallower and deeper groundwater systems.

Because aquifer depressurisation is an intrinsic part of the coal seam gas extraction process, groundwater level impacts cannot be avoided. However because the groundwater system level impacts are not permanent, and irreversible changes to the relevant groundwater environmental values do not occur, then these impacts may be acceptable (notwithstanding impacts caused by inter-aquifer flows). Nevertheless, provisions to make good any losses to existing groundwater users during the period of realised impacts are required. Trigger levels in accordance with legislative requirements are proposed to assess and manage the impacts of depressurisation.

Tables 9.6 and 9.7 provide impact mitigation measures for the depressurisation impacts identified in Chapter 8. Trigger levels and trigger actions are discussed below.

9.4.1.1 Legislative Requirements

The Water and Other Legislation Amendment Bill 2010 (Qld) was introduced to amend existing legislation with respect to groundwater extraction under petroleum tenures (including coal seam gas water). On 1 December 2010 amendments to the Water Act (Qld) 2000 commenced. These amendments included provisions:

- To protect landholders' existing and new water supply bores from the impact of petroleum tenure holders extracting groundwater, by establishing trigger levels and make good obligations for tenure holders, including the requirement for bore assessments.
- For petroleum tenure holders to undertake baseline assessments of water bores.
- For tenure holders to manage their impact on natural springs through the development of a spring impact management strategy. This work will be undertaken by the QWC.

- The management of cumulative impacts of groundwater extraction by petroleum tenure holders by providing for the declaration of Cumulative Management Areas (CMA).
- For groundwater impact reports.
- To appoint the QWC as an independent management body to oversee the groundwater impacts of the petroleum industry.
- For a dispute resolution process for the negotiation of make good agreements.

The Queensland Government has set trigger levels for impacts to water bores and springs under the Water Act (Qld) 2000. The trigger thresholds are used to investigate an individual operators' impact that may cause a decline in water levels and potentially reduce the ability of a water bore to supply water to the bore owner for its intended use. Trigger thresholds are defined as below.

Bore Trigger Threshold - for an aquifer, means a decline in the water level in the aquifer that is:

a) if a regulation prescribes the bore trigger threshold for an area in which the aquifer is situated—the prescribed threshold for the area; or

b) otherwise:

(i) for a consolidated aquifer - 5m; or

(ii) for an unconsolidated aquifer - 2m.

For Springs – a potentially affected spring means a spring overlying an aquifer affected by underground water rights, if:

a) the water level in the aquifer is predicted, in an underground water impact report or final report, to decline by more than the spring trigger threshold at the location of the spring at any time; and

b) the cause of the predicted decline is, or is likely to be, the exercise of the underground water rights.

The spring trigger threshold, for an aquifer, means a decline in the water level of the aquifer that is:

a) if a regulation prescribes the threshold for a particular area the prescribed threshold for the area; or

b) otherwise 0.2m.

Coal seam gas producers have an obligation to manage the impacts of their water extraction on other water users and on springs in accordance with the requirements of the Water Act (Qld) 2000.

The aims of the trigger levels are considered to include the following:

1) To set trigger levels which are distinguishable from natural variation.
2) To set trigger levels that focus monitoring, assessment and make good efforts on genuinely affected bores.

If modelling indicates that an aquifer has the potential to exceed the trigger levels within 3 years, bores within that area are identified as being within an 'immediately affected area' and the petroleum tenure holder is obliged to undertake a bore assessment (if no baseline assessment has been undertaken) and negotiate a make good agreement with the bore owner. The make good agreement will identify the make good measures to be undertaken by the responsible tenure holder if a bore has an impaired capacity due to coal seam gas activities.

Where there may be cumulative impacts due to overlapping tenures, the government will declare a CMA. The QWC has an expanded role under the new arrangement which is to oversee the management of regional cumulative groundwater impacts in a CMA and be responsible for managing activities including:

- Preparing an underground water impact report for the CMA.
- Modelling impacts on groundwater.
- Predicting impacts as a result of water extraction by petroleum tenure holders and designating the responsible tenure holder for specific areas within the CMA.
- Maintaining systems to store data.
- Providing independent advice to the chief executive of DERM.

9.4.1.2 Trigger Actions - Water Bores

Trigger levels provide an early warning system to activate management measures to reduce the likelihood of impacts occurring. The QWC's Groundwater Impact Report will identify areas that have potential to exceed trigger levels and map them as ‘immediately affected’ (within 3 years) or ‘long term affected areas’ within the CMA. For these areas the following will apply:

- More intensive monitoring.
- Detailed hydrogeological assessment (bore assessment).

If a bore owner experiences impaired capacity due to coal seam gas operations, actions would be considered and agreed between the responsible tenure holder and the bore owner.

Under the above approaches, a bore assessment would be undertaken. The bore owner would provide the following to Arrow:

- Bore details (e.g. total depth, screened intervals, stratigraphy).
- Groundwater usage data or metering data.
- Details of bore groundwater levels.
- Details of groundwater pumping equipment and pump setting.

The bore assessment would consider:

- Drawdowns observed in the regional monitoring system.
- Local influences on groundwater conditions (e.g. other extractions such as irrigation use, town supply, industrial, climate, etc).
- Bore specifics and bore metering data.
- Bore condition.
- Available drawdown for the bore.

- Use of the bore.
- Hydrogeological aspects.
- Assess whether material impacts have occurred.
- Assess the effects of cumulative impacts as the result of multiple coal seam gas proponents operating concurrently.

Following completion of a bore assessment, Arrow will negotiate a 'make good' agreement with the bore owner that would document the outcome of the assessment, identify any impacts or potential for impaired capacity and make good measures to be implemented in the event of impaired capacity occurring. Where material impacts were found to have occurred, Arrow would initiate actions to execute the agreed ‘make good’ provisions, such as providing alternative water supplies, replacing pumps or deepening bores.

Establishment of suitable datum levels (baselines) would be effected through a combination of the baseline assessment program across Arrow's tenure area, with consideration of fluctuation caused by seasonal, drought, and other effects. Baseline assessment is considered in section 10.

9.4.1.3 Trigger Actions - Springs

If the projected impact at a spring location exceeds the trigger threshold value of 0.2 m, the coal seam gas producer must investigate the risk to the spring and develop a strategy to manage and mitigate the risks.

If trigger levels are reached, provisions that might be activated include:

- More intensive monitoring.
- Detailed assessment of the hydrogeology hydrology of the spring.
- Providing an alternative water supply to replace the groundwater discharge.
- Re-inject groundwater in key locations to support groundwater levels until normal recovery occurs.
- Other measures.

9.4.1.4 **Injection**

Injection of abstracted groundwater is a potential measure to mitigate aquifer drawdown impacts. Groundwater injection requires investigation of the technical practicality at specific locations and requires that a suitable receiving groundwater aquifer is present, and that impacts to the environmental values of groundwater resources are not adversely affected by the scheme. Under the Water Supply (Safety & Reliability) Act 2008 a Recycled Water Management Scheme must be established or an exemption sought where there is no risk of direct or indirect augmentation of a drinking water supply.

Injection schemes will be spatially constrained by hydrogeology, environmental and economic considerations.

9.4.1.5 Substitution of Groundwater Allocations

The substitution component of Arrow's water management strategy has the potential to mitigate coal seam depressurisation impacts.. Arrow is proceeding with the substitution strategy on the assumption that beneficial use of coal seam gas water in this way will facilitate natural recharge of aquifers in the systems, especially the Condamine Alluvium. The objective is to minimise the net take of water from the system as a result of Arrow's activities.

Further groundwater modelling will be used to support and demonstrate the injection and substitution mitigation measures, and evaluate potential losses from the system as a result of treatment, transfer and evaporation processes. This will include:

- Check/collate updated data on major coal seam gas proponent's abstraction data and well "pod" locations.
- Acquire/collate and represent town, stock, industrial and domestic abstractions.
- Revision of recharge in areas currently considered to be no recharge zones.
- Assess model predictive error and uncertainty.
- Assess model flux/recharge rates.
- Recalibrate model and assess mitigation scenarios.
- Revisit predictive error/uncertainty.

9.4.2 Mitigation of Coal Seam Gas Field Development Impacts

A range of potential impacts relating to field development have been identified. These are summarised in Table 9.8.

The main impact risks are related to well installation, facilities and ancillary plant & equipment.

Changes to groundwater recharge caused by land use change within the coal seam gas fields is envisaged to be insignificant due to the relatively small area affected, compared to the entire project development area. That is, the land-take associated with well heads, access roads, facilities, electricity generation facilities and gathering lines will be low compared with the area of the entire project development area.

To reduce the likelihood of uncontained fuel, oil or chemical release entering the water system, the following recommendations are made:

- Contain all fuel or oil storage facilities within bunded areas.
- Maintain accurate records of fuel, oil or chemical volumes purchased and stored on-site to allow regular quantity auditing.

The mitigation measures should be included in the design phase and monitoring should be conducted as specified in section 10.

The conveyance and storage of hazardous chemicals and effluents should be in accordance with Australian Standards AS1940 – *The Storage and Handling of Flammable and Combustible Liquids* and AS3780 – *The Storage and Handling of Corrosive Substances*, and other relevant industry standards.

All chemicals are to be stored in above ground storage tanks located within suitable secondary containment areas (bunded areas).

The management of waste, domestic and industrial, stored in industry standard facilities will require the use of licensed contractors. Audits of disposal facilities, disposal permits, and working conditions should be conducted to ensure adherence to regulations.

9.4.3 Mitigation of Coal Seam Gas Water Management Impacts

A range of potential impacts relating to storage and handling of coal seam gas water have been identified. These are summarised in Table 9.8.

The construction and design of new dams, whether for the storage of water, either prior to treatment or the resultant brine after treatment must be in accordance with the requirements of the most recent version of “Manual for Assessing Hazard Categories and Hydraulic Performance of Dams” and constructed under the supervision of a suitably qualified and experienced person.

9.4.4 Mitigation of Subsidence Impacts

Land subsidence is a process that can occur over a wide range of temporal scales.

A historical and baseline analysis with the Advanced Land Observation Satellite (ALOS) data covering a time lapse period from January 2007 until January 2011 is initially proposed. This will allow for a detailed analysis of each area of interest and will enable the analysis of the evolution of measured deformation in space and time.

ALOS data is available from three remote-sensing instruments:

- A Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) for digital elevation mapping
- An Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) for precise land coverage observation; and
- A Phased Array type L-band Synthetic Aperture Radar (PALSAR) for day-and-night and all-weather land observation.

9.5 Impact Mitigation and Residual Impacts

Tables 9.6 to 9.8 present the key identified potential impacts associated with the Surat Gas Project, including mitigation objectives and measures for each groundwater system identified.

The unmitigated significance rankings represent significance of impacts prior to the implementation of any mitigation measures. The residual significance rankings refer to the assessed significance of the impacts after mitigation has been applied.

Table 9.6 – Assessment of Direct Impacts of Depressurisation of the Walloon Coal Measures Aquifer System

Impacts	Unmitigated Impact Significance			Mitigation Measures	Residual (Mitigated) Impact Significance	
	Sensitivity	**Magnitude**	**Significance Ranking**		**Magnitude**	**Significance Ranking**
Lower aquifer pressure reduces flow to groundwater discharge features fed by the Walloon Coal Measures	Low	Moderate	Moderate Significance (6)	Support the identification of aquifers providing a groundwater source to springs within the area of potential impact. Develop procedures to manage groundwater drawdown and changes in groundwater quality that could impact on groundwater dependent ecosystems and natural springs. Install and monitor sentry monitoring wells to provide indication of declining trends in aquifer pressures. Where declining trends indicate an impact may occur, implement remedial pressure reversal or hydraulic barrier. Ensure the influence of depressurisation activities does not extend to any identified sensitive area (e.g. groundwater dependent ecosystems) through management of abstraction rates and effective placement of coal seam gas wells.	Very Low	Very Low Significance (2)
Lower aquifer pressure results in reduced supply to existing or future groundwater users accessing groundwater from the Walloon Coal Measures	Low	Very High	High Significance (10)	Undertake baseline assessment of bores where bore owner provides consent. Conduct monitoring of bores within the Walloon Coal Measures. Assess natural variation (i.e. seasonal variation) in groundwater levels. Establish suitable datum levels. Undertake compliance monitoring within the Walloon Coal Measure aquifers, assess trigger levels, establish make-good agreements and implement make-good measures as per agreement. Develop a procedure for investigating the impaired capacity water bores. Make-good measures may include substitution of groundwater allocations with coal seam gas water of equal or better quality to maintain user supply, or supply of groundwater from an alternative source, such as an overlying or underlying aquifer. Verify the preferred water management strategy by modelling effectiveness of substitution on the minimisation of groundwater drawdown in bores. Perform groundwater modelling simulations to predict impacts on groundwater resources in overlying and underlying aquifers to evaluate the suitability of these resources for use in make-good measures. Prepare groundwater monitoring reports in accordance with the P&G, EP and Water Acts.	Low	Low Significance (4)

Table 9.7 – Assessment of Indirect Impacts of Depressurisation of the Walloon Coal Measures Aquifer System

Groundwater System	Unmitigated Impact Significance			Mitigation Measures	Residual (Mitigated) Impact Significance	
	Sensitivity	**Magnitude**	**Significance Ranking**		**Magnitude**	**Significance Ranking**
Depressurisation in adjacent aquifers causes water quality impacts due to aquifer interflows						
Condamine Alluvium and other unconfined aquifers	Moderate	High	High Significance (12)	Undertake baseline assessment of landholder bores where bore owner consent is given. Continue program of aquifer testing in dedicated groundwater monitoring wells to reduce areas of uncertainty and aim to quantify aquifer properties and groundwater velocities / inter-aquifer flows. Continue investigative program that will help quantify the connectivity between the Condamine Alluvium and the Walloon Coal Measures. Install an appropriate regional groundwater monitoring network within the Condamine Alluvium, intermediate aquifer system, coal seam aquifer system and deep aquifer system to: - establish baseline groundwater level and groundwater quality conditions. - assess natural variation (i.e. seasonal variations) in groundwater levels. - monitor groundwater levels during operational phase. - monitor groundwater quality during operational phase. - establish suitable datum levels for each aquifer system. - establish sensitive areas where more frequent monitoring and investigation is required (e.g. groundwater dependent ecosystems). - undertake monitoring of actual groundwater drawdown against trigger levels. - implement make-good provisions where trigger levels are predicted to be exceeded due to project activities. - monitor impacts in CMAs as required by the Queensland Water Commission. Verify the preferred water management strategy by modelling effectiveness of substitution and injection (where conducted) on the minimisation of groundwater drawdown in bores. Consider injection of suitably treated coal seam gas water (if proven technically feasible) as part of management hierarchy to enhance shallow and deep aquifer recovery (in compliance with the P&G, EP Water and Water Supply (Safety & Reliability) Acts. Prepare groundwater monitoring reports in accordance with the P&G and Water Acts.	Low	Moderate Significance (6)
Intermediate groundwater system	Moderate	High	High Significance (12)		Low	Moderate Significance (6)
Coal seam gas groundwater system	-	-	Refer Table 9.6 (direct impacts)		-	Refer Table 9.6 (direct impacts)
Deep groundwater system	High	High	High Significance (16)		Low	Moderate Significance (8)

Groundwater System	Unmitigated Impact Significance			Mitigation Measures	Residual (Mitigated) Impact Significance	
	Sensitivity	**Magnitude**	**Significance Ranking**		**Magnitude**	**Significance Ranking**
Depressurisation in adjacent aquifers due to aquifer leakage causes reduced supply or reduced flow to discharge features such as springs or streams, or impacts to cultural/spiritual values						
Condamine Alluvium and other unconfined aquifers	Moderate	Very Low	Low Significance (3)	Conduct mitigation as above. Minimise impacts of groundwater drawdown on sensitive areas (e.g. groundwater dependent ecosystems) through management of abstraction rates and effective placement of coal seam gas wells. Develop procedures to manage groundwater drawdown and changes in groundwater quality that could impact on groundwater dependent ecosystems and natural springs. Install and monitor sentry monitoring wells to provide indication of declining trends in aquifer pressures. Where declining trends indicate an impact may occur, implement remedial pressure reversal or hydraulic barrier.	Very Low	Low Significance (3)
Intermediate groundwater system	Moderate	Low	Moderate Significance (6)		Very Low	Low Significance (3)
Coal seam gas groundwater system	-	-	Refer Table 9.6 (direct impacts)		-	Refer Table 9.6 (direct impacts)
Deep groundwater system	High	High	High Significance (16)		Low	Moderate Significance (8)
Depressurisation in adjacent aquifers due to leakage through coal seam gas wells						
Condamine Alluvium and other unconfined aquifers	Moderate	Low	Moderate Significance (6)	Construct all coal seam gas production wells in accordance with the standards described in the Petroleum and Gas (Production and Safety) Act 2004 and regulations to that act. Construct all monitoring wells in accordance with the Minimum Construction Requirements for Water Bores in Australia (National Minimum Bore Specifications Committee, 2003). Implement well integrity management system and associated integrity assurance tasks during commissioning and operation of wells. Decommission, repair or convert all wells (production and monitoring) either at the end of their operating life span, or in the event of a failed integrity test in accordance with the Minimum Construction Requirements for Water Bores in Australia (National Minimum Bore Specifications Committee, 2003) and the Petroleum and Gas (Production and Safety) Act 2004 and regulations to that act.	Very Low	Low Significance (3)
Intermediate groundwater system	Moderate	Low	Moderate Significance (6)		Very Low	Low Significance (3)
Coal seam gas groundwater system	-	-	Refer Table 9.6 (direct impacts)		-	Refer Table 9.6 (direct impacts)
Deep groundwater system	High	Low	Moderate Significance (8)		Very Low	Low Significance (4)

Table 9.8 – Assessment of Other Impacts on Groundwater Systems

Activity/impact	Groundwater System	Unmitigated Impact Significance			Mitigation Measures	Residual (Mitigated) Impact Significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Water quality impacts from contamination of shallow, intermediate, coal seam and deep groundwater systems by well installation and sub-surface activities							
Incomplete or incorrect well installation results in interconnection of aquifers and consequential cross-contamination	Condamine Alluvium and other unconfined aquifers	Moderate	Low	Moderate Significance (6)	Construct all coal seam gas production wells in accordance with the standards described in the Petroleum and Gas (Production and Safety) Act 2004 and regulations to that act. Construct all monitoring wells in accordance with the Minimum Construction Requirements for Water Bores in Australia (National Minimum Bore Specifications Committee, 2003). Ensure well drilling is supervised by a suitably qualified geologist to ensure aquifers accurately identified.	Very Low	Low Significance (3)
	Intermediate groundwater system	Moderate	Low	Moderate Significance (6)		Very Low	Low Significance (3)
	Coal seam gas groundwater system	Low	Low	Low Significance (4)		Very Low	Very Low Significance (2)
	Deep groundwater system	High	Low	Moderate Significance (8)		Very Low	Low Significance (4)
Lubricants, drilling fluids and other chemicals used in drilling process contaminate aquifers	Condamine Alluvium and other unconfined aquifers	Moderate	Low	Moderate Significance (6)	Construct all coal seam gas production wells in accordance with the standards described in the Petroleum and Gas (Production and Safety) Act 2004 and regulations to that act. Construct all monitoring wells in accordance with the Minimum Construction Requirements for Water Bores in Australia (National Minimum Bore Specifications Committee, 2003). Select drilling fluids to minimise potential groundwater impacts. Do not use oil-based drilling fluids.	Very Low	Low Significance (3)
	Intermediate groundwater system	Moderate	Low	Moderate Significance (6)		Very Low	Low Significance (3)
	Coal seam gas groundwater system	Low	Low	Low Significance (4)		Very Low	Very Low Significance (2)
	Deep groundwater system	High	Low	Moderate Significance (8)		Very Low	Low Significance (4)

Activity/impact	Groundwater System	Unmitigated Impact Significance			Mitigation Measures	Residual (Mitigated) Impact Significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Spills at the well-pad drain or leak to the borehole leading to contamination of intercepted aquifers	Condamine Alluvium and other unconfined aquifers	Moderate	Low	Moderate Significance (6)	Construct all coal seam gas production wells in accordance with the standards described in the Petroleum and Gas (Production and Safety) Act 2004 and regulations to that act. Construct all monitoring wells in accordance with the Minimum Construction Requirements for Water Bores in Australia (National Minimum Bore Specifications Committee, 2003).	Very Low	Low Significance (3)
	Intermediate groundwater system	Moderate	Low	Moderate Significance (6)		Very Low	Low Significance (3)
	Coal seam gas groundwater system	Low	Low	Low Significance (4)		Very Low	Very Low Significance (2)
	Deep groundwater system	High	Low	Moderate Significance (8)		Very Low	Low Significance (4)
Leaks and spills from sub-surface infrastructure (e.g. gathering lines) resulting in contamination of intercepted aquifers	Condamine Alluvium and other unconfined aquifers	Moderate	Low	Moderate Significance (6)	Consider local groundwater conditions when identifying sites for the installation of underground infrastructure (e.g. gathering lines). Install pipelines in accordance with relevant standards. Consider local biological, groundwater and surface water conditions when identifying sites for coal seam gas water storage dams, treated water facilities and associated brine storage facilities, production facilities and related storage areas.	Very Low	Low Significance (3)
	Intermediate groundwater system	Moderate	Very Low	Low Significance (3)		Very Low	Low Significance (3)
	Coal seam gas groundwater system	Low	Very Low	Very Low Significance (2)		Very Low	Very Low Significance (2)
	Deep groundwater system	High	Very Low	Low Significance (4)		Very Low	Low Significance (4)
Reduced water quality from contamination of shallow, intermediate and coal seam groundwater systems by water storage, processing and distribution infrastructure activities							
Storage of chemicals, fuels, oils Leaching of spills resulting in contamination of groundwater system	Condamine Alluvium and other unconfined aquifers	Moderate	Moderate	Moderate Significance (9)	Store onsite materials in suitable containment systems constructed to industry standards and Australian Standards (AS1940 and AS3780 at a minimum). Install suitable groundwater monitoring networks, where required and maintain quality control/quality assurance procedures to monitor volumes and quantities. Aboveground storage areas will be bunded to contain spills. Develop and implement emergency response and spill response procedures to minimise any impacts that could occur as a result of releases of hazardous materials or any loss of containment of storage equipment.	Low	Moderate Significance (6)
	Intermediate groundwater system	Moderate	Low	Moderate Significance (6)		Very Low	Low Significance (3)
	Coal seam gas groundwater system	Low	Low	Low Significance (4)		Very Low	Very Low Significance (2)

Activity/impact	Groundwater System	Unmitigated Impact Significance			Mitigation Measures	Residual (Mitigated) Impact Significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Waste generation and storage Leaching of waste products results in contamination of groundwater system	Condamine Alluvium and other unconfined aquifers	Moderate	Moderate	Moderate Significance (9)	Store and manage all waste materials (domestic and industrial) in accordance with industry regulations and DERM EA conditions. Use licensed waste management contractors. Conduct audits of disposal facilities, disposal permits and onsite operations to ensure adherence to regulations. Design and construct new dams (either raw water, treated water or brine dams) in accordance with the requirements of the most recent version of “Manual for Assessing Hazard Categories and Hydraulic Performance of Dams” and under the supervision of a suitably qualified and experienced person, and in accordance with relevant DERM schedule of conditions relating to dam design, construction, inspection and mandatory reporting requirements.	Low	Moderate Significance (6)
	Intermediate groundwater system	Moderate	Low	Moderate Significance (6)		Very Low	Low Significance (3)
	Coal seam gas groundwater system	Low	Low	Low Significance (4)		Very Low	Very Low Significance (2)
Waste water and sanitation (effluent) generation and storage Leaching of effluent results in contamination of groundwater system	Condamine Alluvium and other unconfined aquifers	Moderate	Moderate	Moderate Significance (9)	Connect waste water and sewerage systems to sewers where locally present. Alternatively, wastewater treatment and/or re-use systems to be installed to Australian Standards (AS/NZS 1547:2000 – On-site Domestic Wastewater Management) and DERM guidance documents “On-site Sewage Code and Onsite Sewage Facilities: Guidelines for Vertical and Horizontal Separation Distance” and Queensland Water Recycling Guidelines.	Low	Moderate Significance (6)
	Intermediate groundwater system	Moderate	Low	Moderate Significance (6)		Very Low	Low Significance (3)
	Coal seam gas groundwater system	Low	Low	Low Significance (4)		Very Low	Very Low Significance (2)
Impacts to shallow, intermediate and coal seam groundwater systems from infrastructure footprints							
Installation of impervious surface coverings results in lower rainwater infiltration and reduced aquifer recharge	Condamine Alluvium and other unconfined aquifers	Moderate	Low	Moderate Significance (6)	Avoid unnecessary impervious surface coverings, minimise land footprint, and vegetation clearing when designing facilities. Consider local biological, groundwater and surface water conditions when identifying sites for coal seam gas water storage dams, treated water facilities and associated brine storage facilities, production facilities and related storage areas.	Very Low	Low Significance (3)
	Intermediate groundwater system	Moderate	Very Low	Low Significance (3)		Very Low	Low Significance (3)
	Coal seam gas groundwater system	Low	Very Low	Very Low Significance (2)		Very Low	Very Low Significance (2)

Activity/impact	**Groundwater System**	**Unmitigated Impact Significance**			**Mitigation Measures**	**Residual (Mitigated) Impact Significance**	
		Sensitivity	**Magnitude**	**Significance Ranking**		**Magnitude**	**Significance Ranking**
General impacts associated with installation of gas reticulation facilities and compressor stations	Condamine Alluvium and other unconfined aquifers	Moderate	Moderate	Moderate Significance (9)	Where possible avoid site location in shallow groundwater areas (where watertables are less than 5 m below ground surface). Store onsite materials in containment systems constructed to industry standards and Australian Standards (AS1940 and AS3780 at a minimum). Maintain quality control/quality assurance procedures to monitor volumes and quantities. Storage areas will be bunded to contain spills. Store and manage all waste materials (domestic and industrial) in accordance with industry regulations and DERM EA conditions. Use licensed waste management contractors. Conduct audits of disposal facilities, disposal permits and onsite operations to ensure adherence to regulations.	Very Low	Low Significance (3)
	Intermediate groundwater system	Moderate	Low	Moderate Significance (6)		Very Low	Low Significance (3)
	Coal seam gas groundwater system	Low	Low	Low Significance (4)		Very Low	Very Low Significance (2)
Impacts caused by coal seam gas water activities to shallow groundwater systems (Condamine Alluvium and other unconfined aquifers)							
Impact to shallow groundwater caused by seepage of untreated coal seam gas water from storage facilities		Moderate	Moderate	Moderate Significance (9)	Design and construct new dams (either raw water, treated water or brine dams) in accordance with the requirements of the most recent version of "Manual for Assessing Hazard Categories and Hydraulic Performance of Dams" and under the supervision of a suitably qualified and experienced person, and in accordance with relevant DERM schedule of conditions relating to dam design, construction, inspection and mandatory reporting requirements. The number of monitoring wells and their location will take into account site-specific hydrogeology, preferential pathways and potential receptors of impacts. Monitoring bores installed near dams will have groundwater levels and electrical conductivity values monitored monthly, and TDS, EC, pH, major cations, major anions monitoring bi-annually to allow preparation of piper plots and interpretation of results over time. The number of monitoring wells and associated monitoring frequencies will be increased and further investigation triggered where impacts are identified.	Very Low	Low Significance (3)
Altered groundwater flow direction due to seepage of coal seam gas water from storage facilities		Moderate	Low	Moderate Significance (6)		Very Low	Low Significance (3)
Impact to shallow groundwater caused by seepage of brine concentrate from storage facilities		Moderate	Moderate	Moderate Significance (9)		Very Low	Low Significance (3)
Unplanned discharge of untreated coal seam gas water and brine to the land surface leading to groundwater impact		Moderate	Moderate	Moderate Significance (9)		Very Low	Low Significance (3)

9.6 Environmental Constraints

During the detailed project planning phases, locations within the project development area that could potentially be constrained or restricted for development purposes will be identified based on the sensitivity of the environmental values to be protected. That is, the sensitivity of the environmental values will be used to define areas where differing levels of control are required as summarised below:

- Development can proceed with standard mitigation measures. These are areas of low constraint, and contain values of low sensitivity.
- Development can proceed with some additional mitigation measures in addition to standard controls. These are areas of moderate constraint, and contain values of moderate sensitivity.
- Development can proceed with site specific mitigation measures in addition to standard controls. These are areas of high constraint, and contain values of high sensitivity.
- Development is prohibited and defined as a “no-go area”. These are areas of very high constraint, and contain values of very high sensitivity that must be avoided as dictated by conservation status and statutory requirements.

The identified groundwater values include those having a spatial component and also those that are unconstrained spatially. Project activities that may impact upon spatial groundwater values (e.g. outcropping groundwater systems that support springs) will be mitigated by the assignment of the value as either a no-go area, highly constrained, moderately constrained or of low constraint.

10 MONITORING AND COMMITMENT MANAGEMENT

Arrow is committed to understanding, managing and mitigating the potential impacts of coal seam gas operations on the environmental values of local and regional groundwater systems. The impact assessment and evaluation of cumulative impacts allowed for the compilation of mitigation measures to reduce the impacts of the proposed Surat Gas Project and associated activities on groundwater systems. In order to assess the effectiveness of these mitigation measures a series of environment protection measures regarding groundwater monitoring have been compiled.

Management decisions and an adaptive approach to gas field development will also be informed by the results of the monitoring program. As gas field development continues, and groundwater monitoring programs expand, more information about the behaviour of regional groundwater will be used to update and calibrate the numerical model. This can help to reduce future uncertainty and allow management and mitigation measures to be adapted to observed or realised site conditions.

The groundwater monitoring program must be able to demonstrate compliance with the requirements of the P&G, EP and Water Acts. Important standards to comply with include:

- Monitoring and Sampling Manual – Environmental Protection (Water) Policy 2009
- Minimum Construction requirements for Water Bores in Australia or the Minimum Standards for the Construction and Reconditioning of Water Bores that Intersect the Sediments of Artesian Basins in Queensland.
- AS/NZ 5667.11: 1998 – Water Quality Sampling – Guidance on Sampling of Groundwaters
- ISO 5667-18: 2001 Water Quality Sampling – Part 18 – Guidance on Sampling of Groundwater at Contaminated Sites.
- Arrow Groundwater Sampling Procedure.

10.1 Groundwater Monitoring Objectives

The objectives of the groundwater monitoring program are to:

- Provide a configuration of monitoring bores that allows identification of drawdown across the project development area and within key aquifers.
- Gain further understanding of aquifer interactions and verify the understanding of regional hydrogeology.
- Identify long-term groundwater level trends and potential cumulative effects from current and future coal seam gas development.
- Provide information to differentiate effects between operating gas fields and other sources of groundwater variability.
- Develop an “early warning system” that identifies areas potentially impacted by project activities and allows early intervention.
- Provide a mechanism for continuous improvement of the model (recharge/discharge areas, natural variations, aquifer interconnectivity, impacts on groundwater dependant ecosystems, long term trend data and other surface features as more field development data becomes more available).

- Share information with regulatory authorities.

10.2 Environmental Protection Measures

The implementation of environmental protection measures is necessary to assess the impacts of the Surat Gas Project operations on associated environmental values and groundwater quality and quantity. A robust groundwater baseline assessment and groundwater monitoring program will underpin this. This will provide the definitive baseline conditions against which potential impacts can be assessed. This process provides a mechanism for early detection of potential impacts and provides a basis for implementing appropriate contingency and management plans.

10.3 Environmental Baseline and Impact Monitoring

10.3.1 Regional Impacts

Baseline Monitoring

In 2009 Golder (2009a) completed an initial bore inventory of the Dalby development area. The objective of the bore inventory was to identify a number of privately owned bores, using the DERM groundwater database, within a 10 km radius of existing and proposed Arrow coal seam gas activities in the Dalby Development area. Outcomes from this assessment provided information on the origin, quality and groundwater depth of each bore sampled which provided a baseline of groundwater conditions in the Dalby Development area. The selected sample of bores were considered to be representative of geological and groundwater conditions that would be found in the study area.

Arrow are compiling and refining a Groundwater Monitoring and Investigation Strategy in conjunction with other groundwater investigations (both underway and planned for the future). One of the main objectives of this document is to establish a framework for nominating groundwater monitoring sites for both baseline and impact monitoring, and to define a desired density for monitoring aquifer pressure and aquifer water quality for each hydrogeological unit within the project area.

Monitoring Bores (Impact Monitoring)

In order to fulfil the requirements of the legislation governing the coal seam gas industry, and to mitigate potential adverse effects from coal seam gas extraction on a regional scale, the implementation of a groundwater monitoring program that includes a representative suite of bores in the shallow, intermediate, coal seam and deep groundwater systems is recommended. The major groundwater systems to be monitored include:

- **Shallow Groundwater System:** Quaternary alluvium aquifers (i.e. Condamine Alluvium aquifer).
- **Intermediate Groundwater System:** Mooga Sandstone, Gubberamunda Sandstone, Springbok Sandstone.
- **Coal Seam Groundwater System:** Westbourne Formation, Walloon Coal Measures.
- **Deep Groundwater System:** Hutton Formation/Marburg Subgroup, Precipice Sandstone.

The monitoring program will provide water levels and water quality data of the aquifers within potentially impacted areas.

The numerical modelling simulations predicted groundwater drawdowns in the affected aquifers as a result of Surat Gas Project predicted extraction rates over a 30 year period (for scenario 1 – 40 years for scenarios 2 and 3) plus a further 20 years recovery. These are shown in Figures 4.6 to 4.26 in Appendix B. They show how Arrow operations in the 5 development areas might affect current groundwater levels (i.e. levels at the start of 2010) within the shallow, intermediate, Walloon Coal Measures and deep aquifer units. The simulations predict the reduction in hydraulic head, and at what distances from the resource areas this reduction might apply. The drawdown estimates are a tool that will be used to:

- Define areas where Water Act bores (i.e. groundwater users) and/or other environmental values may be impacted over time.
- Provide guidance on nominating locations and targeting resource aquifers for future monitoring well installations.
- Define areas where existing private or government bores can be utilised for on-going monitoring.

The monitoring program should focus on areas that have potential for greatest impact, e.g. in the vicinity of Water Act bores. On the basis of the impact assessment and numerical modelling, nested groundwater monitoring points (bores or piezometers) should be installed in the applicable aquifers in areas that show greatest vulnerability of groundwater drawdown. The nested sites will allow for both on-going groundwater monitoring and in some cases groundwater quality sampling.

It is recommended that nested sites are installed in locations that show limited groundwater response due to coal seam gas extraction to provide on-going background monitoring that can be used to ensure that the impacts of climatic effects or resource development can be assessed independently of the impacts of coal seam gas water extraction.

Groundwater Monitoring Plan: Phase 1

Consistent with the Water Act Qld (2000), Arrow has prepared a Baseline Assessment Plan as part of its underground water impact reporting obligation. In addition Arrow will continue to refine its Groundwater Monitoring and Investigation Strategy.

10.3.2 On-site Impacts

Confirmed details of the Arrow Surat Gas Project field development will not be finalised until appraisal drilling programs are complete. These programs will be conducted progressively over the life of the project. Thus the layout of coal seam gas production wells and associated infrastructure, including coal seam gas water dams, facilities, gas and water gathering line networks have not yet been finalised.

Monitoring should be in compliance with any DERM standards that may apply, but at a minimum, a suitable network of shallow groundwater monitoring bores should be installed in the vicinity of storage facilities (including dams, any underground storage tanks and non-bunded above ground fuel/chemical storage facilities) to ensure detection of migrating contaminants. The number of monitoring bores and their location will take into account site-specific hydrogeology, preferential pathways and potential receptors of impacts. Bores installed near dams should have groundwater levels and electrical conductivity values monitored monthly, and TDS, EC, pH, major cations, major anions monitoring bi-annually to allow preparation of piper plots and interpretation of results over time. Bores installed near non-bunded fuel and chemical storage facilities will have groundwater levels and site specific contaminants monitored annually.

Monitoring Subsidence

Coal seam Gas projects require continuous monitoring of surface motion to understand the potential subsidence impacts associated with coal seam gas depressurisation. Also important is an understanding of the baseline conditions. A historical analysis using ALOS satellite data covering a time lapse period from January 2007 until January 2011 will provide a baseline from which to detect displacements.

Deliverables from this technique include a calibrated global map, and vector files for measurement points. Calibrated global maps show the mean deformation rate, and will be useful to detect large scale deformation, and to correlate these patterns with other data (i.e. geology, structure, wells, injection data, etc.).

Vector files contain information about the location of points, the quality of the measurements and the detailed value of the deformation for each acquisition date (the time series or time evolution of any deformation) and allow a detailed analysis of each area of interest.

10.4 Other Monitoring

10.4.1 Aquifer Testing

A program of aquifer testing is also proposed in dedicated groundwater monitoring bores. These sites will be selected to reduce areas of uncertainty (based on the current groundwater model) and in the understanding of the boundaries between geological formations e.g. Springbok Sandstone/ Walloon Coal Measures contact. Work will mainly be aimed at quantifying aquifer properties but will also consider flow velocities/leakage.

10.4.2 Condamine Connectivity

It is well established that the Condamine Alluvium hosts a groundwater resource of local significance. This, coupled with recent desktop investigations (Hillier, 2010) and proposed development of coal seam gas resources in the underlying Walloon Subgroup, has generated interest in the degree of hydraulic connection between the two units.

Arrow has coal seam gas tenure over the western portion of the Condamine Alluvium. A detailed understanding of the hydrogeology of the alluvium and underlying Walloon Coal Measures is of interest to Arrow.

The Walloon Coal Measures are overlain by the Westbourne Formation, a significant confining formation consisting primarily of low permeability interbedded shales and sandstones. Furthermore, deposition of a 'hydraulic separation layer' (comprising clay and other low permeability material) at the base of the Condamine Alluvium may restrict the movement of water between the Alluvium and Walloon Coal Measures. Current conceptual modelling implies that groundwater movement between the Walloon Coal Measures and overlying aquifers is low where these confining layers are present.

These confining layers may be absent beneath some parts of the Condamine Alluvium where the Alluvium is incised into the Walloon Coal Measures and the 'hydraulic separation layer' is not present. Arrow has commenced an investigative program that will help quantify the connectivity between the Condamine Alluvium and the Walloon Coal Measures. The program will involve:

- Monitoring the effects of groundwater abstraction from the Condamine Alluvium to estimate horizontal and vertical hydraulic conductivity between the Alluvium and Walloon Coal Measures;
- An investigative drilling program that will provide greater definition of the interface between the two units and evaluate the geological and hydrogeological properties of the material at the interface of the units;
- Groundwater chemistry studies to characterise mixing and migration between the units; and
- Groundwater modelling to understand important processes in the system and predict potential impacts utilising the connectivity data obtained through investigative components of the study.

Arrow has developed a scope of work for investigation in consultation with the QWC, key stakeholders and independent experts in the areas of hydrogeological field testing, aquifer geochemistry, groundwater modelling and local knowledge of the Condamine Alluvium.

10.5 Response Requirements

If impaired capacity is found in a landholder bore, Arrow will initiate a bore assessment which is comprised of the following phased investigation response:

- Verifying groundwater levels in the nominated bores, and investigating groundwater levels in compliance monitoring bores.
- Request bore information and groundwater data from affected parties.
- Review and assess data.
- Advise bore owner in writing of findings.
- If impaired capacity (bore can no longer produce quality or quantity for the authorised purpose and the impact is due to coal seam gas activities) is confirmed, implement make good provision.

10.6 Beneficial use and Coal Seam Gas Water

The beneficial use of untreated associated water, in particular for irrigation purposes, can have potential to impact on land and the environment. Where untreated associated water beneficial use schemes are proposed, land capability assessments may be required to ensure the scheme is sustainable and doesn’t result in land degradation, environmental impact, or groundwater impact.

Any beneficial use schemes for reuse would be subject to meeting the criteria and investigation requirements as applicable to achieve DERM approval under the Environment Protection (Waste) Regulation and other relevant statutes.

Strategic monitoring of shallow groundwater at beneficial use sites is expected to be a requirement for such schemes.

These requirements, and the design of monitoring plans and locations, will generally be site-specific and require individual assessment.

This impact assessment assumes that the legislative framework to enable the beneficial use of coal seam gas water under Arrow’s water management strategy will be in place to facilitate third party use of the water.

10.7 Data Management and Reporting Requirements

A structured database will host all groundwater data (i.e. groundwater levels and groundwater quality).

Groundwater monitoring reporting will be conducted in accordance with the P&G, EP and Water Acts. Reports will be submitted annually and at a minimum will provide comment on:

- Changes to the monitoring network from the previous report (i.e. any new or damaged monitoring bores).
- Most recent and historical monitoring results, trends, and any changes to trends.
- Comparison of actual groundwater levels with projected modelled groundwater levels.
- The current projections of the extent of water level impacts on the coal seam aquifers and adjacent aquifers.
- Any complaints lodged by bore owners.

10.8 Cumulative Impacts

Because the Arrow Surat Gas Project is likely to co-exist with other regional groundwater users, including competing coal seam gas developments, power stations, urban water supplies, coal mines, etc, the impact assessment process and modelling needed to consider the potential cumulative effects of identified present and future high volume groundwater users.

Some of the regional users identified are presented in Table 10.1. Figure 10.1 shows the locations of proposed projects that have cumulative impact potential.

Table 10.1 – Proposed projects having cumulative impact potential

Proposed Project	Proponent	Stage	Components	Location	Timing	Groundwater Specific Comments
Arrow Surat Pipeline (formerly Surat-Gladstone Pipeline) Pty Ltd	Arrow Energy	IAS submitted to DERM in December 2008. EIS lodged July 2009. EIS approved January 2010.	467 km long buried gas pipeline.	Pipeline located from Queensland's Surat Basin gas fields to Gladstone. The pipeline will start adjacent to the Kogan North Central Gas Processing Facility in the Surat Basin gas fields.	Construction to commence in 2011. LNG production in 2013. Pipeline technical design life of 40 years.	Information from the EIS indicates that interception of groundwater during construction works is considered unlikely. Hydrotest water will be sourced from existing boreholes in accordance with abstraction limits. Any groundwater springs and groundwater dependant ecosystems have been avoided through pipeline re-alignment. The volume of water used to hydrostatically pressure test the pipeline has been calculated at 82 ML. It is considered unlikely that any significant impact on groundwater will occur.
Australia Pacific LNG Project	Origin Energy and Conoco Phillips	IAS lodged March 2009. EIS lodged January 2010. Project approved with conditions by the Queensland CG in November 2010. Project approved with conditions by DSEWPC in February 2011.	Coal seam gas fields. 450 km gas transmission pipeline. Development of LNG facility (18 Mtpa) on Curtis Island (4 x 4.5 Mtpa trains).	Coal seam gas fields (Walloons Gas fields) are located in the Surat and Bowen Basins, extending from Wallumbilla to Millmerran on the Darling Downs. LNG plant will be located at Curtis Island, within the Curtis Island Industry Precinct, Gladstone.	LNG export (first train) 2014. Train two is scheduled for 2015. Trains three and four are scheduled for post 2015. Pipeline construction 18 months. Project life of approximately 30 years.	Extraction from 10 tenement areas, with a combined abstraction peaking at 170 ML/day in 2026.
Bloodwood Creek Queensland – Stage 2 (Commercial Gas Production)	Carbon Energy (Operations) Pty Ltd.	IAS issued December 2009. Stage 2 TOR issued May 2010.	Expansion to ~ 40 operational panels. A 30MW electrical power generation plant fuelled by syngas. Carbon dioxide (CO_2) separation.	Located at Bloodwood Creek between Dalby and Chinchilla in Surat Basin.	40 - 50 year production life. CEOps is currently operating an initial UCG demonstration trial (Stage 1) at Bloodwood Creek that is producing syngas.	
Cameby Downs Expansion Project	Syntech Resources Pty Ltd	Final TOR issued. EIS in preparation –January 2012 to submit to DERM.	Expansion of open cut coal mine to produce approximately 15 to 20 Mtpa of product coal for export. Water demand for project is estimated to be 8,000 - 10,000 ML a year for washing of coal, dust suppression and production of potable water.	Cameby Downs mine (ML50233) located ~16km northeast of Miles.	Stage 1 environmental approval has already been granted and overburden removal works have commenced. Stage 2 environmental investigations are currently underway. Works are due to commence in 2014 with a mine life of 30+ years.	Information from the IAS states that groundwater studies have commenced to determine potential impacts of the project, and the suitability of groundwater in the area for use as process water. The Great Artesian Basin aquifers are considered to be of sufficient depth not to be impacted. The extensive alluvial sediments shown on the regional geological map to dominate the project area are shallow or non-existent on the project area, and as such the potential impact from the project on groundwater is considered to be low.
CS Energy – Kogan Creek Solar Boost Project	CS Energy Qld AREVA Solar	Funding for the project includes a $70 million contribution from CS Energy and a contribution of more than $34 million from the Australian Government's Renewable Energy Demonstration Program.	AREVA Solar's Compact Linear Fresnel Reflector technology planned to supply additional steam to the turbine, supplementing the conventional coal-fired steam generation process. The use of energy from the sun will avoid the use of 35,600 tonnes of greenhouse gas emissions annually.	Kogan Creek Power Station.	Operational by 2013.	

Proposed Project	Proponent	Stage	Components	Location	Timing	Groundwater Specific Comments
Elimatta Coal Project	Taroom Coal Proprietary Limited (Taroom Coal)	Initial advice statement lodged October 2009. Final TOR issued –April 2012 to submit to DERM.	Open cut mining over approximately 2,500 ha. Approximately 42 km of rail line to connect the project to the Surat Basin Rail. 12 MW power supply connection.	Situated ~35 km west of Wandoan and 380 km northwest of Brisbane.	Commencement date for production is mid 2013. The mine will operate for approximately 25 years.	Water supply sources for mining and processing activities for the proposal could include water from local coal seam gas extraction projects and groundwater from the site open-cut pit mining thermal coal at up to 8 Mt/y run-of-mine (ROM) coal to produce 5 Mt/y of product coal for export.
Emu Swamp Dam Project	Southern Downs Regional Council (SDRC) previously Stanthorpe Shire Council.	EIS lodged January 2008. Supplementary EIS being prepared. SDRC currently investigating water supply options – research nearing completion with options identified and presented to Council for decision in April 2010. The Emu Swamp Dam EIS process is on hold until this process concludes.	Either a 5000 ML urban water supply dam or a 10,500 ML urban and irrigation water supply dam. Urban Pipeline linking the dam to the Mt Marlay Water Treatment Plant and a Combined Urban and Irrigation Dam connected to a number of irrigators in Stanthorpe Shire.	15 km southwest of Stanthorpe.	Construction time of 15-18 months	
Felton Clean Coal Demonstration Project	Ambre Energy (Felton) Pty Ltd	IAS lodged March 2009. Final TOR issued June 2009. Currently preparing a draft EIS.	Operation of an open cut coal mine and a DME pilot plant to produce syngas for the production of 455 t/day of DME and the co-generation of electricity. Mine Stage 1: coal production 800,000 tpa. Mine Stage 2: coal production 3.8 Mtpa.	30 km southwest of Toowoomba and 10 km southeast of Pittsworth. Mining operation will commence approximately 1 km to the west of Hodgson Creek and will progress to the west prior to moving south.	Unspecified at this stage.	The groundwater sources in the project area are the alluvial plains of Hodgson Creek, the Walloon Coal Measures, the Hutton (Marburg) sandstones and the remnant basalts. All the groundwater resources in the area have been allocated for use by landholders. The exploration activities have located minimal groundwater within the lease area.
Gladstone Liquefied Natural Gas (GLNG)	Santos Ltd	EIS lodged March 2009. Supplementary EIS lodged in November 2009. EIS approved by Queensland CG in May 2010. Project approved with conditions by DSEWPC in October 2010. FID taken 31 January 2011.	Coal seam gas fields. Construction of 435 km gas pipeline. Development of LNG facility (10 Mtpa).	Coal seam gas fields around Roma, Emerald, Injune and Taroom. Gas pipeline from the gas fields to Gladstone. LNG facility, Curtis Island Gladstone.	Transmission pipeline construction to commence 2011, operation 2013. LNG Facility construction (train 1) to commence mid 2013, completion by late 2014. LNG Facility construction (train 2) to commence mid 2013, completion by late 2017, with operation commencing in early 2018. LNG Facility construction (train 3) to commence mid 2018, completion by late 2021 with operation commencing in early 2022.	Bowen Basin abstractions not considered relevant to this study. Roma abstractions commenced in 2008, and in 2009 at approximately 4.6 ML/day.
Gladstone Liquefied Natural Gas (Fisherman's Landing)	Gladstone Liquefied Natural Gas Pty Ltd (GLNG)	IAS lodged to DERM May 2008. EIS completed 2009. Project potentially redundant due to Shell takeover of Arrow. Fisherman's landing site may be used for storage facility for Arrow LNG Plant.	2.6 Mtpa mid-scale LNG facility (Two stages). First stage producing up to 1.6 MTPA LNG / year. Proposed second stage will double Stage 1 capacity within three years.	Fisherman's Landing - Port of Gladstone (Wharf No.5). Coal seam gas fields - Surat and Bowen basins – uncertain sources of supply now that Shell have taken over Arrow. If project progresses may represent an alternate supply pathways for Arrow Coal Seam Gas in times of shutdown or over supply.	LNG Facility construction to commence November 2008. Commissioning of train 1 October 2011. Expected life of 25 years. Timeline altered due to Arrow purchase of GLNG and subsequent Shell purchase of Arrow. Fisherman's landing site may be used for storage facility for Arrow LNG Plant.	

Proposed Project	Proponent	Stage	Components	Location	Timing	Groundwater Specific Comments
Nathan Dam and Nathan Pipeline	Sunwater	IAS lodged March 2008. EIS public consultation Late 2010. EIS supplementary (if required) Q2 2011.	888,000 ML Dam. 260 km pipeline.	Dawson River, ~75 km downstream of Taroom and 315 km upstream of the confluence of the Dawson River with the Fitzroy River. Nathan Pipeline will transport water from Nathan Dam to Surat Coal Basin.	Scheduled to complete detailed design in Mid 2012. Construction to commence in Early 2013. Commission to complete in Mid 2015.	No impact on groundwater levels as a result of this project is anticipated. However, along the junction of the Precipice Sandstone outcrop near the proposed dam site, artesian waters reaching the surface form the Taroom Boggomosses (mound springs). Boggomosses Area Nos 1 and 2 are listed on the Register of the National Estate. The Boggomosses provide a specialised wetland habitat because they are fed by artesian groundwater in a region where other sources of water are often lacking. They support significant invertebrate life, highlighted by the localised land snails Adclarkia dawsonensis and Elsothera hewittorum.
New Acland Coal Mine Stage 3 Expansion Project	New Hope Coal Australia	IAS lodged April 2007. EIS lodged August 2008. Amended EIS lodged October 2009. EIS approved by CG November 2009. EIS public comment until February 2010. Supplementary EIS and advisory agencies comment expected Q2, 2011.	Open cut coal mine.	Located 14 km north-northwest of Oakey and 35 km northwest of Toowoomba. Mining Lease Application 50232. Mineral Development Licence 244.	Construction period commencing in 2010 to 2013. Project is expected to extend coal production at the mine until approximately 2042.	The EIS states that the coal handling and preparation plant for the mine will require a water supply of up to 5050 ML/a of raw water to achieve its maximum production rate. During 2010, the WWRF pipeline will be completed and will provide a water supply of 3,000 ML per annum to the Project site. In addition, NAC possesses options to increase this water supply to a maximum of 5,500 ML per annum. This water supply option will satisfy all water requirements for the Project and significantly decrease the reliance on groundwater resources to only a small supply for potable water requirements. A numerical groundwater model was used to predict the impact of groundwater drawdown from mine pit depressurisation. The worst case scenario (high transmissivity and at the end of mine life) indicates that the radius of influence within the Walloon Coal Measures aquifer (zero drawdown) extends approximately 5 km from MDL 244's boundary. Drawdown in the Walloon Coal. A drawdown of 5 m is unlikely to have any impact on the operation of existing pumping bores in the Walloon Coal Measures or Marburg Sandstone Aquifers.
Queensland Curtis LNG Project (QCLNG)	QGC Pty Ltd (BG Group Business)	EIS lodged August 2009. Supplementary EIS lodged February 2010. Project approved with conditions by the Queensland CG in June 2010. Project approved with conditions by DSEWPC in October 2010. FID taken 31 October 2010.	Coal seam gas fields. Construction of 380 km gas pipeline. Development of LNG facility (12 Mtpa).	Coal seam gas fields, Surat Basin. Gas pipeline, Surat Basin to Gladstone. LNG facility, Curtis Island, Gladstone.	Construction phase 2010 to 2013. Operation phase 2014 to 2021.	This operation covers QGC's northern, central and southern development areas, with most water coming from the central area. During 2009, combined abstraction is understood to be around 29 ML/day.
Queensland Hunter Gas Pipeline Project	Hunter Gas Pipeline Pty Ltd	Assessed as not a controlled action by DSEWPC in December 2006 Pipeline license issued by QLD government in April 2007 (PPL 124) Project conditions issued by NSW government in February 2009.	831 km gas pipeline.	Runs from Wallumbilla Gas Hub in Qld to Newcastle. The pipeline will pass through ten local government areas in NSW.	Delayed for at least a year. Construction was expected late 2010- 2011. Now expected to commence construction in 2012.	The preliminary environmental assessment report indicates that after construction of the pipeline, water for hydrostatic testing of the pipe would be sourced from local watercourses.

Proposed Project	Proponent	Stage	Components	Location	Timing	Groundwater Specific Comments
Spring Gully Power Station	Origin Energy Power Ltd	IAS lodged November 2004. EIS completed in 2006.	30 coal seam gas wells. 500 MW base load power station. Expansion of existing Spring Gully power station. 1000 MW combined gas fired power station constructed in two 500 MW stages.	The power station will be located at Spring Gully, Lot 16 on Plan AB174, ~80 km northeast of Roma in Southern Queensland.	In June 2007 Origin committed to the construction of the Darling Downs Power Station, which has recently, commenced. This has delayed the construction of the Spring Gully Power Station. Once commenced, power station construction to take 30-34 months.	Cooling water required by the power station will be sourced from coal seam gas water produced from Origin's nearby coal seam gas fields. The aquifers of particular relevance to the power station site (i.e. those aquifers that may be affected in the short and long term) occur within the Hutton Sandstone and the Precipice Sandstone. The operation of the power station will produce significant amounts of blowdown water which is proposed to eventually be reinjected into the ground once gas has been extracted as part of the coal seam gas production process.
Surat Basin Rail	Surat Basin Rail Pty Ltd	EIS lodged January 2008. Final TOR issued 2008. EIS submitted for public comment until March 2009. Supplementary EIS then lodged in November 2009. EIS complete.	Open access, multi-user, 210km single railway track with up to eight passing loops. Rail infrastructure corridor will be approximately 60 m wide and will be located wholly within the proposed Surat Basin Infrastructure Corridor State Development Area.	New rail infrastructure of 210 km that will connect the Western Railway system near Wandoan with the Moura Railway system near Banana. Located in central Queensland from Wandoan to Banana in the Surat Basin.	Construction commencement anticipated in the 2011/12 financial year. Completion expected in the 2014-15 financial year. Design life of the railway is a minimum of 50 years. Railway construction to take approx 33 months (6 months early works, 24 months main construction and 3 months commissioning).	In the supplementary EIS, more details were provided and indicated that based on a conceptual construction schedule, the assessment of the total water required for construction has been revised at 4,200 ML. It has been proposed that: Area 1 (Ch 0 km - 90 km from Wandoan) is supplied with water from the GAB Basin and/or the Dawson River. Approximately 2,700 ML is estimated to be required in this area over the entire construction phase (30 -36 months) of the Project. Area 2 (Ch 90 km - Ch 210 km from Wandoan) is proposed to supplied with water from the Dawson River and/or disused mine water. A total volume of 1,500 ML of construction water will be required in this area, with overland flow storages constructed to minimise the take of water from the Dawson River and GAB where possible. Note that Area 1 is within the groundwater model extent. Area 2 is partially within the groundwater model extent.
Wandoan Coal Project	Xstrata Coal Queensland Pty Ltd	IAS lodged December 2007. EIS lodged December 2008. Supplementary EIS prepared October 2009. Project approved with conditions by the Queensland CG in November 2010. Federal government approval with conditions in March 2011.	30 Mtpa open cut coal mine. Rail spur from proposed Surat Basin Rail Project.	Located ~ 350 km northwest of Brisbane and 60 km south of Taroom. The coal resource falls within three Mining Lease applications: 50229, 50230 and 50231. Coal fields are situated in the Surat and Bowen basins, to the south and north of Roma.	First coal expected for export post 2012.	The shallow mining is envisaged to impact on shallow alluvium, weathered, and coal seam aquifers. No impacts on the deep Hutton or Precipice GAB aquifers are envisaged from the mining activities due to the thick layers of sediments between the mining and the GAB aquifers and the vertical separation being in the order of 400 m and absence of conduits. Groundwater related supply options for construction water demands are: Wandoan Town Bore No. 2 15793 No.2, RN58700 appears to be capable of continually supplying at least 40 L/s. Production bores in the coal seams to be mined as part of the Project. Investigations into the water yields of the coal seams are ongoing – production bores could be established in water-bearing areas of the coal seams to supplement construction water supplies while depressurisation the coal aquifers ahead of mining – however yields are extremely low – and thus the volume of water potentially available from this source is limited. Existing bores in the GAB. A new bore into the precipice aquifer of the GAB. An option to construct a third bore into the Precipice

Proposed Project	Proponent	Stage	Components	Location	Timing	Groundwater Specific Comments
						aquifer is under consideration. Consideration was originally given to drawing operational supplies from the GAB. However, initial estimates of the impacts of drawing such a large demand over an extended period were assessed to be unsustainable. The Proponent is currently assessing two alternative options for the supply of operational raw water (via separate EISs), being: Coal seam gas water sourced from Berwyndale (owned by Queensland Gas Company) and Talinga (owned by Origin) to the south of the Project site Glebe Weir on the Dawson River (owned by SunWater).

NOTES:

AU$ = Australian dollars
CG = Coordinator General
CO_2 = carbon dioxide
DERM = Department of Environment and Resource Management
DME = di-methyl ether
DSEWPC = Department of Sustainability, Environment, Water, Population and Communities (formerly DEWHA)
EIS = Environmental Impact Statement
FID - financial investment decision
ha = hectares
IAS – initial advice statement
km = kilometre
LNG = liquefied natural gas
ML = megalitres
Mtpa = million tonnes per annum
MW = megawatts
SDRC = Southern Downs Regional Council
TOR = terms of reference
tpa = tonnes per annum
UCG = underground coal gasification

Mechanisms for cumulative impacts on groundwater values in the study area can occur via the following processes:

- Depressurisation activities that cause concurrent groundwater drawdown in the same groundwater system(s).
- Subsurface and surface activities that can potentially contaminate the same groundwater system(s).
- Activities that can potentially contribute to increased rates of subsidence in the same region.

10.8.1 Cumulative Impacts - Depressurisation

The numerical groundwater modelling considered scenarios that accounted for cumulative effects of other significant groundwater users as well as Arrow, including coal seam gas developments by Santos, QGC and Origin. The modelling results show that cumulative effects can be significant due to the volumes of groundwater abstracted by other gas field operators, Table 8.2 shows the maximum drawdowns predicted for modelling scenario 3 in comparison to the Arrow only modelling scenario (scenario 1). The modelling and results are described in section 7, and in Schlumberger 2011 (Appendix B).

Under the Water Act 2000 where the water level impacts of coal seam gas producers overlap, a “cumulative management area” will be established by the government. Within a cumulative management area, the QWC will be responsible for relevant activities like groundwater impact monitoring, modelling and preparation of cumulative impact reports. Inside these areas, bore owners will deal with the QWC rather than any individual coal seam gas producer. QWC will be supported by a technical advisory panel to review the data collected quarterly and an industry advisory panel, comprising members from the coal seam gas industry; and importantly from the agriculture, environment and community sectors.

The QWC also has the responsibility for management of cumulative impacts from coal seam gas operations on springs. The QWC has prepared Terms of Reference for assessment of identified priority springs and will prepare a Springs Impact Management Strategy (SIMS). The outcomes of the SIMS will enable Arrow Energy to refine their monitoring, mitigation and management strategies to minimise impacts to groundwater dependent ecosystems associated with springs.

10.8.2 Cumulative Impacts – Contamination of Groundwater Systems

A variety of surface activities (e.g. storage of hazardous materials) and subsurface activities (e.g. drilling and installation of wells, and exploration drilling by a number of proponents across sectors) have the potential to create a cumulative impact. It is assumed that adherence to all industry standards as they relate to the appropriate storage, handling and disposal of hazardous materials and the drilling and installation of wells will mitigate potential cumulative impacts. Monitoring programs conducted by all proponents will ensure that water quality indicators are used to trigger the implementation of response actions in the event of leaks, spills or inadequate well installations.

10.8.3 Cumulative Impacts – Regional Subsidence

ALOS satellite data is considered by industry to be the most effective tool to monitor subsidence. Arrow and the other three major coal seam gas proponents are currently outlining a framework to monitor the cumulative impacts associated with subsidence.

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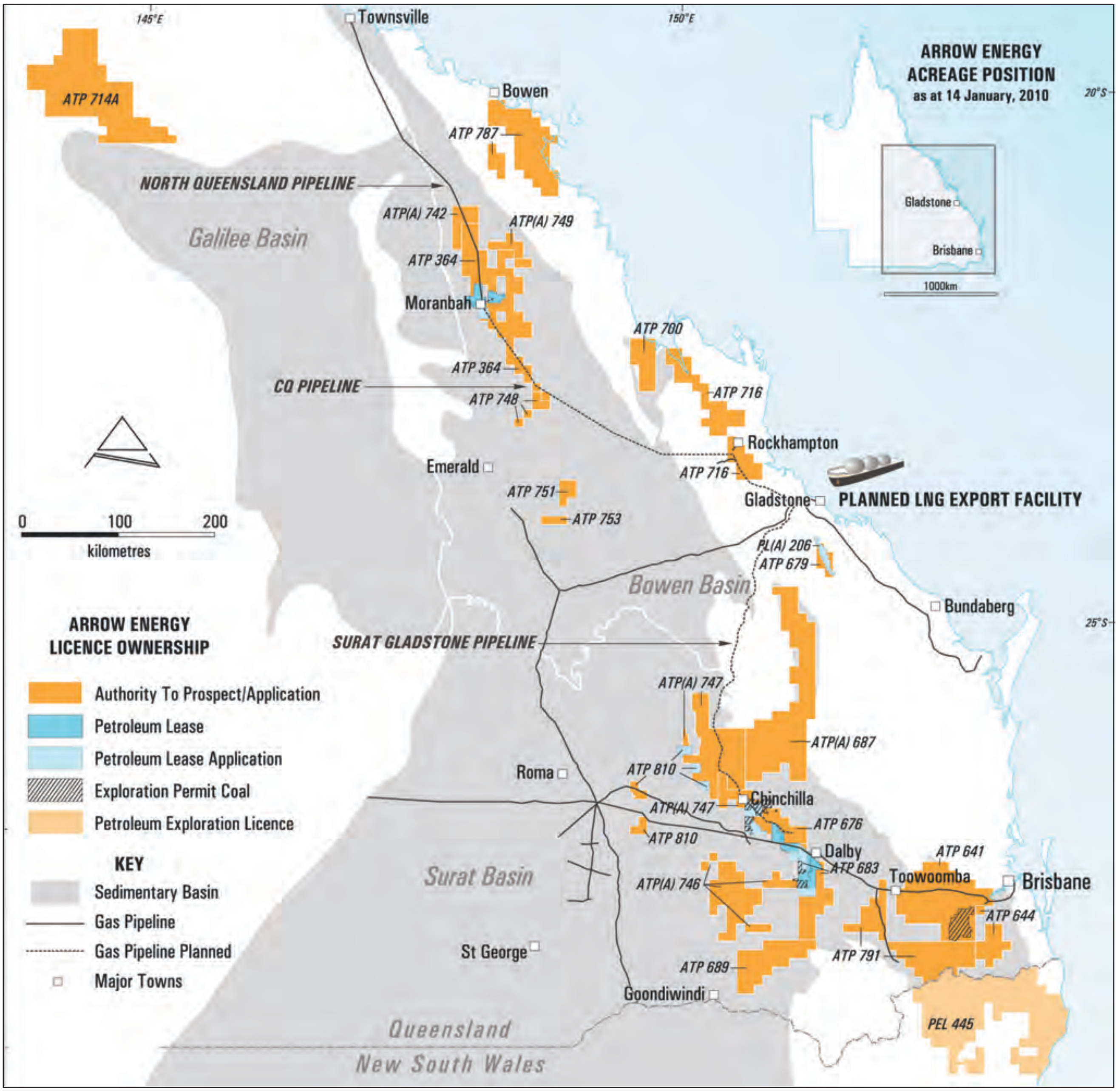
Figures

Arrow Energy Surat Gas Project
Groundwater Impact Assessment Report



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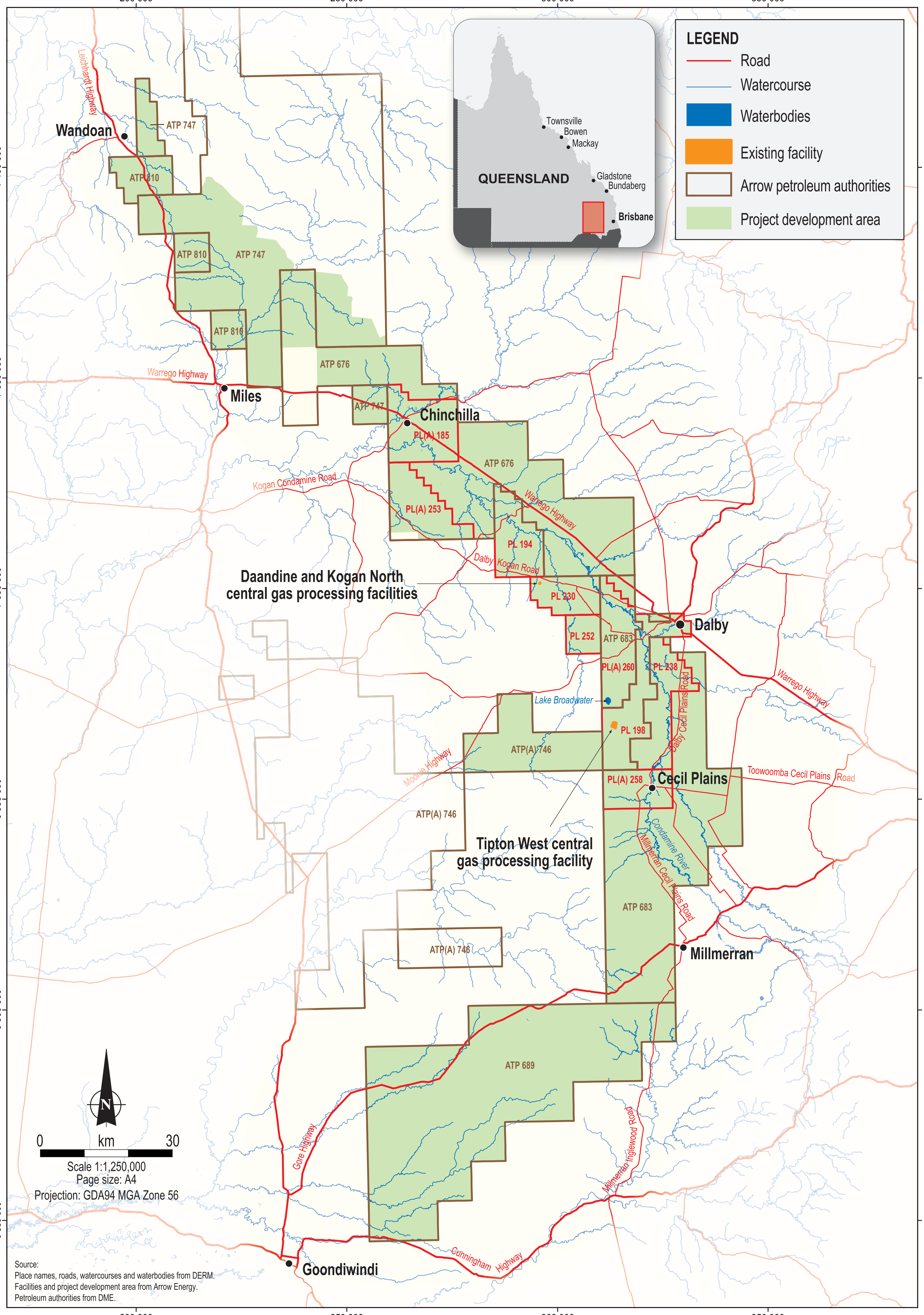
Arrow Energy acreage position

Figure No: 1.1



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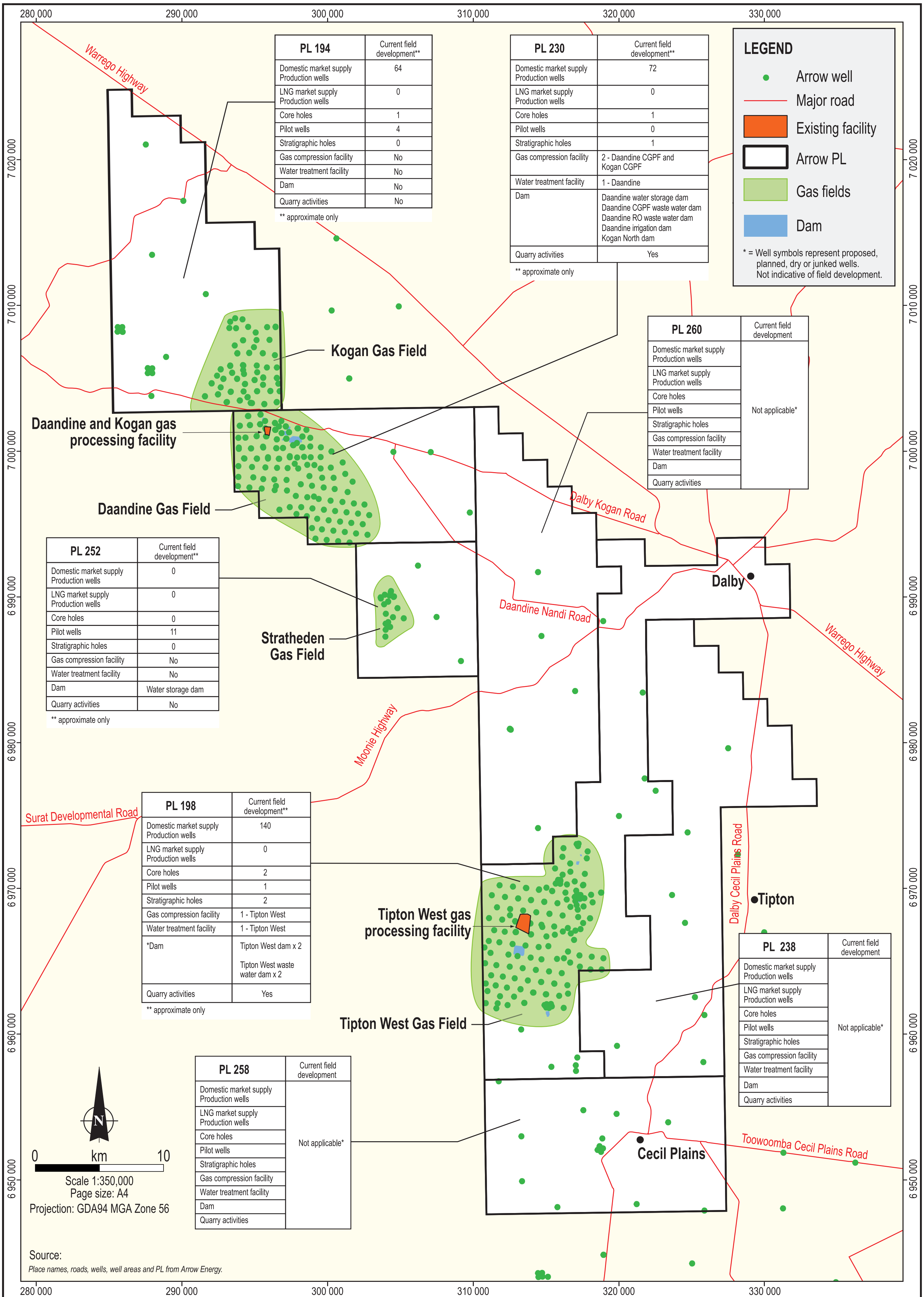

PL 194	Current field development**
Domestic market supply Production wells	64
LNG market supply Production wells	0
Core holes	1
Pilot wells	4
Stratigraphic holes	0
Gas compression facility	No
Water treatment facility	No
Dam	No
Quarry activities	No

** approximate only

PL 230	Current field development**
Domestic market supply Production wells	72
LNG market supply Production wells	0
Core holes	1
Pilot wells	0
Stratigraphic holes	1
Gas compression facility	2 - Daandine CGPF and Kogan CGPF
Water treatment facility	1 - Daandine
Dam	Daandine water storage dam Daandine CGPF waste water dam Daandine RO waste water dam Daandine irrigation dam Kogan North dam
Quarry activities	Yes

** approximate only

PL 260	Current field development
Domestic market supply Production wells	Not applicable*
LNG market supply Production wells	
Core holes	
Pilot wells	
Stratigraphic holes	
Gas compression facility	
Water treatment facility	
Dam	
Quarry activities	

PL 252	Current field development**
Domestic market supply Production wells	0
LNG market supply Production wells	0
Core holes	0
Pilot wells	11
Stratigraphic holes	0
Gas compression facility	No
Water treatment facility	No
Dam	Water storage dam
Quarry activities	No

** approximate only

PL 198	Current field development**
Domestic market supply Production wells	140
LNG market supply Production wells	0
Core holes	2
Pilot wells	1
Stratigraphic holes	2
Gas compression facility	1 - Tipton West
Water treatment facility	1 - Tipton West
*Dam	Tipton West dam x 2 Tipton West waste water dam x 2
Quarry activities	Yes

** approximate only

PL 258	Current field development
Domestic market supply Production wells	Not applicable*
LNG market supply Production wells	
Core holes	
Pilot wells	
Stratigraphic holes	
Gas compression facility	
Water treatment facility	
Dam	
Quarry activities	

PL 238	Current field development
Domestic market supply Production wells	Not applicable*
LNG market supply Production wells	
Core holes	
Pilot wells	
Stratigraphic holes	
Gas compression facility	
Water treatment facility	
Dam	
Quarry activities	

coffey environments

Date: 09.06.2011
MXD: ArrowEnergy_UpstreamLNG.mxd
File Name: 7040_GW_02_F01.03_GIS_GL

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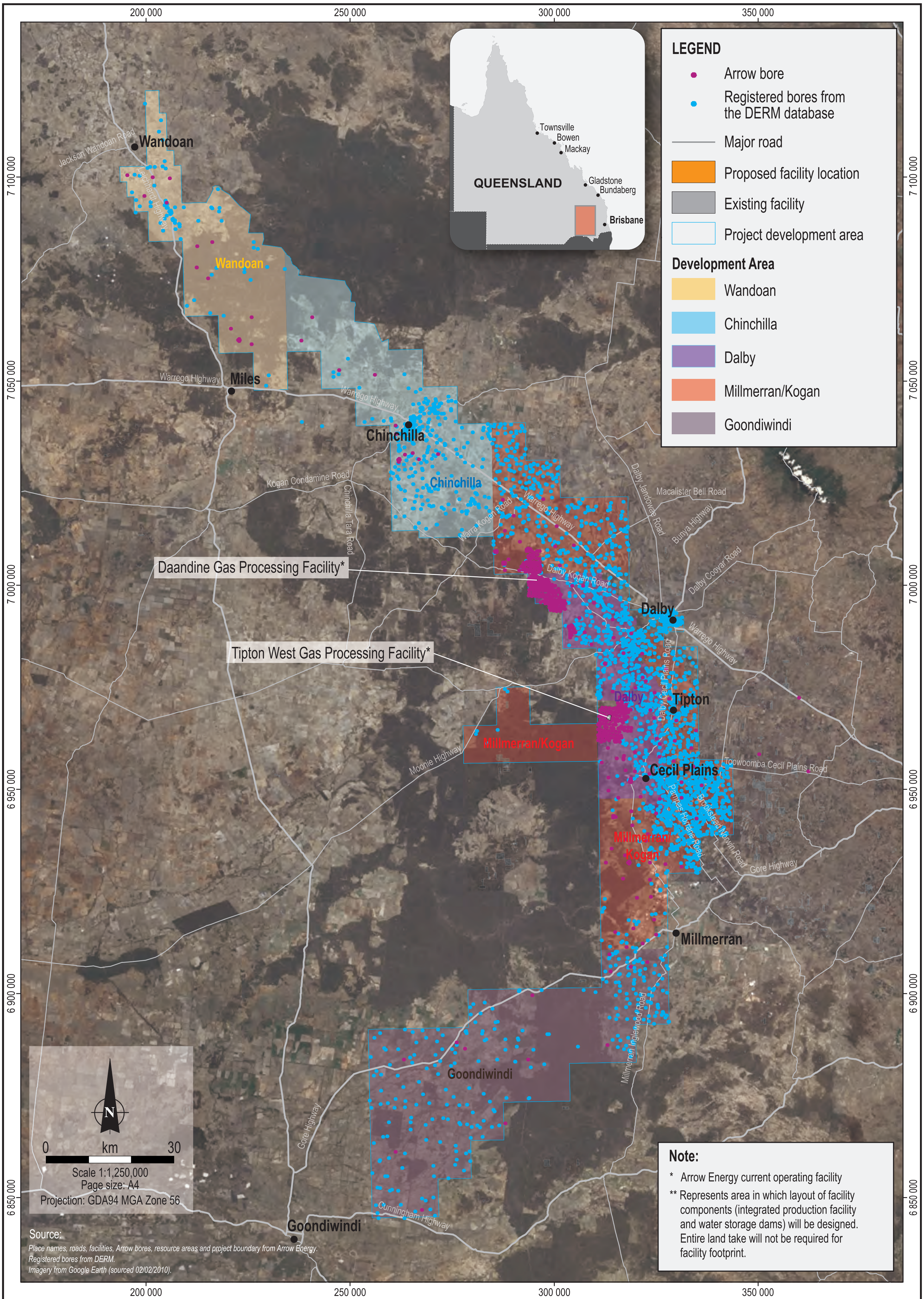
Current field development information (Dalby resource area)

Figure No: 1.3



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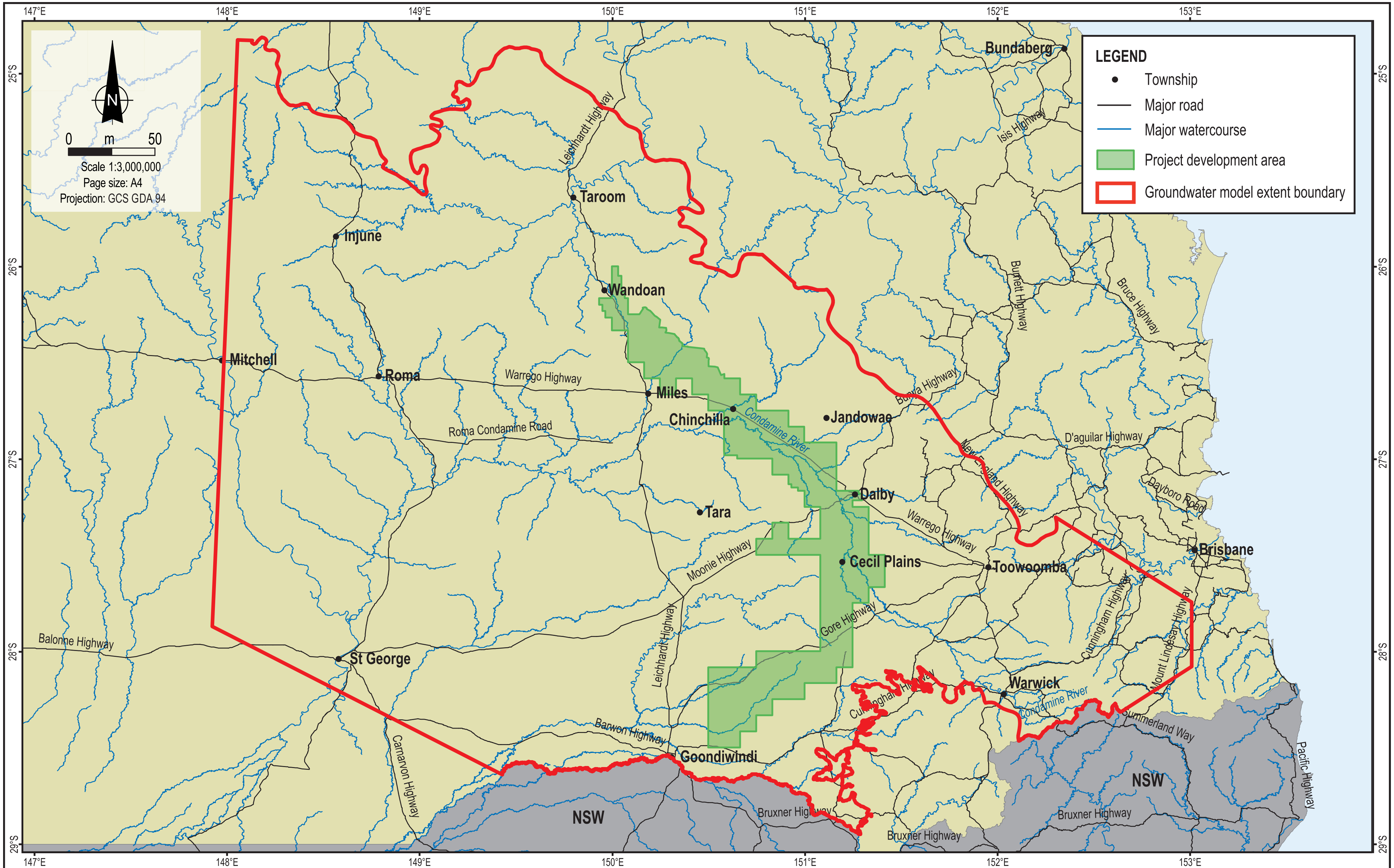

Source:
Place names, roads and watercourses from GEODATA250k.
Groundwater modelling domain from Schlumberger.

coffey environments

Date: 24.02.2010
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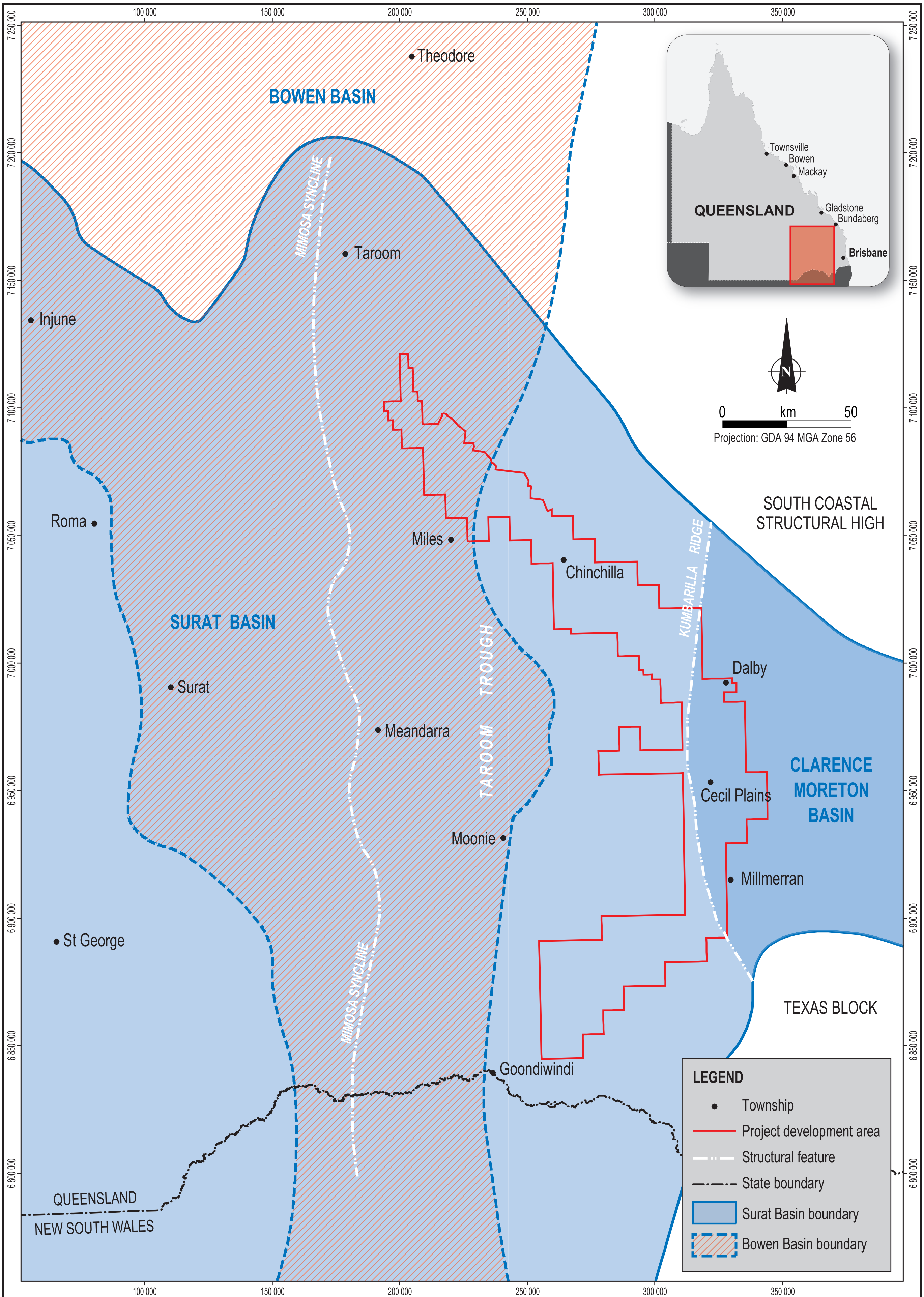
Arrow Energy

Surat Gas Project

arrow energy go further

Groundwater modelling domain

Figure No: 2.2



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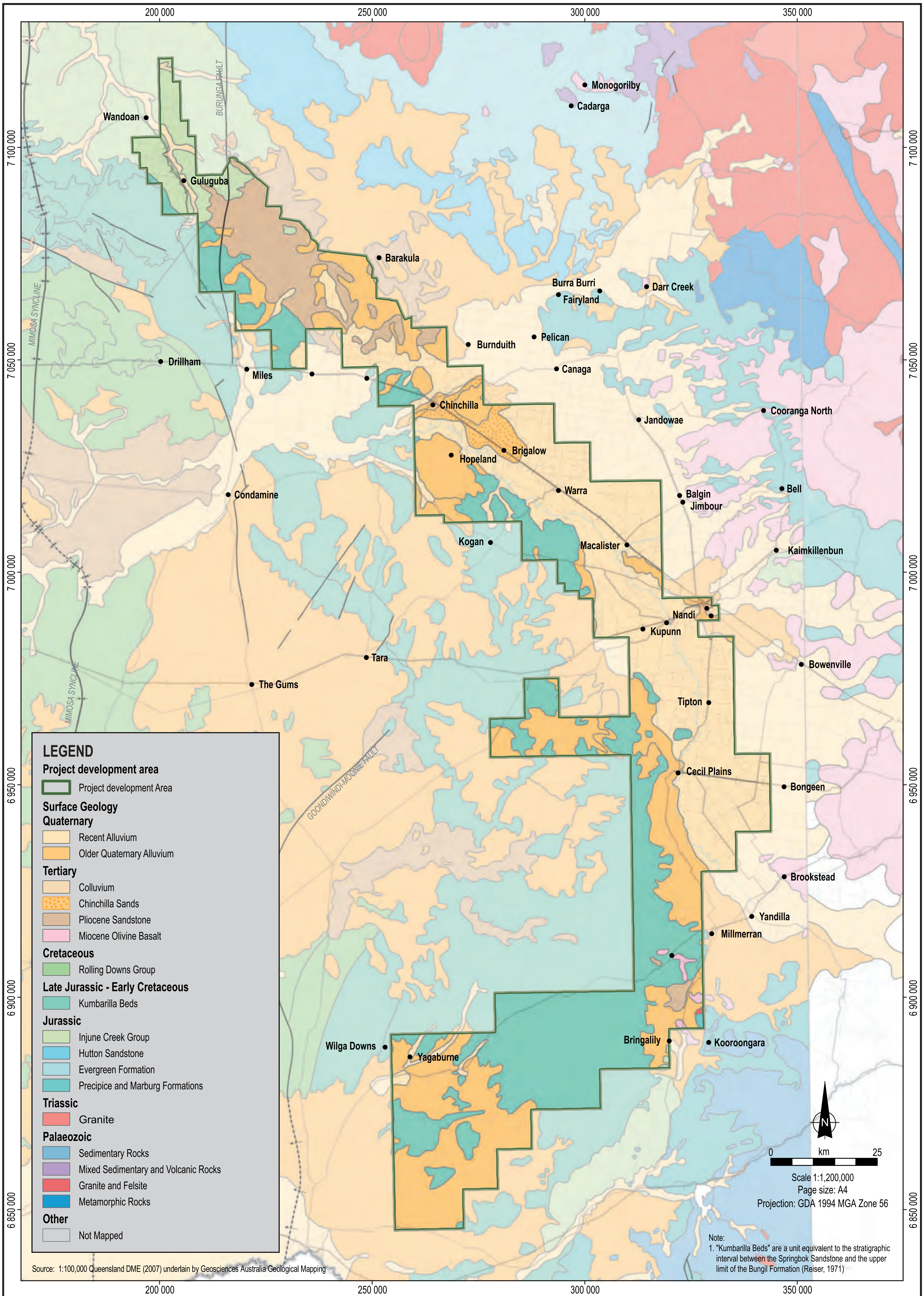


coffey environments

Date: 18.05.2011
MXD: ArrowEnergy_UpstreamLNG.mxd
File Name: 7040_GW_02_F03.02_GIS_GL

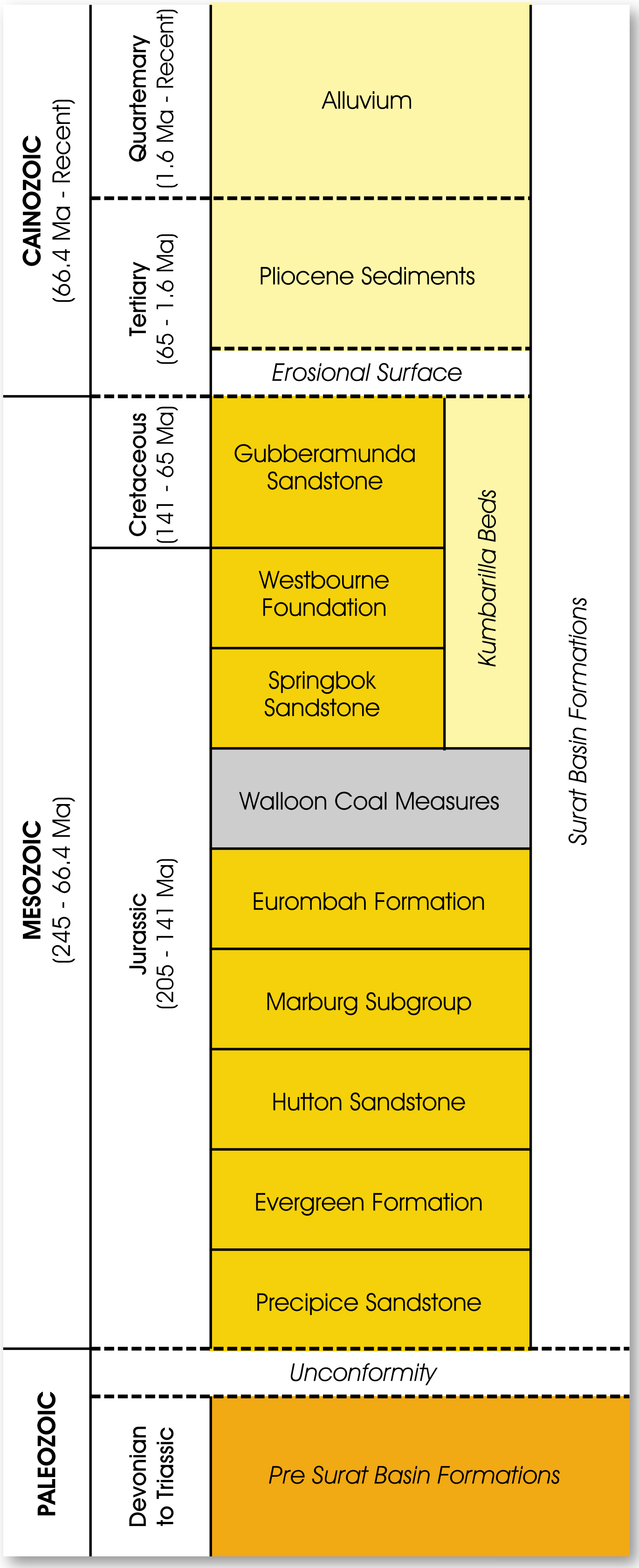
Arrow Energy Limited

Surat Gas Project

arrow energy go further

Surface geology of the study area

Figure No: 3.2



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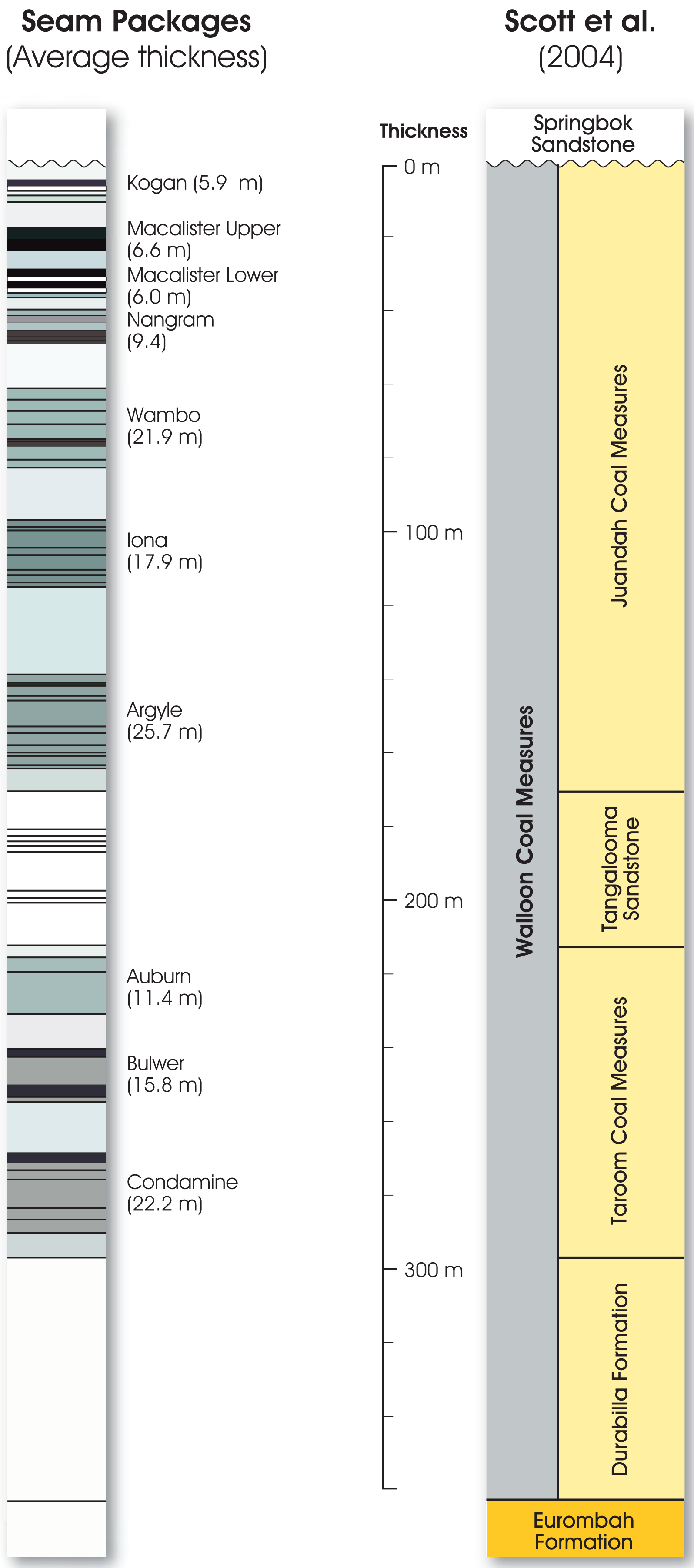
	File Name: 7040_GW_02_F03.03_GIS_HB	Surat Gas Project			



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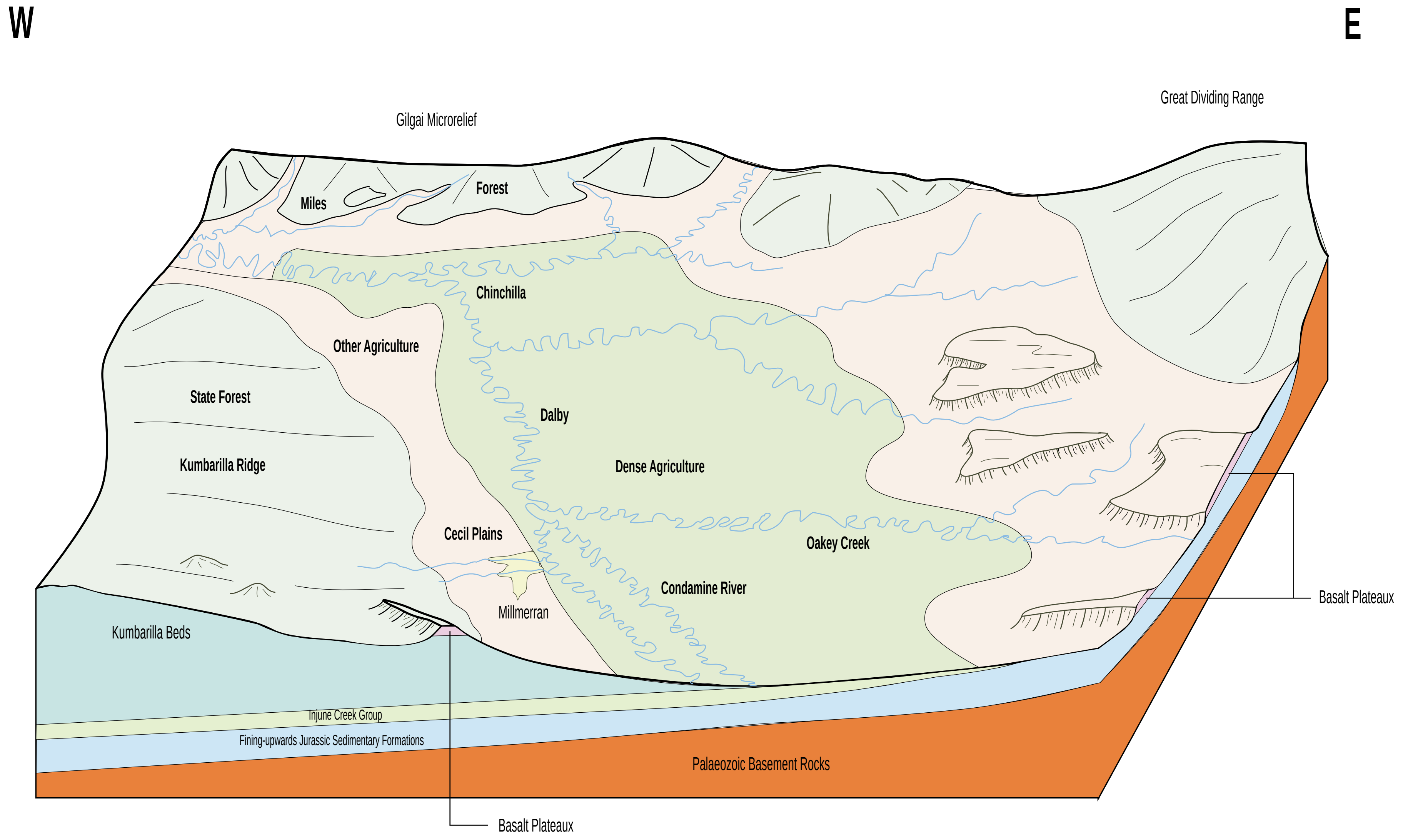
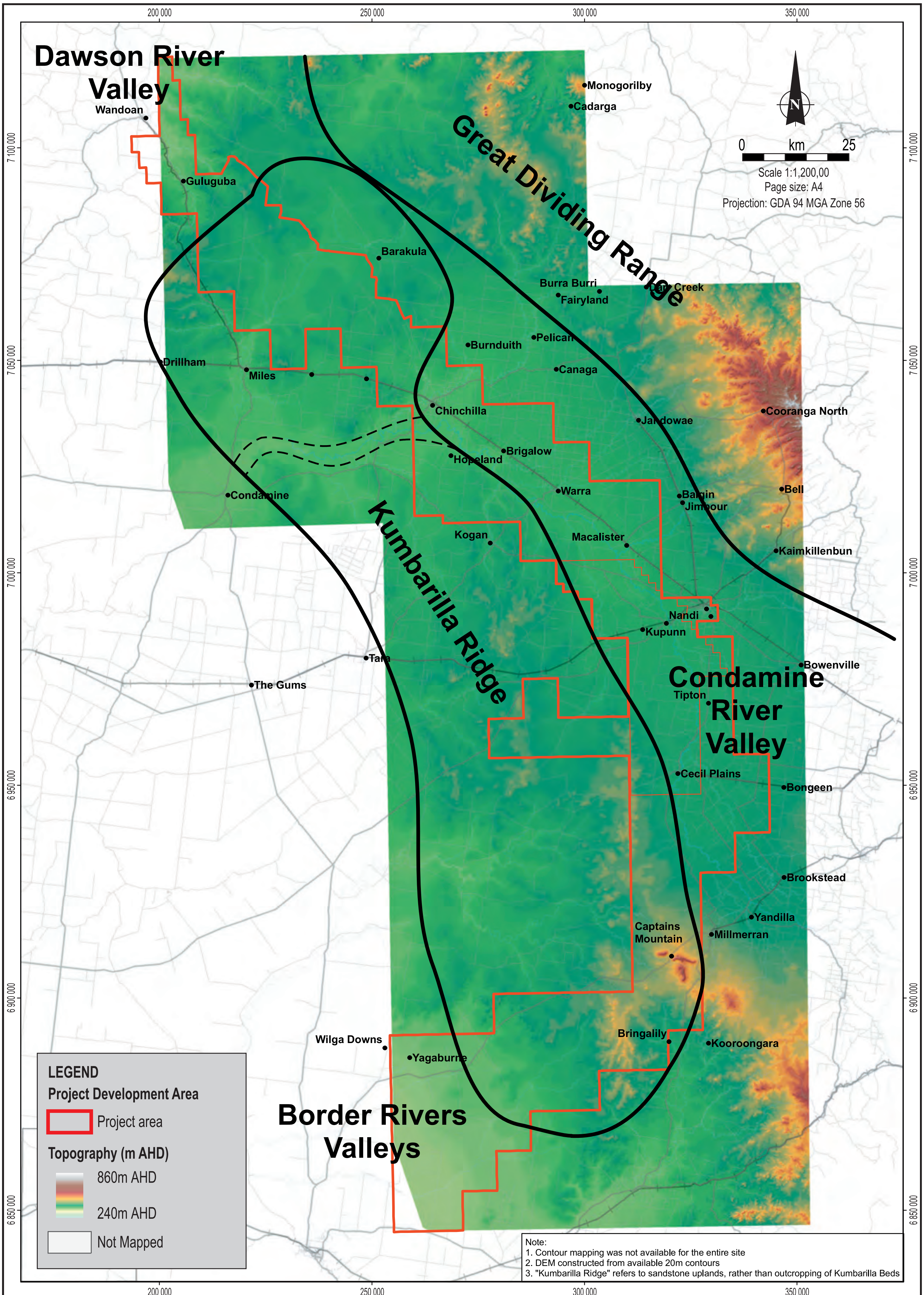
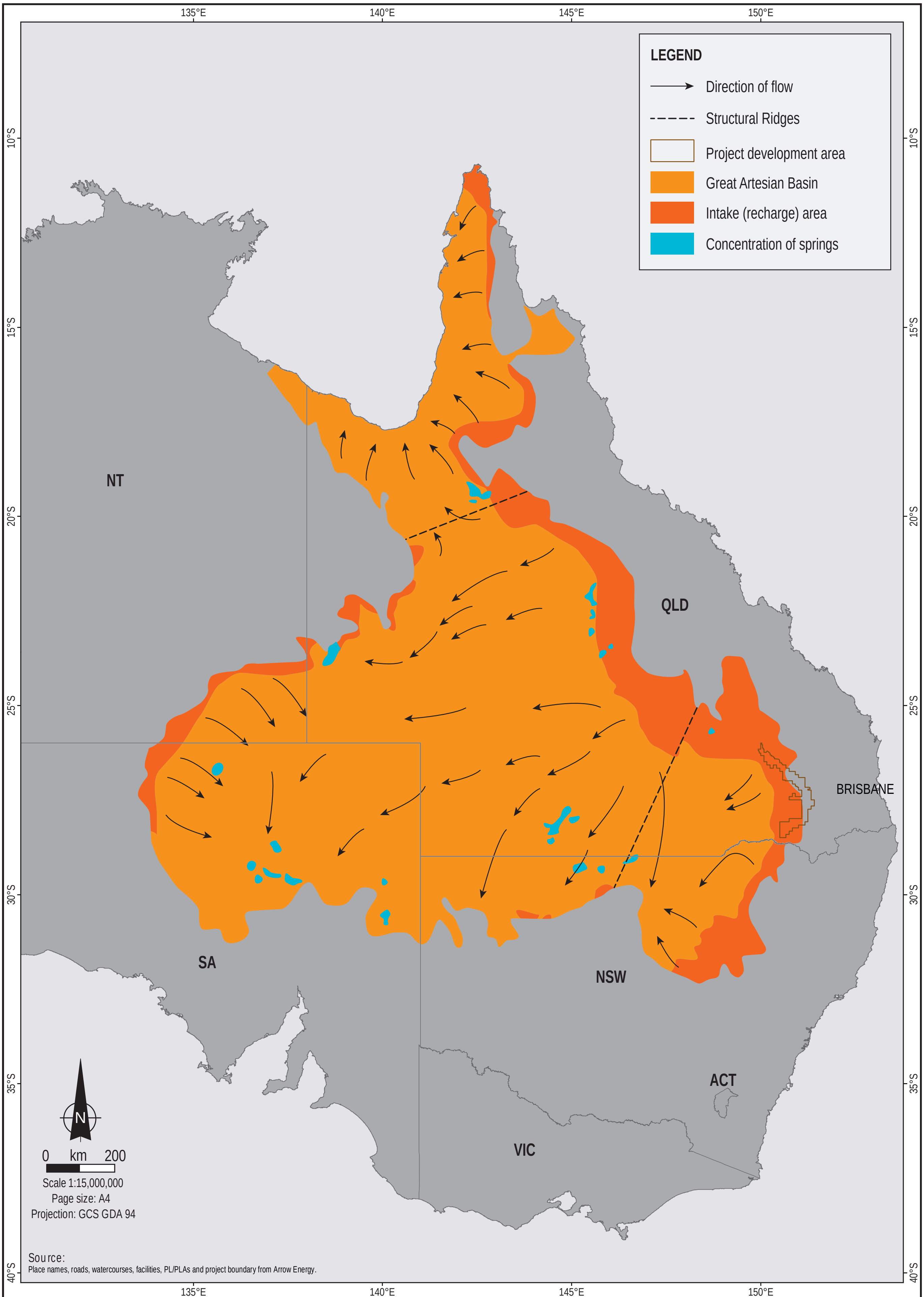


coffey environments	Job No: 7040	Arrow Energy	arrow energy go further	Block diagram - Condamine River valley environment	Figure No: 3.5
	File Name: 7040_GW_02_F03.05_GL	Surat Gas Project			



coffey environments	Date: 18.05.2011 MXD: Arrow_Topography_Map.mxd File Name: 7040_GW_02_F03.06_GL	Arrow Energy Limited Surat Gas Project	arrow energy go further	Topography and physiography of the study area	Figure No: 3.6



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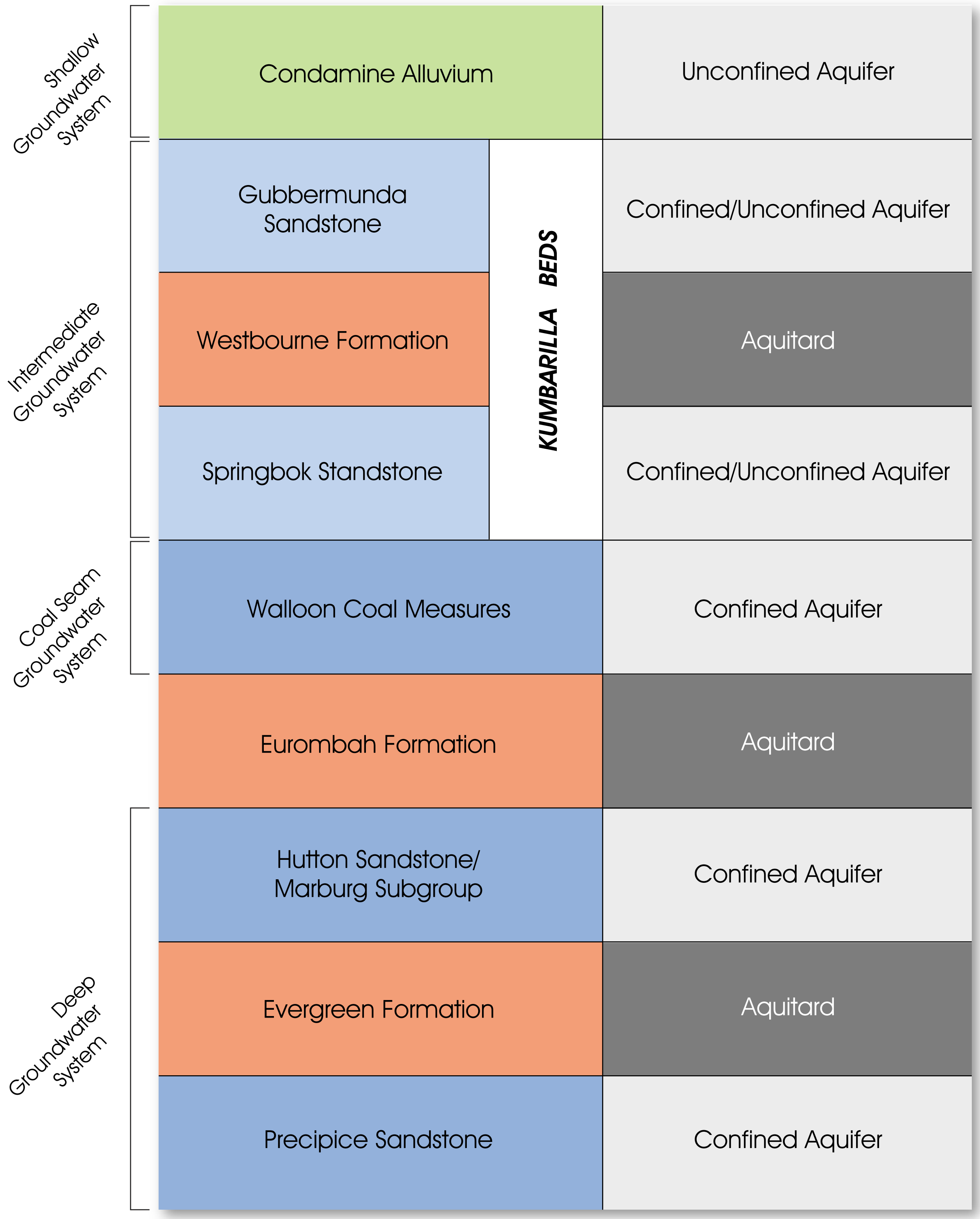

coffey environments	Job No: 7040	Arrow Energy	arrow energy go further	Formation-aquifer relationships	Figure No: 4.2
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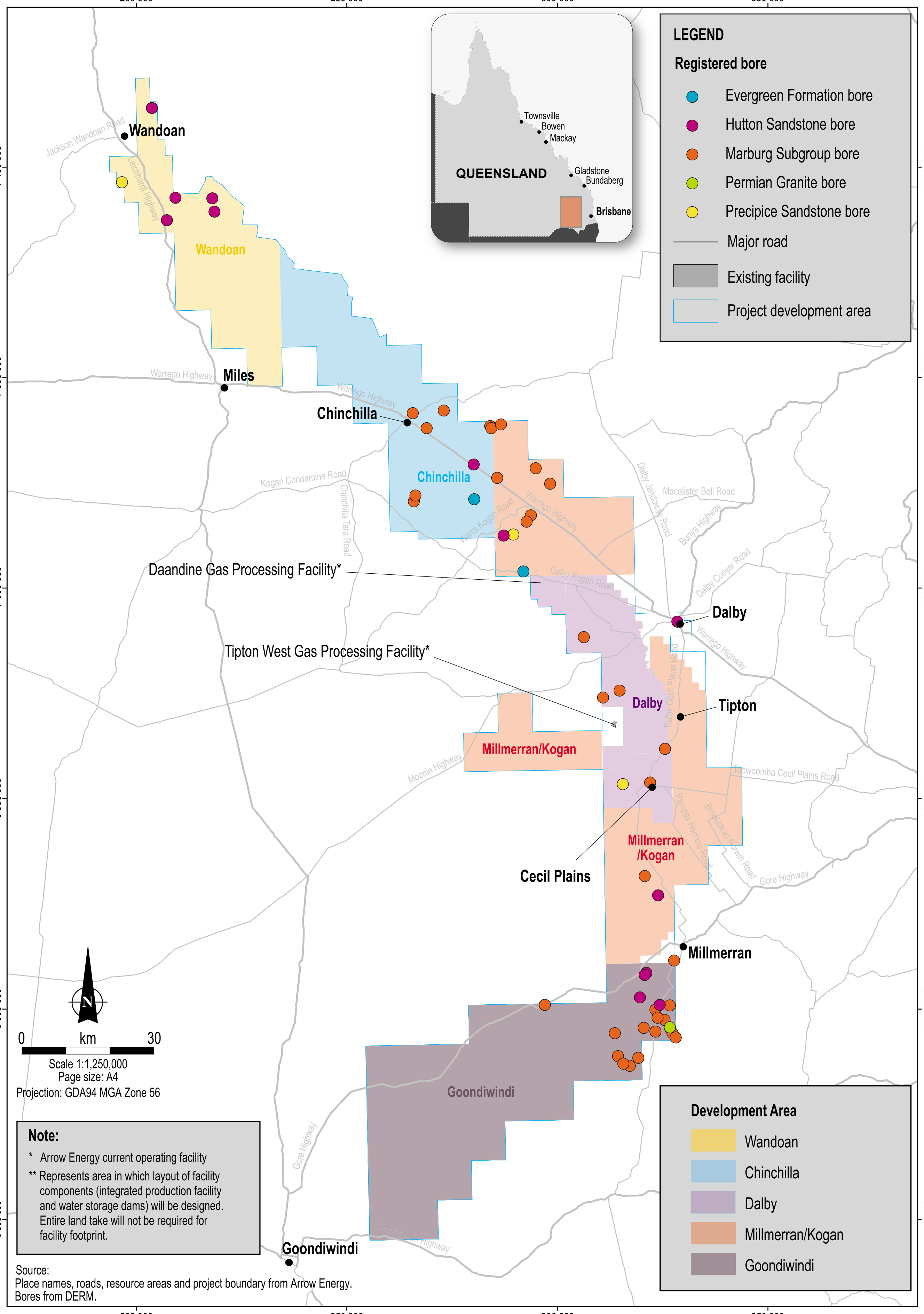

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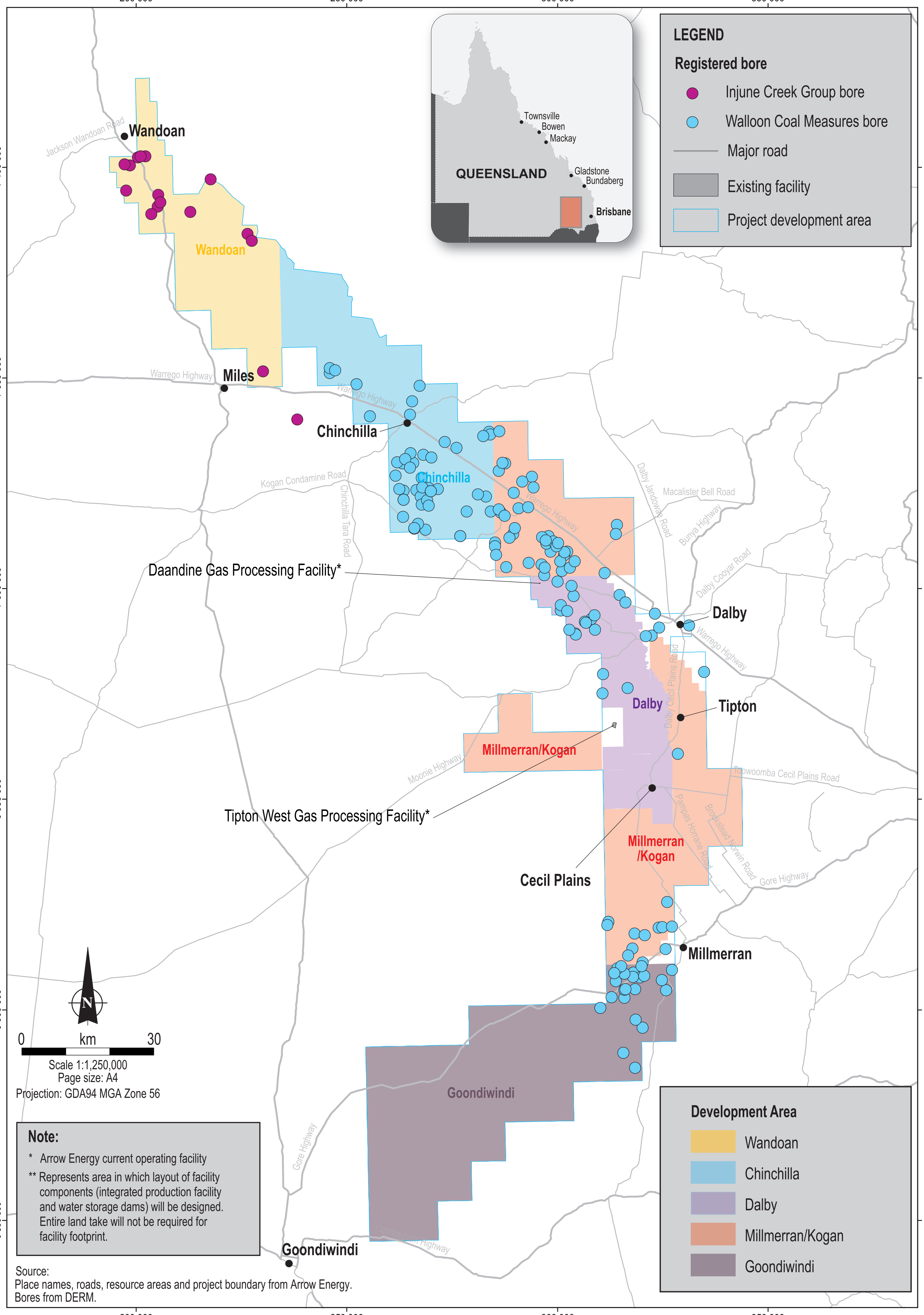
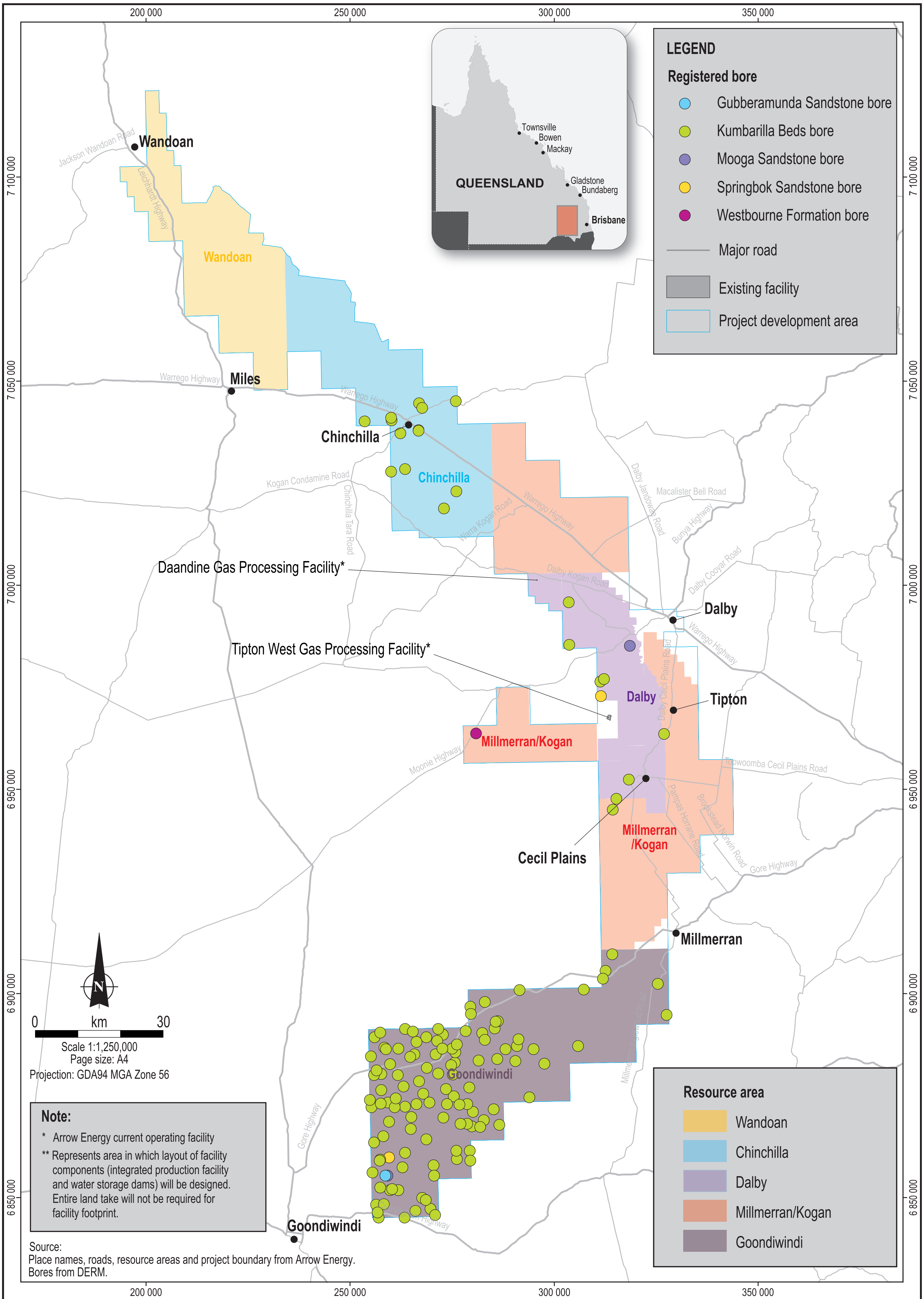


Source:
Place names, roads, resource areas and project boundary from Arrow Energy.
Bores from DERM.

coffey environments	Date: 09.06.2011 MXD: ArrowEnergy_UpstreamLNG.mxd File Name: 7040_GW_02_F04.03b_GIS_GL	Arrow Energy Surat Gas Project	arrow energy go further	Distribution of registered bores from the DERM database in the Walloon Coal Measures	Figure No: 4.3b



coffey environments

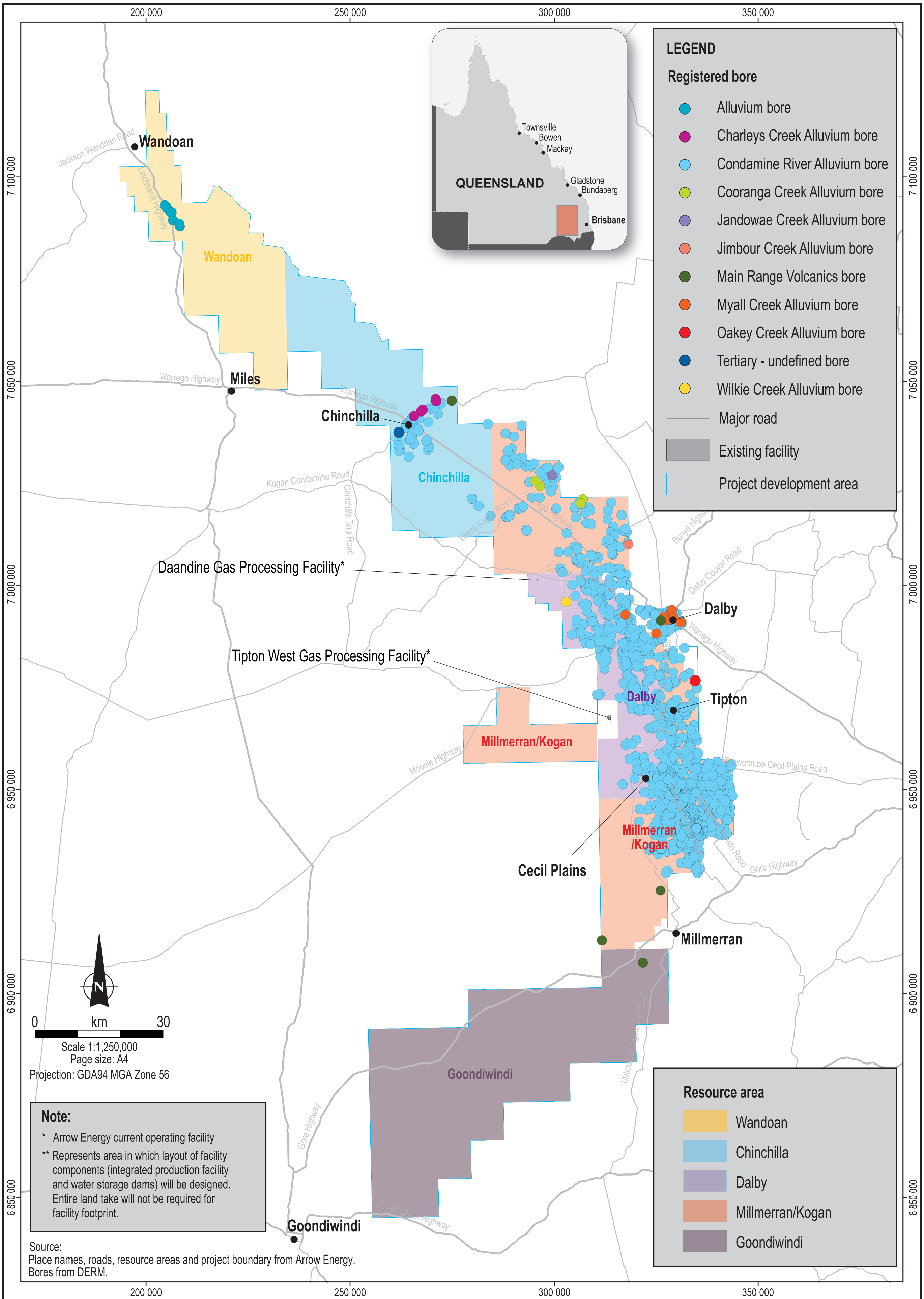
Date: 09.06.2011
MXD: ArrowEnergy_UpstreamLNG.mxd
File Name: 7040_GW_02_F04.03c_GIS_GL

Arrow Energy
Surat Gas Project

arrow energy go further

Distribution of registered bores from the DERM database in the intermediate aquifer units

Figure No: 4.3c



coffey environments

Date: 09.06.2011
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File Name: 7040_GW_02_F04.03d_GIS_GL

Arrow Energy

Surat Gas Project

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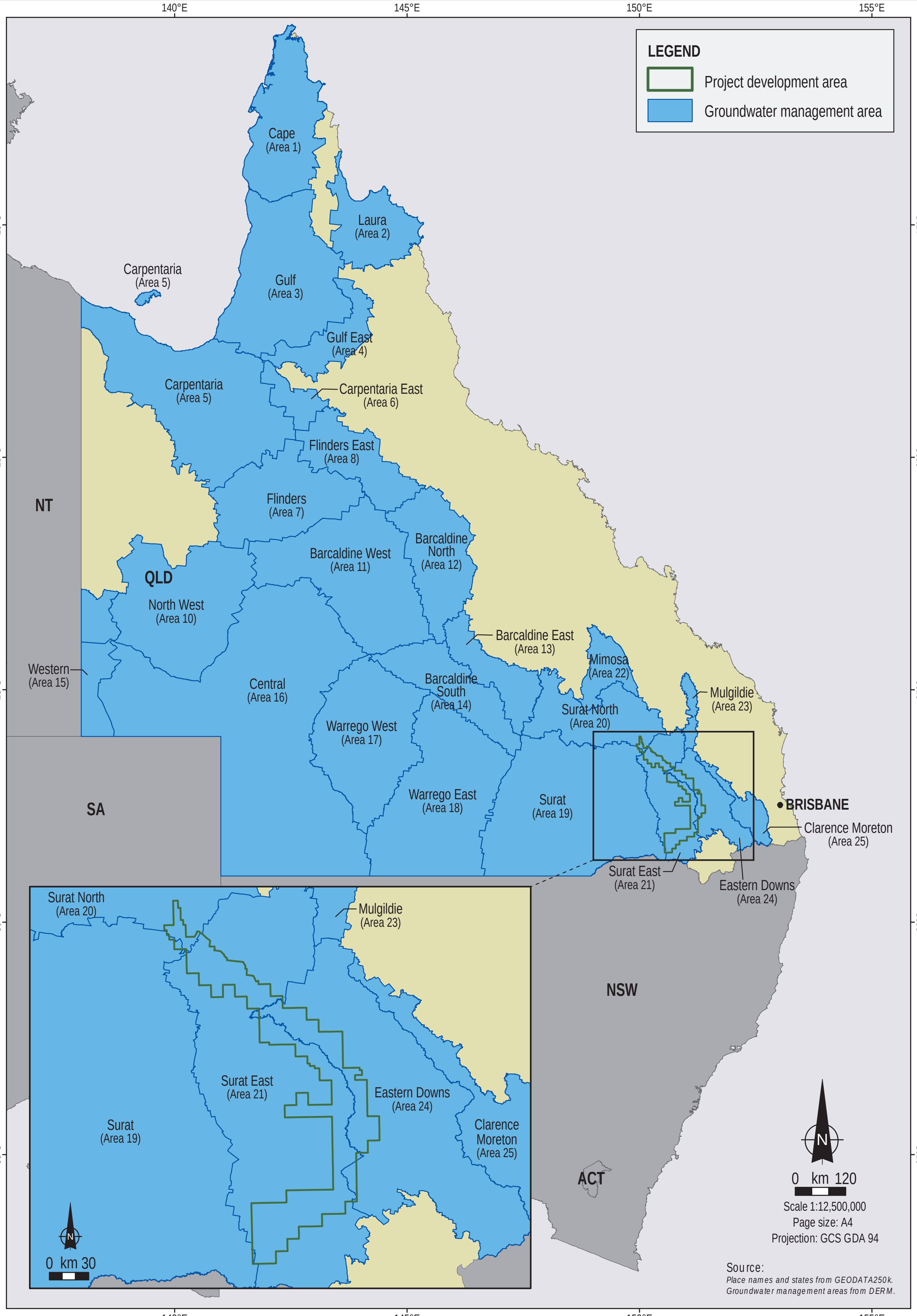
Distribution of registered bores from the DERM database in the shallow aquifer units

Figure No: 4.3d



coffey environments

Date: 18.05.2011
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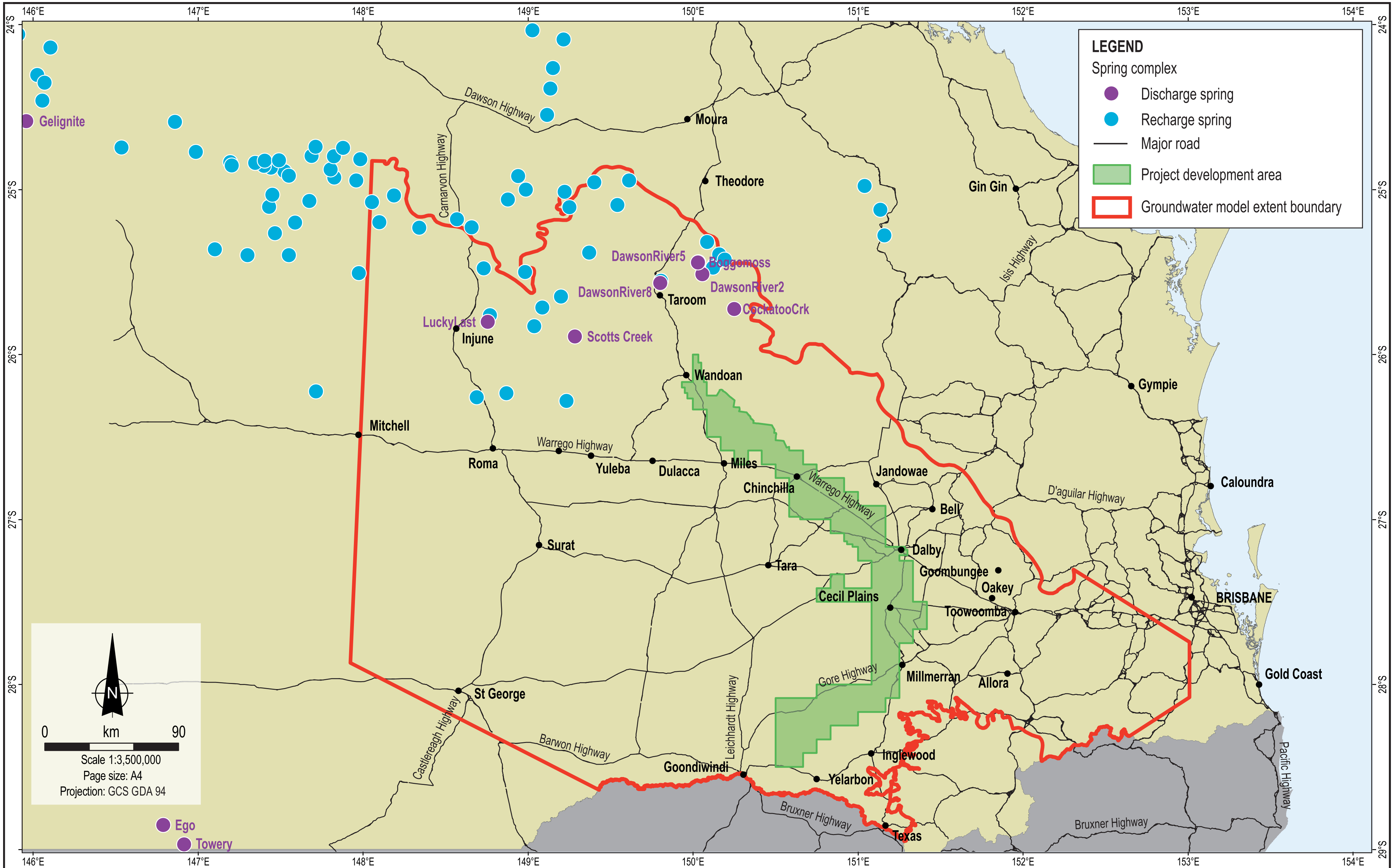
arrow energy go further

Groundwater management areas Queensland

Figure No: 4.4



Source:
Place names and roads from GEODATA250k.
Groundwater model extent boundary from Schlumberger.
Spring complexes from EPA.
Project development area from Arrow Energy.

coffey environments

Date: 09.06.2011
MXD: 7040AC_GW02_GIS003_v1_1
File Name: 7040_GW_02_F04.05_GIS_GL

Arrow Energy

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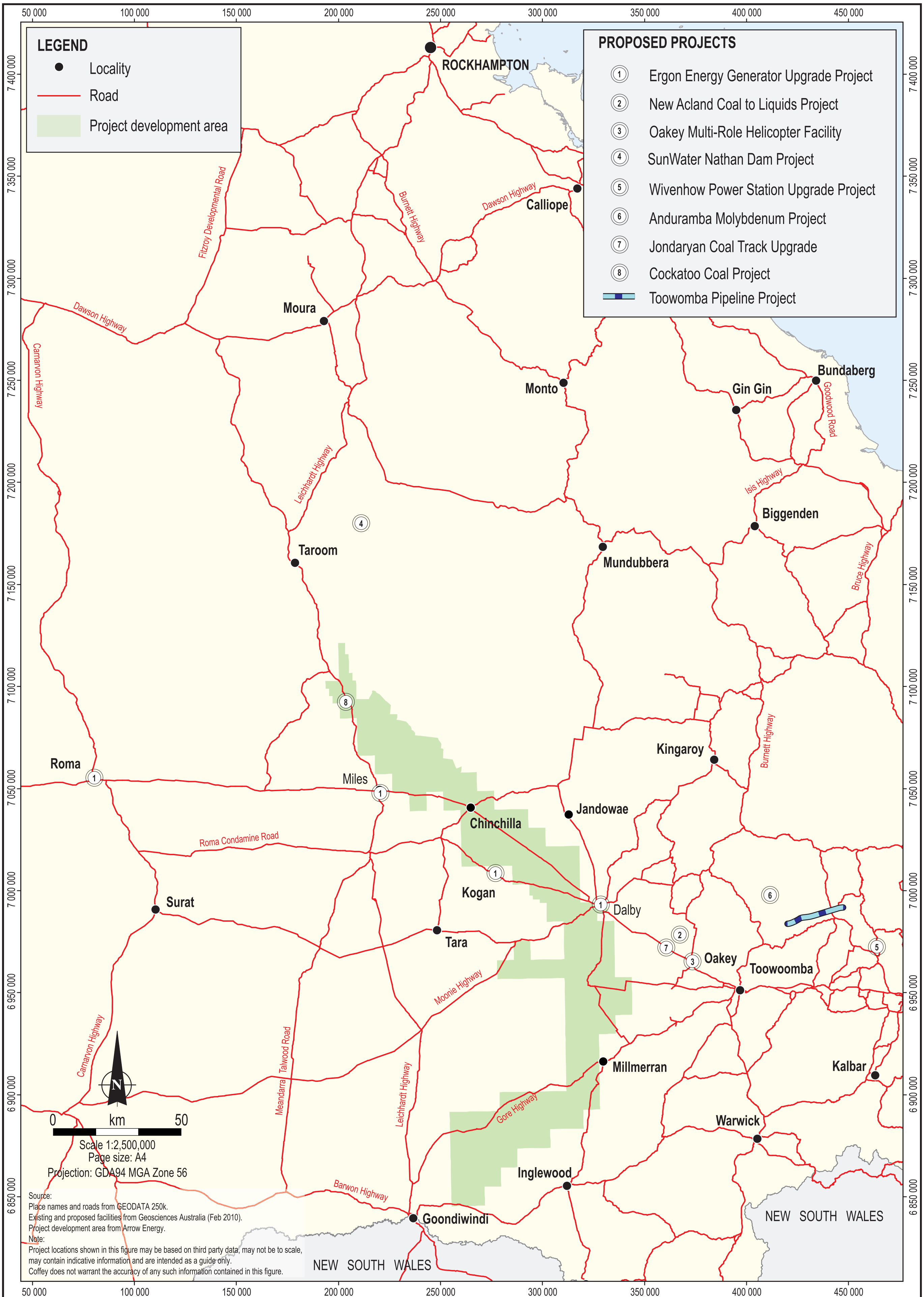
Location of groundwater springs within the groundwater model extent

Figure No: 4.5



coffey environments

Date: 07.07.2010
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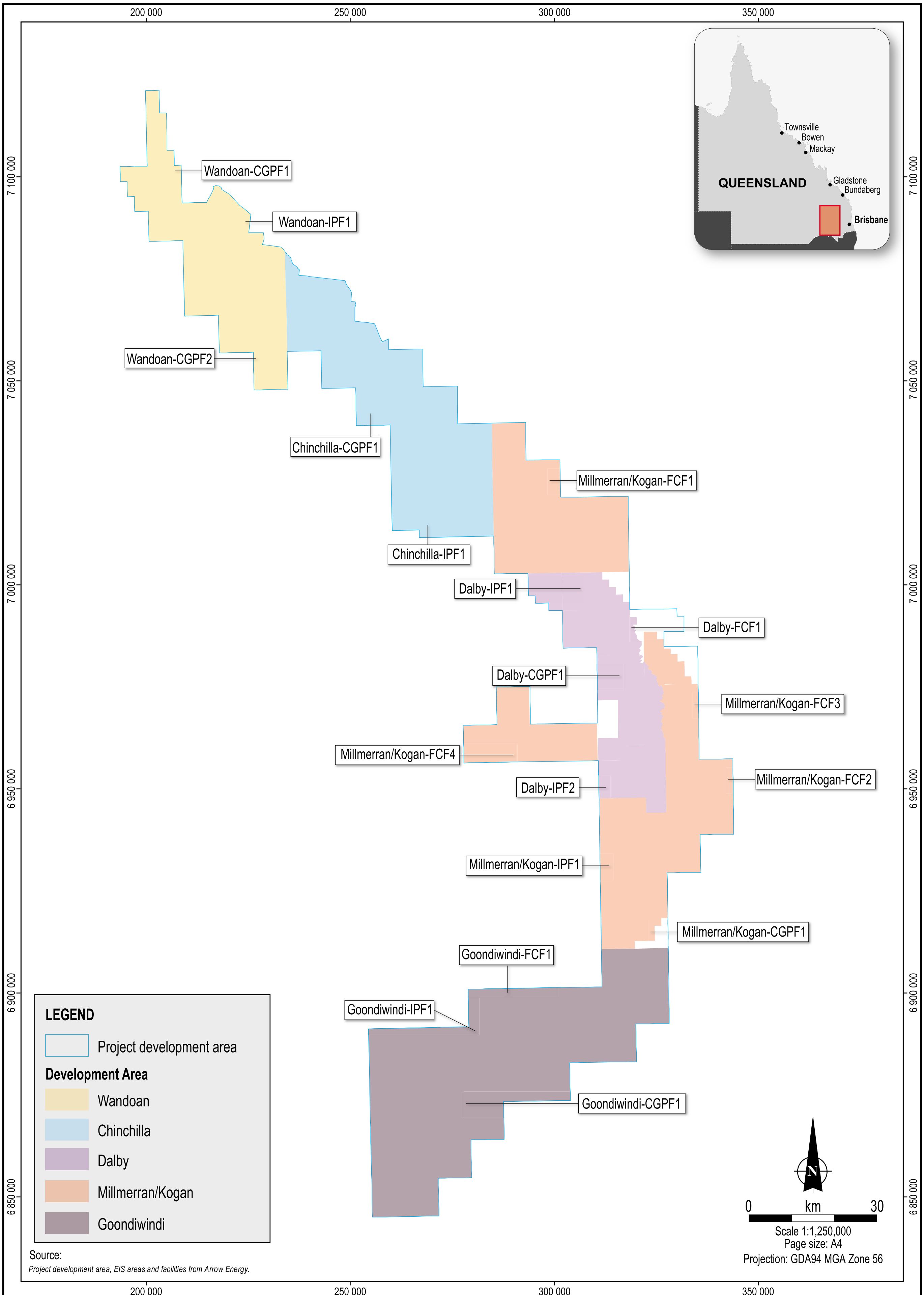
arrow energy go further

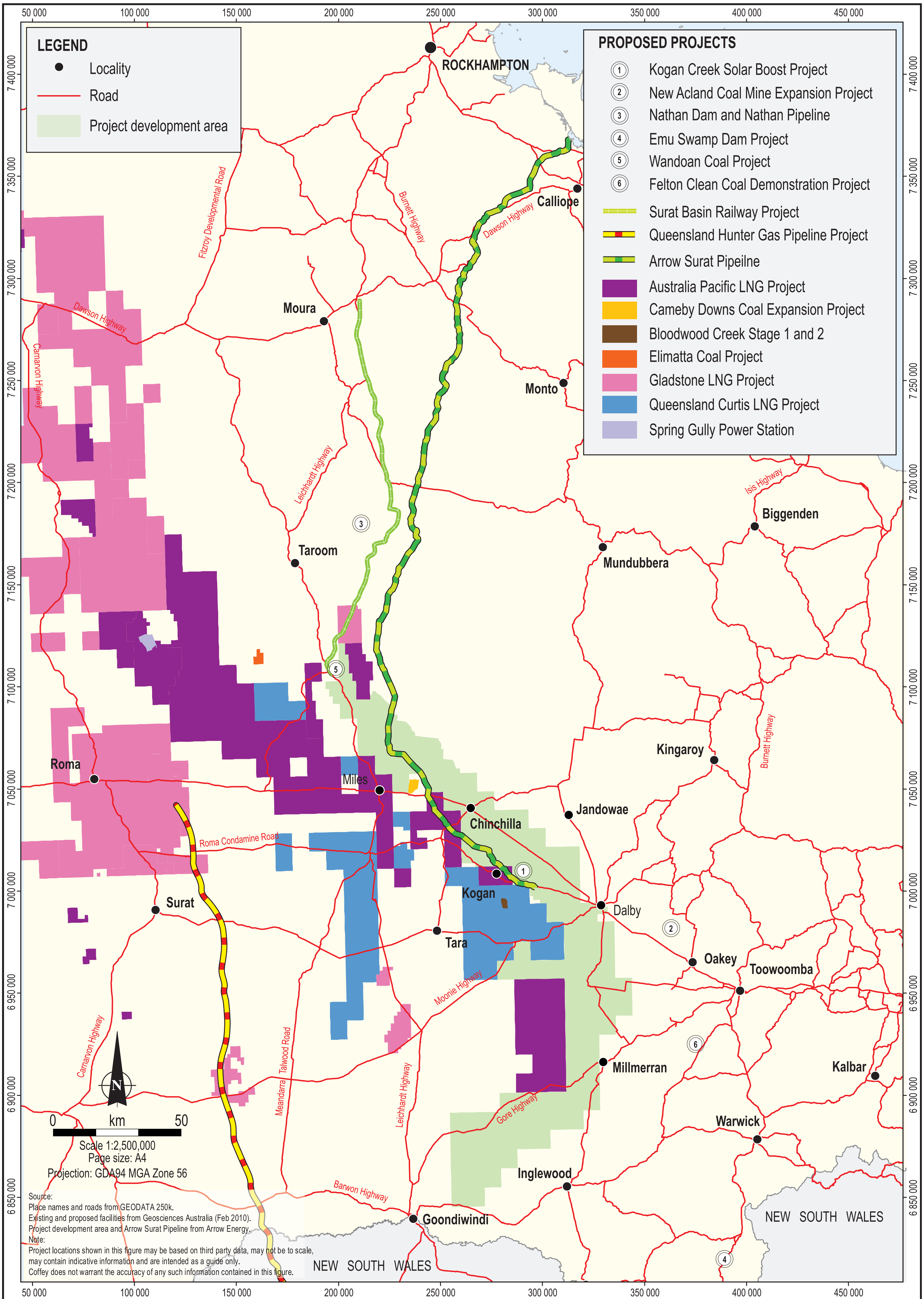
Major projects underway or under construction in the Darling Downs

Figure No: 4.6



Source:
Project development area, EIS areas and facilities from Arrow Energy.

coffey environments	Date: 08.08.2011 MXD: 7040AC_GW02_GIS006_v1_1 File Name: 7040_GW_02_F06.01_GIS_GL	Arrow Energy Surat Gas Project	arrow energy go further	Development regions and facility areas	Figure No: 6.1



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Date: 09.06.2011
MXD: 7040AC_04_GIS039_v1_1
File Name: 7040_04_F10.01_GIS_GL

Arrow Energy
Surat Gas Project

arrow energy go further

Approximate locations of projects to be considered in cumulative impact assessment

Figure No: 10.1

Appendix A
Arrow groundwater quality data

Arrow Energy Surat Gas Project
Groundwater Impact Assessment Report

GROUNDWATER QUALITY DATA FROM TIPTON AND DAANDINE WELLS

Sampled AUGUST 2009		
Tipton West Well Number	**Conductivity (mS/cm)**	**pH**
TT 16	7.93	8.15
TT 17	8.71	8.02
TT 18	8.64	8.05
TT 19	8.66	8.08
TT 30	6.55	8.03
TT 33	7.27	8.02
TT 34	7.42	7.93
TT 35	5.53	8.34
TT 36	5.19	8.49
TT 37	5.81	8.53
TT 37T	5.87	8.22
TT 38	5.84	8.61
TT 38T	5.54	8.21
TT 39	6.82	8.32
TT 40	7.25	8.14
TT 44T	6.03	8.12
TT 45T	5.98	8.45
TT 47	6.72	8.33
TT 48	6.94	8.15
TT 49	8.43	8.01
TT 51	5.52	8.43
TT 53	5.77	8.19
TT 54	5.86	8.42
TT 55	7.17	8.11
TT 56	7.40	7.96
TT 58	6.73	8.39
TT 59	5.87	8.36
TT 60T	6.03	7.31
TT 61	5.41	8.14
TT 61T	5.64	8.32
TT 62	4.13	8.48
TT 63	6.46	8.34
TT 64	6.97	8.25
TT 65	7.82	7.99
TT 66	6.52	8.4
TT 67	5.76	8.19
TT 68T	5.98	8.47
TT 69	5.52	8.34
TT 69T	5.44	8.4
TT 70	5.92	8.41
TT 71	5.96	8.34
TT 72	6.03	8.22
TT 73	6.96	8.15
TT 74	6.26	8.28
TT 75	5.72	8.59
TT 76	6.02	8.06
TT 77	6.20	8.33
TT 79	7.00	8.05
TT 82	6.00	8.03
TT 85	6.76	8.31
TT 88	6.54	8.76
TT 90	7.04	8.32
TT 91	7.30	8.12
TT 92	6.31	8.37
TT 93	6.99	8.37
TT 95	7.66	8.34
TT 95T	5.47	8.02
TT 96	6.95	8.35
TT 96T	5.59	8.24
TT 97	6.88	8.14
TT 98T	5.32	8.18
TT 99	7.64	8.28
TT 99T	5.79	8.44
TT 100	7.65	8.16
TT 100T	5.20	8.11
TT 102	6.74	7.64
TT 102T	5.78	7.94
TT 103	8.80	8.05
TT 104	8.28	8.13
TT 106	8.29	8.19
TT 107	9.03	8.03
TT 108	8.83	8.07
TT 109	7.77	7.95
TT 110	6.77	8.01
TT 113	6.48	8.05
TT 114	7.75	8.05
TT 115	8.64	8
TT 116	7.91	8.22
TT 117	7.27	7.9
TT 119	8.42	7.79
TT 120	5.60	8.29
TT 121	5.14	7.97
TT 122	5.27	8.35
TT 123	5.80	8.34
TT 124	5.38	8.16
TT 127	5.39	8.08
TT 128	5.49	8.22
TT 129	6.92	8.38
TT 130	7.46	8.38
TT 131	6.39	8.09
TT 132	6.02	8.18
TT 133	6.63	8.28
TT 134	6.31	8.38
TT 135	6.71	8.23

Sampled SEPTEMBER 2009		
Daandine Well Number	**Conductivity (mS/cm)**	**pH**
10	11.03	7.69
10T	5.44	8.28
15	9.42	8.01
15T	5.87	8.43
18	9.33	7.65
18T	5.73	8.11
19	8.54	8.21
19T	6.03	8.46
20	10.80	7.88
22T	3.48	8.31
26	7.37	8.33
26T	4.83	8.46
27	8.82	8.11
27T	5.80	8.48
28	8.42	8.16
28T	6.08	7.99
29	7.88	8.17
29T	6.35	8.35
30T	6.46	8.13
44	7.2	8.13
44T	3.87	8.27
45	7.9	8.17
45t	3.87	8.27
46	4.6	8.36

Appendix B
Numerical groundwater modelling

Arrow Energy Surat Gas Project
Groundwater Impact Assessment Report

Schlumberger
WATER SERVICES

ARROW ENERGY LIMITED

GROUNDWATER MODELLING OF THE SURAT BASIN

6-114/R4

ARROW ENERGY LIMITED
GROUNDWATER MODELLING OF THE SURAT BASIN

June 2011

6-114/R4

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REPORT REVIEW SHEET

GROUNDWATER MODELLING OF SURAT BASIN	
Report no:	6-114/R4
Client name:	Arrow Energy Limited
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Date	**Issue No**	**Revision**	**SWS Approval**
21st April 2011	1	Draft	Mark Anderson
3rd June 2011	2	Final	Mark Anderson

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1 INTRODUCTION

1.1 Background

Arrow Energy Limited (Arrow) is developing coal seam gas (CSG) operations in the Surat Basin, Queensland. Arrow commissioned Schlumberger Water Services (SWS) to undertake numerical simulation of the groundwater produced in association with CSG operations (associated water) and to predict how this may interact with the wider groundwater system. Predictions from the modelling are required as an input to the Environmental Impact Statement (EIS) currently being prepared and managed on behalf of Arrow by environmental consultants Coffey Environments Australia Pty Ltd (Coffey). This report provides a factual record of the modelling.

1.2 Purpose

The modelling is required to predict the changes in groundwater levels that will occur in response to the abstraction of associated water from the coal seams within the Walloon Subgroup. These changes may not be confined to the Walloon Subgroup however, and the model should be sufficiently robust to allow for an assessment of the potential effects on all sensitive groundwater resources in the area to be undertaken.

1.3 Key issues

The Arrow abstraction is projected to occur over a large area (~270 km by 30 km). In addition, the model is required to simulate abstraction from other CSG producers in the area. Therefore a regional scale model is required that incorporates a significant vertical hydrostratigraphic sequence. The issues that this size may have on the modelling include:

- A balance is required between model cell size (therefore number of model cells) and model run / processing time.
- A model of the required size and extent cannot produce very fine scale predictions without making impractical demands on processor power and simulation times.
- A model of the required size may not be able to implicitly simulate unconfined and confined conditions.
- Over the extent of the model the scale of impacts (drawdown) will vary laterally from many metres in the confined aquifers close to abstraction, to tens of centimetres away from abstraction and in the overlying unconfined units.
- The groundwater system within the model domain is affected by many processes (including rainfall recharge, groundwater abstraction and regional flow). None of these processes and stresses are known to a high degree of accuracy and are likely to have varied over time.

- Variability of geological and groundwater data coverage over the horizontal and vertical model extent.
- Sensitivity analyses with many hydraulic parameters complicates interpretation.
- Simplification of heterogeneous and anisotropic systems is required because of data limitations and the requirement to restrict model complexity.
- The modelling will produce a significant amount of output due to the number of layers and the time steps at which model predictions are required.

The model has been designed primarily to allow for the prediction of drawdown within this regional system. As illustrated above, to achieve this many complex issues need to be addressed. As a result, and as with all models, the model may not be the best tool to answer questions which diverge from this primary function.

1.4 Study approach

Development of the model involved several distinct stages, which are described briefly below and more comprehensively in the following sections. In accordance with the scope of work and SWS proposal these activities included:

1. Development of a geological model of the Surat Basin:

The regional scale geological model of the Surat Basin previously produced for Arrow by SWS (6-114/R1) was extended vertically to represent a more complete stratigraphic dataset and laterally to incorporate the expanded Arrow Development Area. This geological model provided the physical basis for the numerical model.

2. Development of model inputs:
   - Hydraulic parameters for each lithological unit
   - Groundwater level observations for use in calibrating the groundwater model
   - Model boundary conditions
   - Past, present and future groundwater abstractions

A literature review was undertaken with the aim of defining a set of realistic values and ranges of values of hydraulic parameters and model inputs.

The available groundwater level data was prepared for use in assigning the boundary conditions and calibrating the flow model. The raw (public and government) data set contains thousands of monitoring bores in the study area. The dataset was used to provide an idealised representation of groundwater conditions prior to commencement of CSG operations in the area. A set of time variant groundwater observations from Arrow monitoring bores provided the calibration dataset for the recent historical period.

3. Development and calibration of a groundwater flow model based on the above:

Steady state and time variant models were produced that reproduce the observed groundwater levels described above to a suitable level of accuracy. The results of the calibration are presented in terms of statistical significance and with groundwater hydrographs.

4. Undertaking a set of predictive scenarios and sensitivity analysis:

A predictive model was constructed that uses the calibrated parameters and starting conditions from the final time variant model. The model was used to simulate different abstraction scenarios, and to investigate the sensitivity of predictions to changes in key hydraulic parameters.

5. Reporting:

This report was prepared to document and interpret the modelling to a degree suitable for submission with the Arrow EIS.

1.5 Report structure

The report is divided into the following sections:

Section 2 – CONCEPTUAL MODEL, providing a summary of the regional geological and hydrogeological setting for the project. This section also details the development of the geological model of the Surat Basin.

Section 3 – NUMERICAL GROUNDWATER MODELLING, describes the construction and calibration of the numerical groundwater model.

Section 4 – PREDICTIVE MODELLING, describes the construction of the predictive model and the simulation results.

Section 5 – SENSITIVITY ANALYSIS, describes the results of a sensitivity analysis of several key model input parameters.

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2 CONCEPTUAL MODEL

2.1 Introduction, physical setting and data sources

2.1.1 Regional geology

Arrow's existing CSG facilities are located near the town of Dalby within the Surat Basin of southeast Queensland. Arrow's current leases and tenure extend for approximately 120 km along the strike of the coal measures of the Walloon Subgroup. However, the Surat Gas Project development area (on which the EIS is based) is larger than this, following a broad arc that extends approximately 60 km further north and 80 km further south, as illustrated by Figure 2.1.

The Surat Basin forms the eastern section of the Great Artesian Basin (GAB) which underlies much of Queensland, New South Wales, South Australia and the Northern Territory and comprises an extensive sequence (up to ~3,000 m) of sandstone, siltstone and mudstone units. Large impervious units separate the multilayered aquifers which are composed of continental quartzose sandstone deposits of Triassic, Jurassic and Cretaceous age. These aquifers are large, sheet like deposits that are generally continuous across the extent of the basin.

Exon (1976) states that the basin is bounded in the east by the Auburn Arch and the New England Fold Belt and between these two basement blocks it intertongues with the Clarence-Moreton Basin across the Kumbarilla Ridge. To the west the basin intertongues with the Eromanga Basin across the Nebine Ridge and its broad southerly extension, the Cunnamulla Shelf. In the south, it is bounded by the Central-West Folded Belt and in the north it has been eroded such that outcropping rocks are part of the older Bowen Basin.

2.1.2 Geographic setting and climate

The topography that is intersected by the Surat Gas Project development area is relatively uniform and ranges from about 320 to 370 mAHD. Higher elevation ridges are intersected to the north and south and these reach elevations of 390 mAHD and 570 mAHD respectively. The elevations decrease gradually to the south west (minimum 190 mAHD) and increase to the northwest and southeast. The Dawson River cuts a distinctive feature to the north (minimum elevation about 170 mAHD) and the Main Range Volcanics and granites that outcrop along the eastern margin of the basin form the highest features (over 1,000 mAHD).

The Surat Basin climate ranges from temperate to hot. Towards the west the rainfall decreases and temperatures increase. Average rainfall at the Miles Township weather station is 656 mm/year (1885 – 2005) and the average potential evaporation is 1,730 mm/year (1969 – 2005). The greatest rainfall occurs between November and February and the lowest between April and September.

All streams are ephemeral and characterised by high variations in duration and volume of flows which are linked to rainfall which is summer dominant in most years. However, remnants of intense cold fronts and low pressure systems sweeping in from the Southern Ocean can result in significant rainfalls during winter and spring (Kellett, 2003).

2.1.3 Well database

The geological modelling and groundwater level analysis has been based on data and information from the following sources:

- Arrow Energy Limited:
  - stratigraphic information (mainly Walloon Subgroup)
  - groundwater pressures at specific CSG monitoring wells.
- Queensland Petroleum Exploration Database (QPED), maintained by Queensland Department of Mines and Energy:
  - stratigraphic information for 'open file' petroleum exploration wells (both company and Geological Survey interpretations).
- Queensland Groundwater Database, maintained by Department of Environment and Resource Management (DERM):
  - stratigraphic information
  - basic completion information
  - standing water levels.
- The Water Entitlement and Registration Database (WERD):
  - management units (aquifers) for licensed groundwater bores
  - groundwater licence allocations.
- The Surat and Bowen Basins, Southeast Queensland (edited by Peter Green, 1997):
  - stratigraphic descriptions, environment and structure.
- Surat Basin, Australia - Subsurface stratigraphy, history and petroleum (Power and Devine, 1970):
  - structure surfaces, strata extent and subcrop/outcrop interpretations.
- A Summary of the Hydrogeology of the Southern Eromanga and Surat Basins of the Great Artesian Basin (Henning, 2005).
- A description of the geology of the Surat Basin (Exon, 1976).

These data were collated in an in-house relational database (MS Access) to facilitate the assessment of the various geological, completion and time-series information available. Links between geology/strata, completion type and monitoring/observation data are often absent for the DERM data (the Queensland Groundwater Database is not intended as an analytical tool, but exists as a collection of information tables).

2.2 Geological model

2.2.1 Introduction

The well database has been queried to produce control data summaries for the structure tops of each of the primary Surat Basin strata that are present in the area of interest. These data, where possible, have been incorporated with published accounts of strata extent and outcrop/subcrop (Power and Devine, 1970) which are based on earlier assessments of drill hole and wireline interpretations to infill data gaps left by the well database. All commonly recognised strata between the ground surface to the Triassic basement are included in the model. Both permeable and intervening low permeability siltstones and mudstones within the basin have been included as this sequence of aquifers and confining units will collectively govern the vertical progress of depressurisation from CSG production.

2.2.2 Stratigraphy

The strata are summarised below based on the background information presented by Green (1997), Goscombe and Coxhead (1995) and Exon (1976). The formations are presented from youngest (uppermost) to oldest.

Main Range Volcanics

The Tertiary Main Range Volcanics are located to the east of the basin and typically occur in a large area on the Great Dividing Range. The Main Range Volcanics unconformably overlie the Surat Basin and comprise extrusive and pyroclastic volcanic rocks of Late Oligocene to Early Miocene age. In general, the Main Range Volcanics are reported as sub-horizontal flows of dark grey, fine and coarse grained, olivine basalt.

Condamine Alluvium

The Condamine Alluvium consists of unconsolidated sands, gravel, silts and clay and is associated with the Condamine River and its tributaries. The alluvium uncomformably overlies the Surat Basin and is present within the existing Arrow CSG fields.

Lower Cretaceous Sequence

Lithological units of the Lower Cretaceous have been combined for the purposes of this project, but each is described below (listed from youngest to oldest):

- *Griman Creek Formation*: Consists predominantly of sandstone and siltstone. The maximum thickness is 400 m in the Surat Inlier, but is thinner towards the margins of the basin.
- *Surat Siltstone*: Consists of interbedded siltstone and mudstone. The thickness ranges from 100 to 130 m.
- *Coreena Member*: Consists of siltstone grading into labile and sublabile sandstone and then mudstone. The member is generally about 100 m thick, thinning to less than 50 m in the west and thickening to over 150 m in the east.
- *Doncaster Member*: Consists mainly of mudstone and siltstone. The member is thickest in the centre of the basin and thinnest to the north. The thickness varies little though and is generally between 100 to 150 m.
- *Bungil Formation*: Mainly fine grained lithic sandstone, mudstone and siltstone, with subordinate sublabile and quartzose sandstone that grades into coarse-grained sandstone. Its thickness ranges from less than 100 m in the north and west to over 300 m in the southeast.

Mooga Sandstone

Mainly quartzose to sublabile sandstone. Three subunits are generally present; a lower sandstone, a middle massive mudstone and an upper (thickest) sandstone. It is distinguished from the Orallo and Bungil Formations by the relative abundance of porous aquifers with bicarbonate water. The unit was deposited by streams draining the surrounding higher elevation areas. In the central area the Mooga Sandstone thickens to as much as 200 m, whereas towards the margins it is rarely over 100 m thick.

Orallo Formation

Thinly bedded siltstone and mudstone and thickly bedded friable fine to coarse-grained calcareous lithic sandstone. The formation becomes finer grained upward and rests conformably over the Gubberamunda Sandstone over most of the basin. The Orallo was formed by streams that generally flowed towards the centre of the Surat Basin. The formation reaches thicknesses in excess of 150 m in the north, central and southern parts of the basin and thins to zero to the west.

Gubberamunda Sandstone

Late Jurassic sandstones, quartzose and sub-labile with minor siltstone and mudstone interbeds. Deposition occurred in a range of environments from high energy braided streams to low energy meandering river systems. The sandstones are permeable and form a major fresh water aquifer, but become finer grained towards the west. The unit is generally less than 100 m thick, but it increases to greater than 200 m in the central sections of the basin.

Westbourne Formation

A well developed mudstone, sandstone, siltstone and coal unit (Norwood Mudstone Member) forms the lower part of the Westbourne Formation over much of the Surat Basin. The Formation consists of inter-bedded shales and siltstones and very fine-grained, quartzose sandstones. Deposition occurred in a lacustrine or lacustrine deltaic plain environment. Thickness ranges from less than 100 m in the west to over 250 m in the east. Maximum thicknesses occur along the eastern side of the Taroom Trough.

Springbok Sandstone

Late Jurassic, cross-bedded, labile sandstone with carbonaceous siltstone and mudstone and rare thin bentonite and coal lenses. The sandstone was deposited in a range of environments from low energy fluvial to deltaic and paludal. It is generally less than 50 m thick, although it may reach 150 m thick in the central parts of the basin. The lowest few metres consist of very coarse-grained sediments.

Kumbarilla Beds

This refers to the consolidated formations that outcrop in the vicinity of the Kumbarilla Ridge. These beds are equivalent to the sequence from the Springbok Sandstone to the Bungil Formation. The equivalent formations can be recognised in some of the outcrop areas, but deep weathering and extensive soil cover make it impractical to map the formations separately.

Walloon Subgroup

In the Surat basin the Walloon Coal Measures consist of coal interbedded with argillaceous sandstones, siltstones and mudstones along with minor calcareous sandstones, impure limestones and ironstone. The sandstone units are typically very fine to medium grained and indurated. In general, the coals are located in the upper half to three-quarters of the Measures, with mudstones, siltstones and lithic sandstones dominant in the lower part. Deposition occurred within environments ranging from swamps to high sinuosity fluviatile systems. Maximum thicknesses of around 500 m have been recorded in the vicinity of the Mimosa Syncline, west of Miles. The formation thins to the southwest and onlaps the Roma and Walgett Shelves.

Hutton (and Marburg) Sandstones

Middle Jurassic, well sorted, cross-bedded, quartzose to sub-labile fluvial sandstone with minor thin conglomerate beds and thin beds of siltstone and mudstone. Typically very porous and permeable and forms an important aquifer in the region, particularly near outcrop. It reaches a maximum thickness of 250 m (coincident with the Mimosa Syncline). Some wells exhibit a distinct division within the unit; a lower sub-labile sandstone and siltstone and an upper more quartzose sandstone and siltstone. The Hutton Sandstone is a stratigraphic equivalent of the Marburg Subgroup, which refers to the unit in the eastern portion of the Surat Basin and within the Clarence Moreton Basin.

Evergreen Formation

The Evergreen Formation is a mudstone/siltstone and sandstone sequence that incorporates the Boxvale Sandstone Member. The Boxvale Sandstone Member commonly comprises thinly to thickly bedded, fine to coarse grained, cross bedded, quartzose sandstones. The thickest sections, of the order of 300 m, are observed in the vicinity of Miles. Along the eastern and western margins of the basin the Evergreen Formation has a higher percentage of sandstone than in other areas.

Precipice (and Helidon) Sandstones

Early Jurassic, medium to coarse grained, porous, quartzose sandstone with well developed, medium scale, planar cross-bedding. In the western section of the basin, the Precipice Sandstone is an important oil reservoir, hosting the Roma and Moonie oil fields. The unit becomes finer grained in the upper part with minor siltstone bands. It has a maximum thickness of 150 m to the north of the Surat Basin but averages around 50 m everywhere else. The Precipice pinches out to the southwest of the Surat Basin. The Precipice Sandstone is often referred to as the Helidon Sandstone in the eastern portion of the Surat Basin and in the Clarence Moreton Basin. The Helidon Sandstone is a stratigraphic equivalent of the Precipice Sandstone and its type section is located within the Lockyer Valley.

Upper Triassic – undifferentiated

The upper Triassic strata consist mainly of mudstone and coal with interbedded sandstones. The sandstone components are medium to coarse-grained, fair to poorly sorted, quartzose and generally possess a white clay matrix. A well developed porosity is often observed. The strata represent initial infilling of the subsidence surface of the underlying Bowen Basin by fluvial and overbank deposits.

2.2.3 The geological model

The geological model has been constructed using the Petrel software (v2009.1). The model extends over the majority of the Surat Basin between 148 and 153°E and 25 and 29°S (Figure 2.2). The base of the model is set at -2,500 mAHD (metres Australian Height Datum) and the top is set to the natural surface. A 500 m x 500 m grid is used to define the structural surfaces. The model coordinate system is based on the Map Grid of Australia (MGA) UTM Zone 56 projection which has been extrapolated into adjacent UTM zones occupied by the model.

2.2.4 Structure tops and isopachs

An iterative process of gridding and interpolation (using a convergent interpolation algorithm) has been undertaken to generate representative structure tops for each of the preceding strata. The outlier discrimination process is part of this methodology and a number of well sites have been rejected from the final interpretation on this basis.

The final interpreted surfaces (which also incorporate the published interpretations of regional faults and extent of outcrop/subcrop) are presented for selected geological units in Figures 2.3 to 2.6, reduced to mAHD. Isopachs (layer thickness) for each of the primary strata (excluding the undifferentiated Triassic strata) were produced by differencing the respective interpolated structure tops, and are presented in Figures 2.7 to 2.17. Between 1,000 and 2,000 structure top data points were available for the Jurassic and Upper Cretaceous units. Just under 500 structure top data points were available to delineate the Condamine Alluvium, but due to the much smaller extent of this unit, this represents good coverage at the regional scale. The distribution of the points for each structure top is included in the formation thickness figures.

Three east-west cross sections and a single north-south section are provided through the geological model in Figures 2.18 and 2.21.

The overall basin sequence is asymmetric, being wedge-shaped in cross section, with the sedimentary section gradually thickening from the western margin to the central (north-south) axis of the basin and then thinning more sharply to the east. The Goondiwindi-Moonie-Burunga Fault system (Power and Devine, 1970) forms the eastern hinge line of the basin, separating the Mimosa Syncline and the Kumbarilla Ridge. The Arrow Development Areas are located in the vicinity of the Kumbarilla Ridge, a basement controlled structural high.

Power and Devine (1970) attribute the structural framework for the basin, immediately prior to deposition, to a series of major meridional normal faults that were probably established during the early Triassic. These faults (e.g. Goondiwindi-Moonie-Burunga) are downthrown westward and probably represent older fractures that were reactivated prior to Jurassic deposition. The Jurassic and Cretaceous strata are postulated to thicken or bend across these faults without being cut by them. Accordingly, the faults were incorporated in the data interpolation process to reflect this.

The Mooga and Gubberamunda Sandstones and the Orallo, Westbourne and Hutton Formations have been modelled with thicknesses predominantly in the region of 100 to 300 m. The Springbok and Precipice sandstones are thinner and rarely present thicknesses greater than 50 m. The only extensive area of Precipice Sandstone that does present a significant thickness has no stratigraphic control (data) associated with it. The Walloon Subgroup is the thickest formation and reaches more than 600 m in places. The thickness of the Lower Cretaceous sequence also increases to over 600 m, but this occurs down dip (to the south west) where all the constituent units are present.

The Springbok Sandstone outcrops within the Arrow Development Areas. The deepest part of the Springbok occurs to the southwest and central Surat Basin where the top of the unit is at about -1,200 mAHD (1,500 m below ground level (mbgl)).

The Walloon Subgroup outcrops to the east of the Arrow Development Areas, but beneath the Development Areas the upper units of the Walloons are found at about 50 mAHD (250 mbgl). The Precipice Sandstone outcrops to the far east of the Surat Basin and beneath the Arrow Development Areas reaches depths of about -500 mAHD (800 mbgl). In the centre of the basin the Precipice is found at about -2,000 mAHD (2,300 mbgl). The Hutton also outcrops to the east and below the Arrow Development Areas is found at about 0 mAHD (300 mbgl) and in the centre of the basin at about -1,600 mAHD (1,900 mbgl).

2.3 Groundwater levels

2.3.1 Introduction

The relatively long period of groundwater development within the Surat Basin (pre 1900 – 2010) has seen a large scale decline in groundwater pressure or head within the primary sandstone aquifers such that the majority of once artesian bores have ceased to flow, with sub-artesian heads prevailing (Henning, 2005). However, the recent government initiative of capping freely flowing artesian bores has led to some recovery of pressure within certain areas.

Groundwater level data was required to enable calibration of the groundwater model and therefore provide confidence in the predictions it provides.

Due to the difficulties in accurately defining historical abstraction in an area the size and complexity of the Surat Basin, and the nature of the modelling exercise (exploratory impact assessment), the steady state (pseudo equilibrium) model has been calibrated to the publically available data, but the historical model has been calibrated only to Arrow time variant data. Therefore the publically available time variant data is not discussed in the following Sections.

Furthermore, the analysis of observed groundwater level observations assumes that the recorded producing stratigraphy (entered in the DERM database) is accurate. This may not always be the case. An alternative dataset could be produced however that assigns (and checks) the producing stratigraphy(s) based on screen or open interval (or borehole base if no other information is available) and its position within the geological model. This latter method could also make use of a significant number of "orphaned" data that have some completion information, but have not been assigned a producing stratigraphy. However, both techniques will have associated uncertainties / errors. For practical reasons the former method was adopted.

An accurate picture of the current groundwater pressure regime within the basin is complicated by the asynchronous nature of the available monitoring (primarily sourced through the Queensland Groundwater Database) with very few contemporary measurements of head within the vicinity of Arrow's project development area.

The "well database" described in Section 2.1.3 has been queried to provide (for each geological unit) a representative regional groundwater level distribution and recent, time variant, groundwater levels in the vicinity of the Arrow project development area. Analysis of the latter indicated that on top of the background trends, significant perturbation (initiation of mining projects and coal seam gas projects in the area) of the groundwater levels measured in the Walloon Subgroup and adjacent strata is observed from about 1995 onwards. This date was therefore used to define a pre 1995 dataset (mostly single observations).

2.3.2 Pre 1995 water levels

The "well database" has been queried to provide a single observation (the last if there is more than one at any particular location) at each borehole that has been monitored from the first observation recorded in the database (12th December 1901) to 31st December 1994 (Table 2.1). The resultant dataset was contoured and anomalous data (obvious outliers) were removed. The distribution of data points and the contoured groundwater levels are presented in Figures 2.22 to 2.31 (contouring has been restricted to areas of data coverage only).

Initial attempts at contouring data from certain time periods (which were identified to have significant numbers of observations) did not provide sufficient regional coverage. Due to the large number of data points a thorough quality check of each observation was not possible, however, the data clearly identifies regional trends that can be used to aid system conceptualisation and can be used to assign model boundary conditions. The data was therefore considered to be of a quality suitable for calibration of the regional steady state numerical model.

Table 2.1 Summary of observed groundwater levels

Formation	Number	Observations First	Last	Head (mAHD) Minimum	Maximum
Condamine Alluvium	193	1932	1994	290	605
Mooga	255	1914	1994	226	401
Gubberamunda	348	1901	1994	195	719
Westbourne	11	1927	1988	354	532
Springbok	212	1930	1994	166	501
Walloon	100	1952	1994	99	643
Hutton / Marburg	475	1913	1994	24	883
Evergreen	11	1961	1994	213	640
Precipice / Helidon	83	1921	1994	57	717

The following provides a description of the pre-1995 groundwater levels by layer.

Condamine Alluvium

A significant proportion of the observations available are from the 1980 to 1995 time interval (Figure 2.22). They show a roughly southwest to northeast gradient, with lower groundwater levels (300 mAHD) to the southwest and higher levels to the northeast (450 mAHD). Several areas show reduced levels compared to the general trend, and these are most likely due to localised high rates of abstraction.

Kumbarilla Beds

By definition the Kumbarilla Beds are restricted to the area of Arrow development and immediately to the west of this. Most of the data comes from the period in time between 1960 and 1995 (Figure 2.23). The groundwater elevations are more uniform than observed in other units, but peak at about 400 mAHD around an area south of the Millmerran / Kogan Development Areas and reduce to around 250 mAHD to the south and 300 mAHD to the north.

Mooga Sandstone

The observation data display significant variation in this unit, but in general groundwater levels are recorded between 250 and 325 mAHD (Figure 2.24).

Gubberamunda Sandstone

Numerous groundwater observations are available for the Gubberamunda Sandstone (Figure 2.25) but most are located in the northwest of the area of interest (in the vicinity of Roma). There are a number of observations however that are available to the south and west which assist in the development of a regional understanding. The major regional flow direction appears to be from the north to south with potential localised flow system in the vicinity of the Wandoan Development Area where the indicated flow is from south to north. The groundwater levels in the majority of the basin are between 350 and 250 mAHD. Data from the whole observation period (1900 to 1995) has contributed to these contours.

Westbourne Formation

Limited observations are available in the Westbourne Formation (Figure 2.26). All are found to the northwest and all are higher than 350 mAHD. These levels are coincident with the higher levels seen in other units in the north.

Springbok Sandstone

Numerous observations are available but, all are within northern to central parts of the area of interest (Figure 2.27). The contoured groundwater levels show a general flow direction from northwest to southeast. As with the Gubberamunda Sandstone, a localised flow system is defined to the west of the Wandoan Development Area. In this region the primary groundwater flow direction is from the west and south to the north. The highest groundwater levels are found in the northwest (over 400 mAHD) and the lowest to the northeast (less than 250 mAHD) and south east (less than 275 mAHD).

Walloon Subgroup

The distribution of Walloon Subgroup observations covers much of the Arrow Development Areas and extends to outcrop in the east and northeast (Figure 2.28). The data is made up almost entirely from recent observations (1980 – 1995). The contours describe high groundwater levels at outcrop (over 500 mAHD) with groundwater flows to the west where levels reach about 250 mAHD.

Hutton and Marburg Sandstones

The only area not represented with groundwater level observations in these sandstones is found to the south and centre of the Surat Basin (Figure 2.29). Although their historical record shows more variation than the Walloons, regional trends and representative groundwater levels can still be extracted. The heads and flow directions are very similar to the Walloon Subgroup in the vicinity of the Arrow Development Areas and to the east. To the north and northwest the trends are similar to the shallower Gubberamunda and Springbok Sandstones, with two main flow components; one from north to south and another from northwest to northeast.

Evergreen Formation

These data are limited in number and location to the north of the area of interest (Figure 2.30). They do, however, show the same north to south and northwest to northeast flow directions as seen in other units.

Precipice and Helidon Sandstones

The Precipice Sandstone (Figure 2.31) displays very high groundwater levels to the north associated with outcrop at Carnarvon Gorge (above 550 mAHD) and a steep gradient from here to the northeast into the Dawson River catchment (below 250 mAHD). In the southeast there is a substantial gradient to the east (Lockyer Valley) and northwest (Dawson River). The dataset in the area of Arrow developments is limited, and the data that is present is recent (1980 to 1995). There are no data within the central and southern Surat Basin.

2.3.3 1995 – 2009 water levels (Arrow monitoring data)

Arrow provided time variant groundwater pressure data from 13 boreholes within their current area of operations (Figure 2.32). The monitoring captures the period between 2005 and 2010 and is focussed on the Juandah and Taroom Coal Measures. As there may be some uncertainty concerning the elevation of the transducer in some of the holes, the measurements have not been converted to a groundwater head, but instead have been used to calculate drawdown from the initial (stable) measurement.

Table 2.2 presents the characteristics of the holes and observations. The range of observed drawdown is 1 to 26 metres. This range reflects both the distance of the monitoring location from active CSG wellfields and the period of monitoring. For example, Daandine 2 returns the greatest drawdown, and it is likely that this is due both to its position (within the Daandine wellfield) and the fact that it was monitored during the initial stages of wellfield operation (2005 to 2007).

The stratigraphic units within which each bore is open are displayed in Table 2.2. This shows that only one monitoring bore (River Road 1) is open only to the Taroom Coal Measures. Its location, about 20 km south of the nearest Arrow wellfield, means that it is not optimally placed to provide information on the response of the Taroom Coal Measures to historical abstraction. A number of the other holes are open only to the Juandah Coal Measures and these are located in and around active wellfields. The remaining holes are open to both the Juandah and Taroom Coal Measures (and the Tangalooma Sandstone between them). If the hydraulic parameters and groundwater pressures in the two units were significantly different, the observations in this latter group would be biased to some degree to the conditions in the most transmissive unit. However, the data from these two groups of boreholes show no significant differences. This suggests that either the Juandah groundwater system biases the readings (i.e. it is the most transmissive of the two coal measures) or that there is no significant difference between the transmissivity and pressures of the two coal measures. It is unlikely that the Taroom Coal Measures present a significantly higher transmissivity or pressure system than the Juandah Coal Measures, so the latter scenario may be most likely in this case.

The Arrow dataset provides the most useful calibration opportunity, because, unlike all other observations, the stratigraphic unit represented and the hydrogeological stresses that they are responding to are characterised with relatively high certainty.

Table 2.2 Particulars of Arrow monitoring bores

Well Name	Open interval		First reading	Last reading	Drawdown (m)
	Juandah	Taroom			
Kogan North 56	■	■	Feb-09	Jan-10	1.1
Stratheden 2	■		Oct-08	Jan-10	5.1
Stratheden 3	■		Oct-08	Jan-10	2.0
Stratheden 4	■	■	Oct-08	Dec-10	3.9
Longswamp 1	■		Jun-08	Jan-10	5.4
Plainview 1	■		Oct-08	Jan-10	1.5
River Road 1		■	May-08	Jan-10	4.2
River Road 4	■		Nov-08	Apr-09	9.0
Meenawarra 5	■	■	Oct-08	Jan-10	2.4
Meenawarra 6	■	■	Nov-08	Jan-10	2.1
Daandine 2	■	■	Aug-05	Oct-07	25.6
Daandine 24	■	■	Oct-08	Dec-10	2.4
Daandine 25	■		Nov-08	Jan-10	2.7

Note. Shading indicates well is open to the formation.

2.4 Representation of the Walloon Subgroup

To allow groundwater stresses to be simulated more accurately and predictions to be refined, the Walloon Subgroup (as defined in the geological model) was sub-divided into five layers. The division is based on the interpretation of Walloon Subgroup lithology described in the Arrow Field Development Plan (Arrow, 2009), and summarised in Table 2.3. The Walloon sub-divisions adopted are as follows:

- Upper mudstone / siltstone. A thin layer of conceptually low permeability material (which is absent in some areas) separating the Juandah Coal Measures from the Springbok Sandstone above. This unit can be used to assess the sensitivity of predictions to the presence or absence of this unit.

- Juandah Coal Measures. The upper sequence of coal measures, consisting of interbedded coals with sandstones, siltstones and mudstones.
- Tangalooma Sandstone. Distinct fine grained sandstone separating the two coal measure units.
- Taroom Coal Measures. The lower sequence of coal measures.
- Eurombah and Durabilla Formations. Mudstones, siltstones and sandstones.

It is likely that the representative thicknesses of the constituent units will vary considerably over the model domain (Surat Basin), however, as there is very little public data of this detail, the thickness percentages described in Table 2.3 are applied throughout the model. Figure 2.33 displays the resultant formation thicknesses.

As the primary focus of the study is the prediction of the effects of abstraction of water associated with the Arrow CSG operations, this interpretation is considered appropriate.

Table 2.3 Modelled sub-division and thickness of Walloon Subgroup

Formation	Idealised thickness (m) (Arrow, 2009)	Percentage of total Walloon thickness
Juandah above Kogan Coal Measure	10	2
Juandah Coal Measures	240	56
Tangalooma Sandstone	50	12
Taroom Coal Measures	75	18
Durabilla / Eurombah Formations	50	12
Total Walloon Subgroup	425	100

2.5 Hydraulic parameters

2.5.1 Introduction

The observation dataset described above has provided only limited data for calibration of hydrogeological parameters that span many distinct layers, an area of about 120,000 km^2, and a vertical sequence of some 2.5 km. Due to limitations on the number and quality of available groundwater observations for most of the stratigraphic units, this data cannot support a thorough and definitive calibration. Therefore, emphasis is placed on the derivation of a set of initial (basecase) parameters to use in the modelling.

A literature review, focussed on the hydraulic characteristics of the geological formations of the Surat and Clarence Moreton Basins, has been undertaken. Based on a combination of this information and SWS experience in the study area, a set of basecase parameter values have been derived.

2.5.2 Literature review

Overview

The literature review was focussed on the geological units present in the eastern Surat Basin, and the north west of the Clarence Moreton Basin (Table 2.4)

Table 2.4 Geological units relevant to the numerical model

Surat Basin	Clarence Moreton Basin
Condamine Alluvium	
Gubberamunda Sandstone	
Kumbarilla Beds	
Westbourne Formation	Grafton Formation
Springbok Sandstone	Kangaroo Creek Sandstone
Walloon Subgroup / Injune Creek Group (Juandah Coal Measures, Tangalooma Sandstone, Taroom Coal Measures and Durabilla / Eurombah Formations)	
Hutton Sandstone	Marburg Sandstone
Evergreen Formation	Gatton Sandstone
Precipice Sandstone	Helidon Sandstone

Habermehl

Habermehl has been a prolific author of the Great Artesian Basin (GAB) since the early 1980s and much of his work is referenced in reports relating to the GAB and Surat Basin. Habermehl (1980) documented the hydraulic conductivity (K) of the Lower Cretaceous-Jurassic aquifers (Hooray Sandstone aquifers and equivalents) at 0.1 – 10 m/d. This parameter set has been referenced extensively in other documents, and recently by Henning (2005), who also refers to the following:

- average vertical hydraulic conductivity (Kv) of the confining units of 1 x 10^{-1} to 10^{-4} m/d;
- measured transmissivity (T) values of 1 – 2000 m^2/d;
- storage coefficients of between 1 x 10^{-4} – 10^{-5};
- intrinsic permeability from several tens to several thousand millidarcies (equivalent to a K of approximately 0.01 - 3 m/d);
- porosity between 10 – 30 %.

Habermehl (1980) also discussed hydraulic gradients within the GAB (important when considering and implementing boundary conditions) and summarised that within the east and upper sequences, gradients are 1:2000 and 1:1800 respectively.

Department of Natural Resources, Mines and Energy

Environmental Hydrology Associates (EHA, 2006) summarised the available groundwater resources of southeast Queensland and considered the Helidon Sandstone as a potential water supply target for the State Government and the South East Queensland Regional Organisation of Councils. The report summarised and cited from Zahawi (1975) that the Helidon Sandstone (a lateral equivalent of the Precipice Sandstone and Lower Evergreen Formation in the Clarence Moreton Basin) has T values in the range of 9 – 50 m^2/d, storage coefficients of 1.0 x 10^{-5} to 3.8 x 10^{-4}, and average effective porosity between 6 to 19%. Significant yields are available in the Helidon Sandstone with a number of agricultural companies drilling and completing production bores into the aquifer. Examples of high yielding bores provided by EHA (2006), are the Beef City

Feedlot Bore at Aubigny with a 33 L/s supply from 726 to 836 mbgl, and the Hampton Irrigators Bore with a 460 m deep bore at Cabarlah yielding a 32 L/s supply.

In 2004, the Queensland Government Department of Natural Resources, Mines and Energy commissioned Parsons Brinckerhoff (PB) to undertake a Coal Seam Gas Water Management Study. Information provided in the report by industry representatives was that "*regionally, the coal seams are considered an aquitard (non water conducting) more than an aquifer unit*." Hydraulic conductivity values for the coals of 0.12 to 0.01 m/d were provided by PB (2004).

The Department of Natural Resources and Mines produced a series of maps showing groundwater bore exclusion zones for both the Hutton and Precipice Sandstone aquifers. It is understood that the zones marked on these maps were generated using a simple analytical equation using a T value of 50 – 100 m^2/d and a storage coefficient of 5×10^{-4}.

It is understood that the Millmerran Power Station Bores were drilled in the late 1990s into the Marburg Sandstone or Hutton Sandstone. Pumping tests were carried out on these bores and the aquifer is believed to have a T of 30 – 50 m^2/day and S of $1 - 5 \times 10^{-4}$. The Millmerran Town Water Supply Bores are also drilled into the Hutton Sandstone and have similar T values (40 – 75 m^2/d).

Kogan Creek Power Station

The Lagoon Gully No. 1 bore was drilled as a water supply facility for the Kogan Creek Power Station in the late 1990s. This was completed in the Precipice Sandstone and is understood to have a K of 3 - 4 m/d and storage coefficient of 3×10^{-4}. The Lagoon Gully No. 2 bore was also drilled for water supply, however, it was completed in the Hutton Sandstone. The Hutton Sandstone at this site is understood to have a K of 0.05 – 0.09 m/d. No storage coefficient value is available for the Hutton Sandstone as an observation bore was not drilled.

Tong Park

The deep Tong Park bore, located south of Warra, is completed in the Hutton Sandstone. The bore was test pumped and is understood to have provided a T of 15 m^2/d during later analysis.

Arrow

The Arrow Field Development Plan (Arrow, 2009) details the results of testing the Walloon Subgroup members. This includes production testing of the Juandah and Taroom coal seams, and drill stem testing (DST) and core testing of a wider range of formations. The data are summarised in Table 2.5. Distinct permeability versus depth relationships were identified in both the Juandah and Taroom coal seams.

Table 2.5 Summary of Arrow testing of the Walloon Subgroup

Test type	Unit	Permeability (mD)	Equivalent K (m/d)
Production	Juandah	5 - 500	0.005 – 0.5
	Taroom	20 - 100	0.02 – 0.1
DST	Juandah and Taroom	0.2 – 1100	0.0002 – 1.1
Core (from "clean" sandstone portion)	Juandah	8.8 (av. from 17 samples)	0.009
	Taroom	2.0 (av. from 14 samples)	0.002
	Eurombah	26.4 (av. from 3 samples)	0.026
	Hutton	303.9 (av. from 3 samples)	0.304

Note. mD = millidarcies and m/d = metres/day

New Acland Coal EIS

The groundwater section of the New Acland Coal EIS document was compiled by SKM (2009) for New Hope Coal Australia and contained a number of relevant hydraulic testing results for the Surat Basin stratigraphy. These results are summarised as follows:

- Walloon Coal Measures:
  - Transmissivity – 6.5 to 8.2 m^2/d (deep), 31 to 47 m^2/d (shallow);
  - Estimated K of 0.1 m/d;
  - Storage coefficient – lower S for the deep (6 x 10^{-5}) as is fully confined, higher S (0.006) for shallow as is semi-confined (leaky); and,
  - "*Although short-term pumping tests indicate that the coal seams behave as discrete aquifers separated by carbonaceous mudstones and siltstones, it is likely that over the long-term the seams will behave as one aquifer system when stressed by dewatering during mining operations. Pumping tests conducted as part of the Project baseline assessment suggest that a leaky aquifer system exists. Vertical movement of groundwater occurs where the confining layer of carbonaceous mudstone and siltstone is thin or absent within the coal measures*".
- Tertiary Basalt:
  - Transmissivity – 150 m^2/d, thickness 1 – 90 m, K of 1.6 m/d;
  - Storage coefficient – 0.05 – 0.001, unconfined to semi-confined; and,
  - Recharge of 80 mm/yr.
- Marburg Sandstone (lateral equivalent of the Hutton Sandstone in the Clarence Moreton Basin):
  - Transmissivity – 14 m^2/d;
  - Hydraulic conductivity of 0.028 m/d; and,

    - Storage coefficient - 0.003, confined.

- Helidon Sandstone (lateral equivalent of the Precipice Sandstone in the Clarence Moreton Basin):

    - Transmissivity – 45 – 200 m^2/d; and,

    - Hydraulic conductivity of 0.26 – 3.9 m/d.

Wandoan Coal Project EIS

Another recent document relevant to the Surat Basin is the Wandoan Coal Project EIS prepared by PB (2008). PB carried out a pumping test within the production bore completed in the Upper Macalister, Lower Macalister and Wambo coal seams of the Walloon Coal Measures. The testing resulted in T values of 7 m^2/d for the monitoring bores (K of 0.17 m/d) and a storage coefficient value of 3.23 x 10^{-3}. Whilst PB (2008) state that "*water levels within the shallow monitoring bore monitoring the Kogan coal seams, did not respond for the duration of the test. This suggests a limited vertical hydraulic connection between the shallow and deep coal seams at the borehole location*." They also discuss that the water level in the shallow monitoring bore (completed in the shallower Kogan coal seam) decreased by 0.03 m at the end of the pumping test (1,440 minutes), suggesting some limited vertical connection. It is noted that there is 12 m of interburden between the shallow and deep aquifer completions at this site.

Santos GLNG Project EIS

URS (2009) recently completed the shallow groundwater component for the Santos GLNG Project EIS. Whilst no direct testing of the GAB was carried out as part of this investigation, URS (2009) have referred to previous studies relating to the Hutton Sandstone. They summarise the following parameters:

- thickness of 120 – 180 m;

- transmissivity of 100 – 150 m^2/d;

- storage of 5 x 10^{-4}; and,

- porosity of 20 – 25%.

MatrixPlus (2009) carried out the deep groundwater component for the Santos GLNG Project EIS. Similar to URS (2009), no direct testing had been carried out and certain parameters were defined from the monitoring of the CSG operations. They summarise the following parameters:

- storage coefficient of 1 x 10^{-4} was assumed for all coal measures, this was later refined to 1.3 x 10^{-4} based on model calibration;

- average transmissivity for the coal measures of 5 m^2/d; and,

- Precipice Sandstone T of 50 m^2/d and S of 1 x 10^{-4}.

MatrixPlus (2009) document available permeability and transmissivity data for the coal seams (Upper Juandah, Lower Juandah, Upper Taroom and Lower Taroom) in the Roma area (Table 2.6) and available aquifer parameters for surrounding geologic formations.

Table 2.6 Formation parameters – Comet Ridge and Roma Fields (after MatrixPlus, 2009)

Formation	Average Thickness (m)	T (m^2/d)	K (m/d)	Parameter Source	No. of Samples analysed	Comments
Gubberamunda Sandstone	84 (20 – 260)	11	0.13	Flow Tests	1	Aquifer. Mostly highly developed aquifer in Surat Basin. Average K probably higher
Injune Ck Formation (equiv to the Walloon Coal Measures)	396 (< 1000)	32	0.08	Flow Tests		Confining beds, some permeable beds
Eurombah	50 (20 – 80)	6.8	0.14	Flow Tests	2	Confining beds, some aquifer layers. Average K probably lower
Hutton Sandstone	150 (100 – 350)	21	0.14	Flow Tests	20	Aquifer
Evergreen Formation	105 (10 – 260)		0.008	AHA Report	Not known	Confining layer

CSIRO

Barnett and Muller (2008) developed a groundwater model for the upper Condamine Valley. In this report they reference Huxley (1982) and Hansen (1999), and both of these authors had documented aquifer parameters for the alluvial sediments. The alluvium presents transmissivity values of up to 400 m^2/d (K of > 30 m/d) in areas to the east of Cecil Plains and near Brookstead, along the North Branch of the Condamine River (Huxley, 1982). In other areas, the K of the alluvial sediments is considerably less and the heterogeneous nature of the system provides a spatial and vertical variability. Barnett and Muller (2008) also reference specific yield values from Huxley (1982) with an average estimate of 6.5% within the main Condamine River area and greater than 10% to the south between Brookstead and Ellangowan.

The following hydraulic parameters were adopted in the calibrated numerical groundwater model produced by Barnett and Muller (2008); horizontal hydraulic conductivity (Kh) values between 0.01 and 12 m/d, Kv : Kh ratio in the order of 1:10 and 1:1000 (the majority between 1:10 and 1:20), specific storage of 5 x 10^{-6} /m and specific yield between 4% and 6%.

The report also refers to an estimate of K (0.01 to 0.1 m/day) of the weathered bedrock beneath the alluvial plains by Huxley (1982). This weathered bedrock beneath the alluvium is likely to represent different formations at different locations, and may include part of the Kumbarilla Beds, Walloon Coal Measures and the Marburg or Hutton Sandstone.

2.5.3 Basecase model parameters

Table 2.7 contains a summary of the parameters adopted as a basecase to the pre-calibration groundwater model. A documented parameter range is also shown, as assessed from the literature.

Measured Kv data are scarce. The values presented in Table 2.7 have been defined based on the general description of units provided by Green (1997) and Goscombe and Coxhead (1995). Three categories were defined:

- Kv : Kh = 1 : 10. Formations comprising predominantly sandstone
- Kv : Kh = 1 : 50. Mixed sequences of sandstones and finer sediments
- Kv : Kh = 1 : 100. Formations comprising predominantly mudstones / siltstones.

All adopted model parameters are within the reported ranges where available, with the exception of the K value for the Evergreen Formation. It is considered that the single measured value available for this unit may represent an upper bound and therefore a lower model value would be more appropriate.

Table 2.7 Summary of pre-calibration basecase model parameters

Formation	**Kh (m/d) (Documented Range)**	**Kv : Kh ratio**	**Specific storage (m^{-1}) (Documented Range)**
Condamine River Alluvium	5 (0.01 - >30)	1 : 10	5% (10% – 4%)*
Gubberamunda Sandstone	0.5 (0.1 – 5)	1 : 10	5×10^{-6} (1×10^{-6} – 1×10^{-7})
Kumbarilla Beds	0.1	1 : 50	5×10^{-6}
Westbourne Formation	0.001	1 : 100	5×10^{-6}
Springbok Sandstone	0.5	1 : 10	5×10^{-6}
Juandah Coal Measures	0.1 (0.0001 – 1)	1 : 100	5×10^{-6} (6×10^{-5} – 6×10^{-7})
Tangalooma Sandstone	0.1	1 : 50	5×10^{-6}
Taroom Coal Measures	0.1 (0.0001 – 1)	1 : 100	5×10^{-6}
Durabilla / Eurombah Formation	0.05 (0.03 – 0.14)	1 : 50	5×10^{-6}
Hutton Sandstone	0.1 (0.05 – 1.25)	1 : 50	5×10^{-6} (3×10^{-5} – 1×10^{-6})
Evergreen Formation	0.001 (0.008)	1 : 100	5×10^{-6}
Precipice Sandstone	1 (0.1 – 4)	1 : 10	5×10^{-6} (5×10^{-6} – 1×10^{-7})
Triassic (upper 200 m)	0.0001	1 : 50	5×10^{-6}

* specific yield

2.6 Groundwater abstraction

2.6.1 Introduction

An understanding of historical and projected future abstractions within the study area is required to assist calibration of the model and to then undertake the predictive simulations. This data has been provided to SWS by Coffey Environments and is described below. Both historical and future data are limited to major (CSG) abstractions only, and even though the number of small abstractions may be significant over the study area, and contribute to local and regional groundwater trends, accurate and complete records are not available to describe the location and abstraction rates for those wells. Inaccuracies in the abstraction data would therefore introduce the potential for inappropriate calibration and model parameter values. Furthermore, the goal of the modelling is to provide estimates of the groundwater impacts in response to CSG activities in excess of the background levels. In order to do this, an assessment is required independent of the non-CSG abstractions.

2.6.2 Historical abstraction

Although abstraction in the period prior to 1995 has been significant, due to the reasons described above it is not possible to incorporate this with any accuracy into the model. For the purposes of this study only historical CSG abstractions have been considered. The data pertaining to Arrows operations are based on measured values. The data pertaining to the other CSG producers is constructed from a combination of reported and projected abstractions. The abstractions are:

- Arrow operations. Water production from Arrow's Dalby Development Area commenced in 2005 and has increased annually since then. The operation is split between 4 main wellfields (from north to south; Kogan North, Daandine, Stratheden and Tipton). Kogan North and Daandine were the first wellfields online (from the middle of 2005). The greatest abstraction occurred at Tipton West (7.7 ML/d in the second half of 2009). The maximum combined abstraction from the 4 wellfields was 12.0 ML/d, also in the second half of 2009. This information was provided as monthly averages for each wellfield. The data was further simplified for the purposes of modelling to 6 monthly averages.

- QGC operations. The QGC operation is split between Northern, Central and Southern Development Areas. Data provided by Coffey shows that water has been produced by QGC since 2007 and the majority has come from the Central Development Area. Combined abstraction in 2010 was about 48 ML/d.

- Santos operations. Data provided by Coffey for the Roma Field indicates that water was first produced by Santos in 2008. By 2009 abstraction was 4.6 ML/d and by 2010 it was 7.1 ML/d. Other Santos resources are located in the Bowen Basin and are therefore not relevant to this study.

- Origin operations. Data was not available for the actual historical abstractions at existing Origin operations; however projected values for 2010 were available. These were split into 3 areas termed Groups 1, 2 and 3. In 2010 only Group 2 was active, producing a projected 4.0 ML/d.

The historical rates of CSG associated water production data are presented in Table 2.8.

Table 2.8 Historical abstraction associated with CSG activities in the Surat Basin (ML/d)

CSG Field	2005	2006	2007	2008	2009	2010
Kogan North	3.0	4.1	3.0	2.8	2.5	2.1
Daandine	0.1	0.4	2.0	2.7	2.8	2.6
Stratheden	0.0	0.0	0.0	0.0	0.4	0.0
Tipton	0.0	1.9	4.7	6.5	7.4	4.8
Arrow Total	*1.8*	*6.7*	*9.7*	*12.0*	*12.9*	*9.5*
NDA	0.0	0.0	0.0	0.0	2.0	6.0
CDA	0.0	0.0	18.0	22.0	25.0	32.0
SDA	0.0	0.0	0.0	0.0	2.0	10.0
QGC Total	*0.0*	*0.0*	*18.0*	*22.0*	*29.0*	*48.0*
Origin			*Unknown*			*4.0*
Santos (Roma)	*0.0*	*0.0*	*0.0*	*1.5*	*4.6*	*7.1*
CSG Total	3.6	13.4	55.4	69.5	88.4	68.6

2.6.3 Projected data

Projected groundwater abstraction rates from Arrow and other CSG producers in the Surat Basin have been provided by Coffey and Arrow. The data is presented in Figures 2.34 to 2.36, and the locations of the projects are provided in Figure 2.37.

The projected groundwater abstraction from Arrow operations (termed the "reference case") includes associated water derived from LNG export and domestic supply projects. The abstractions were provided to the following level of detail:

- LNG Export. This has been provided based on EIS area (Wandoan, Chinchilla, Dalby, Millmerran / Kogan and Goondiwindi) and further divided by gas compression facility (either CGPF (Central Gas Processing Facility), IPF (Integrated Production Facility) or FCF (Field Compression Facility)). The total projected groundwater abstraction from these facilities is 633,814 ML.
- Domestic gas supply. This data is based on a 80TJ/d gas supply and has been split between Kogan (PL 194), Daandine (PL 230) and Tipton West (PL 198) fields. The total projected groundwater abstraction associated with domestic supply is 61,190 ML.

The individual Arrow facilities are projected to produce a peak associated water production of between 40 and 60 ML/d. The Wandoan facilities are the first online (2014) and the Goondiwindi facilities are the last (2030). The projected peak in total Arrow abstraction is in 2031 (131 ML/d) and this is associated with the peaks in Goondiwindi and Millmerran / Kogan facilities. Projected abstraction is also significant in the early time series, and is above 80 ML/d from 2017 to 2026. From the peak in 2030 projected abstraction from facilities reduces rapidly and ceases after 2038.

Abstraction associated with Arrow domestic supply is small compared to that associated with the LNG facilities. Projected abstraction peaks at 11.0 ML/d in 2013 and gradually declines to 2.4 ML/d in 2041.

The projected abstraction from QGC operations is available for each of the three development areas (Figure 2.35). The peak in combined abstraction occurs in 2014 at 189 ML/d, although abstraction greater than 160 ML/d is predicted from 2013 until 2023. The Southern Development Area provides the majority of this water. Abstraction continues until 2051.

Abstraction from Origin operations is divided between 10 development areas. The combined abstraction is predicted to peak at about 170 ML/d in 2026. For the purposes of this study the development areas have been merged into three groups; Group 1 (Combabula / Ramyard, Woleebee and Carinya areas), Group 2 (Dalwogan, Condabri, Talinga / Orana and Kainama areas) and Group 3 (Gilbert Gully area).

Of the various Santos CSG operations, only the Roma Field taps the coal seams within the Surat Basin. The field is predicted to produce groundwater until 2034 and reaches a maximum rate of 14 ML/d in 2013.

It is understood that that there are additional projects planned for development in the vicinity of the Surat Gas Project that will involve the abstraction of groundwater. These projects are not quantitatively included in the predictive groundwater model as they are likely to abstract negligible volumes of groundwater in comparison to the major CSG proponents.

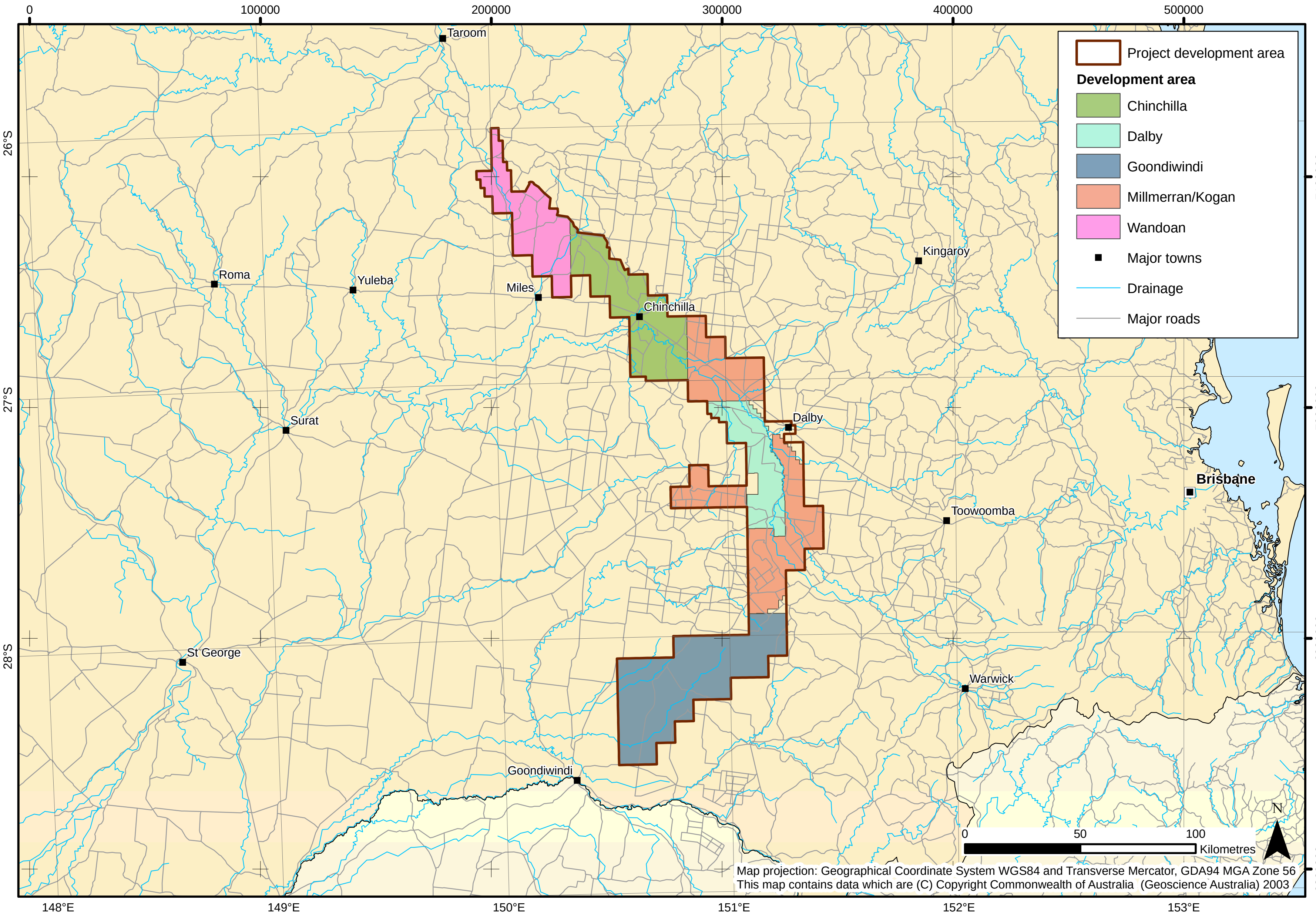

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Figure 2.1 Arrow Development Areas

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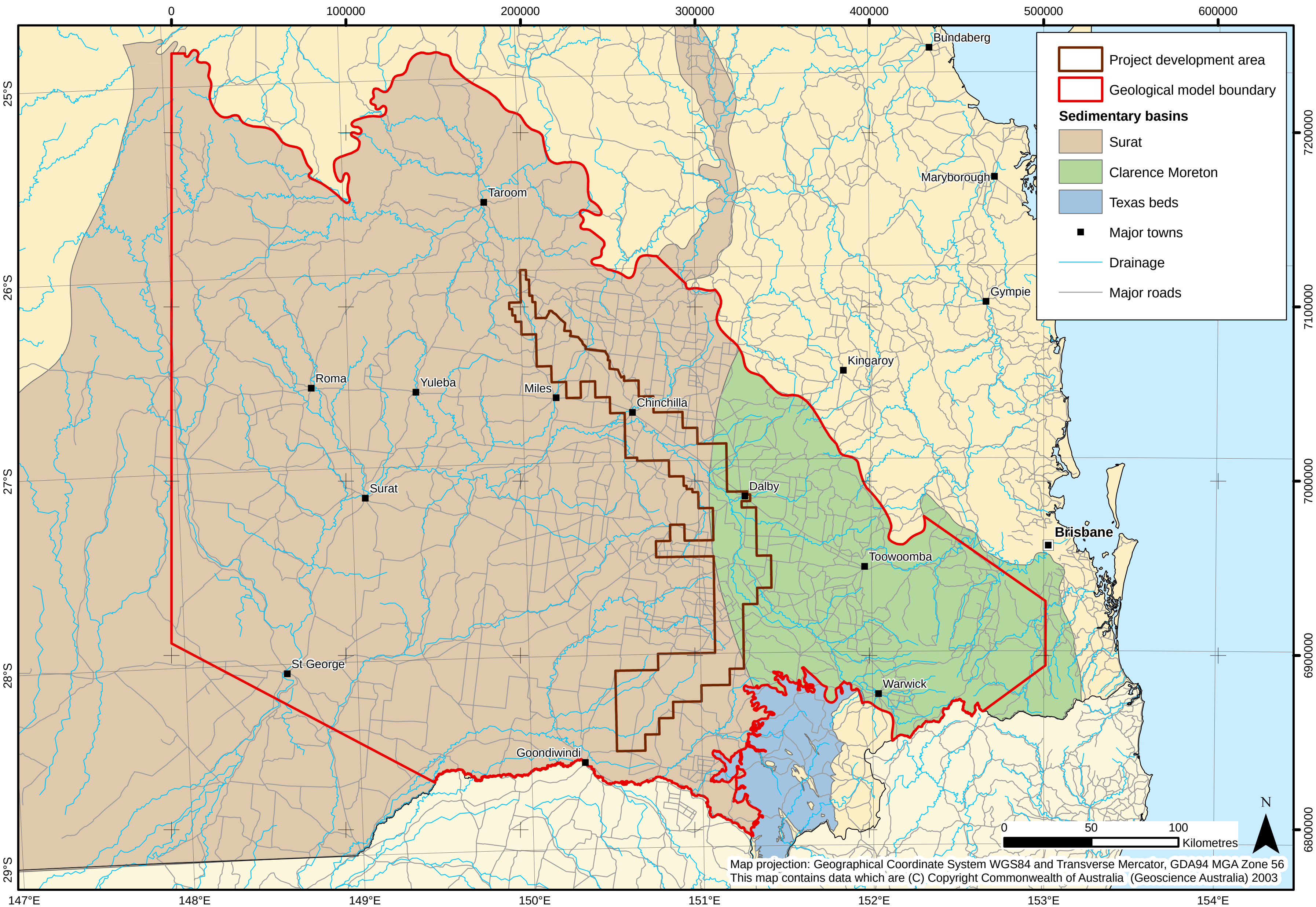

Figure 2.2 Petrel model extent

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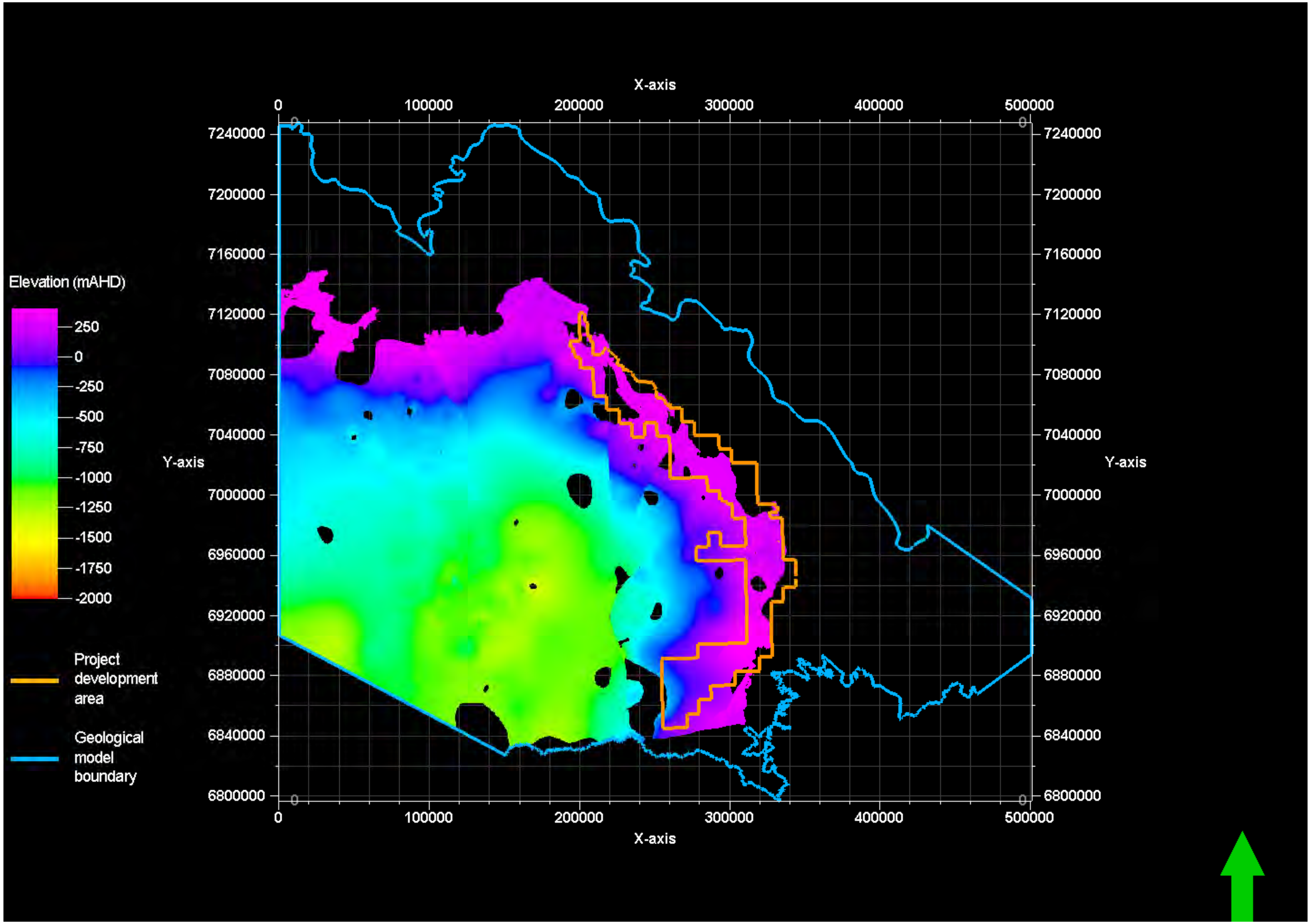

Figure 2.3 Elevation of top of Springbok Sandstone

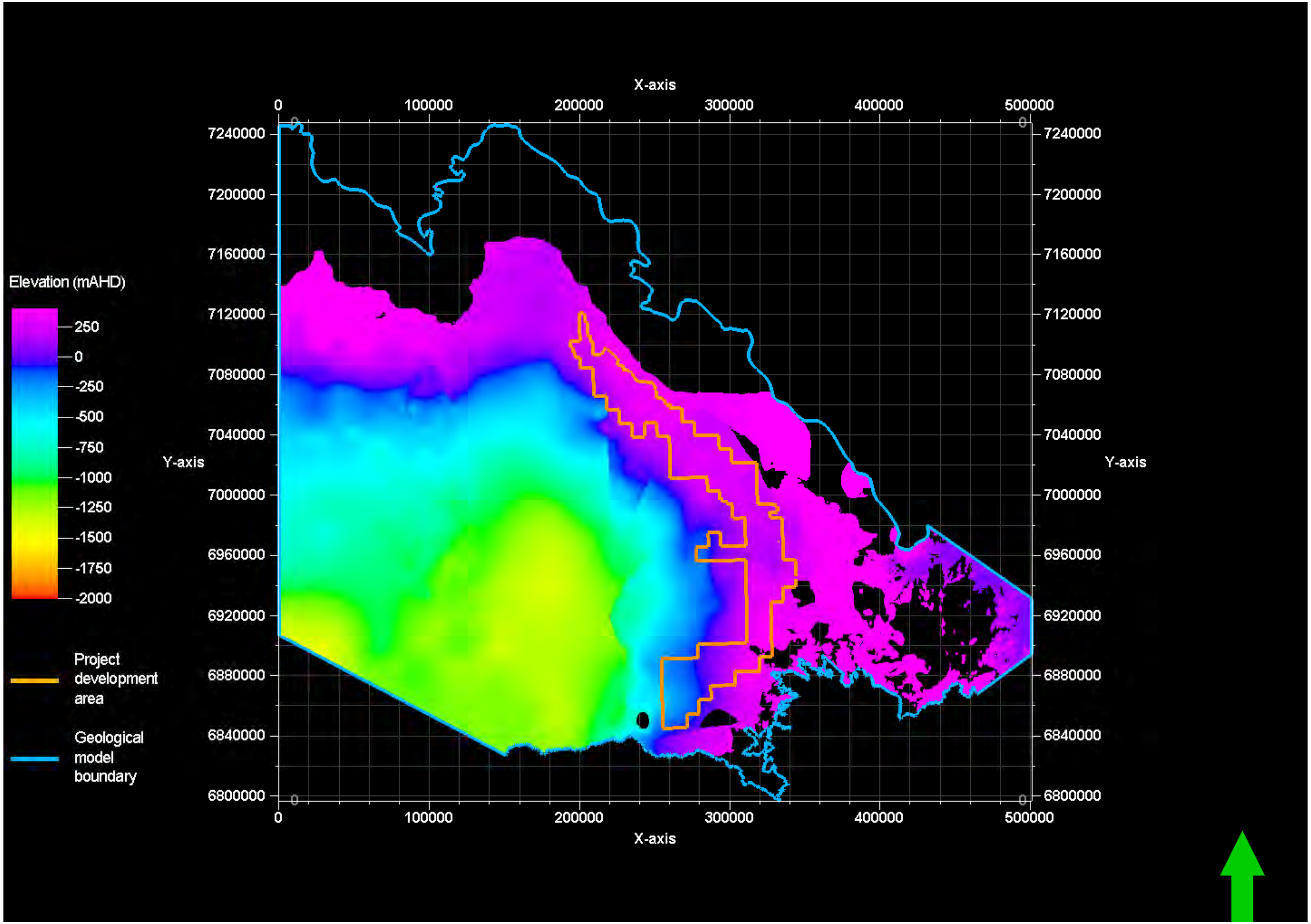

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Figure 2.4 Elevation of top of Walloon Subgroup

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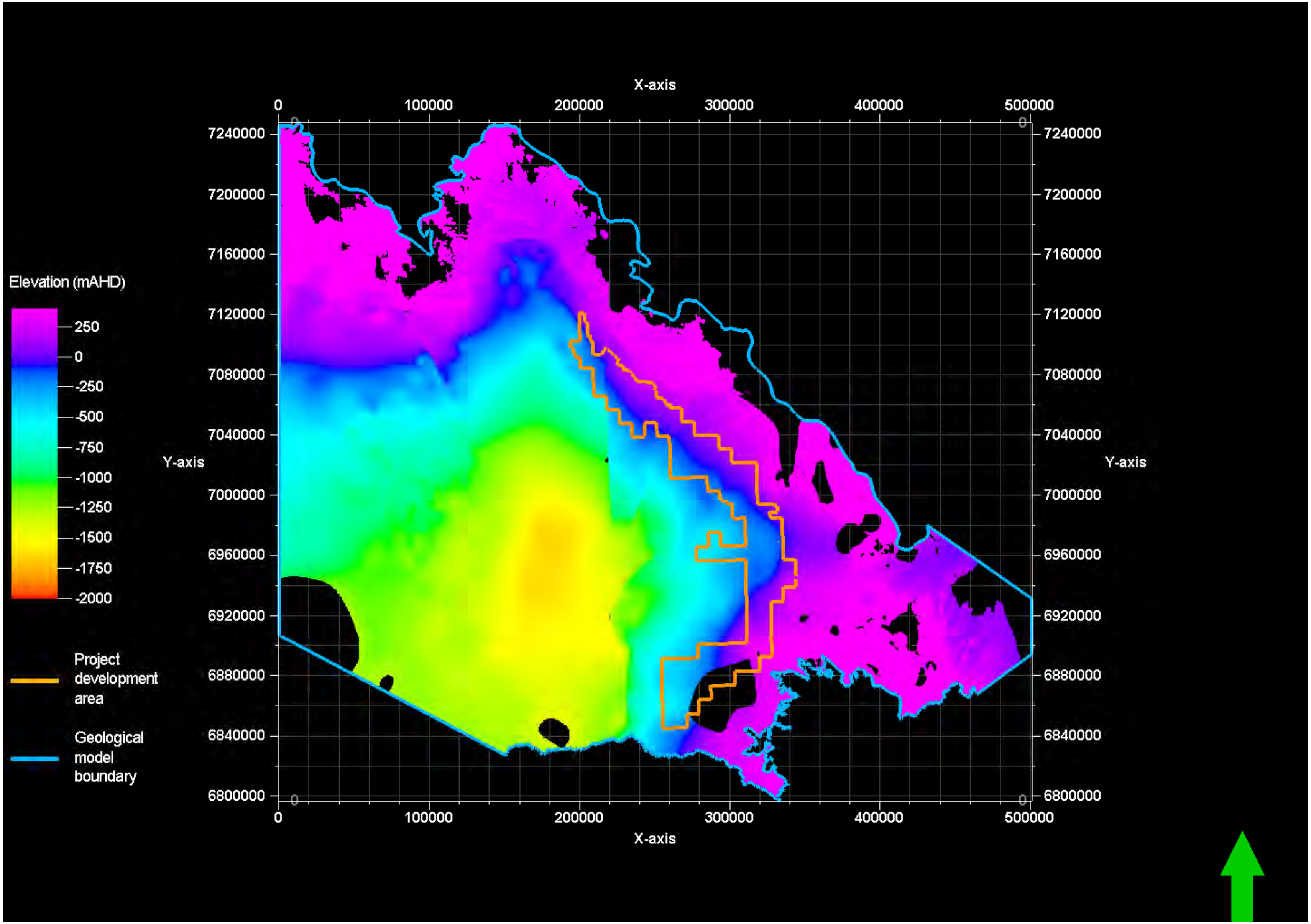

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Figure 2.5 Elevation of top of Hutton Sandstone

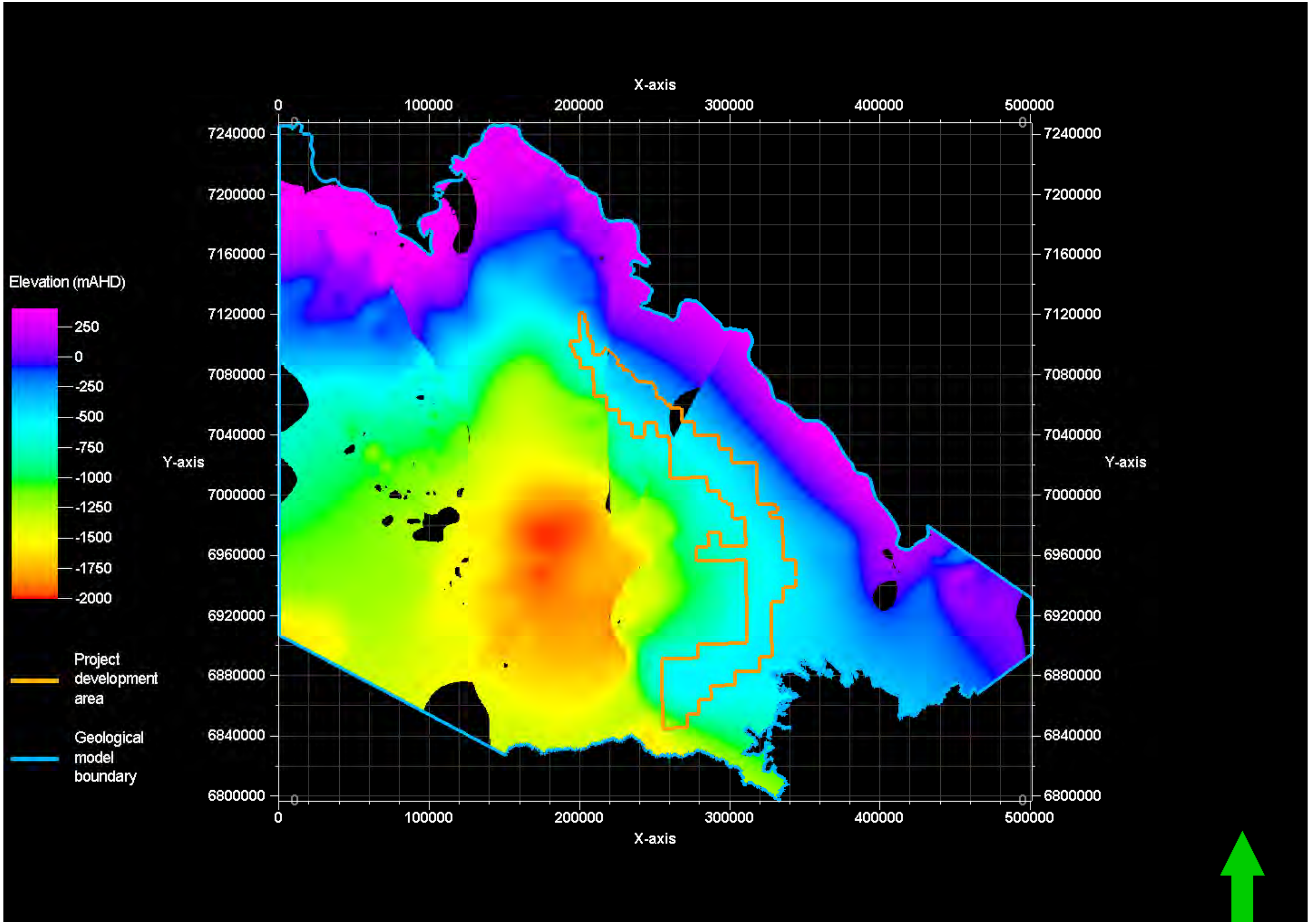

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Figure 2.6 Elevation of top of Precipice Sandstone

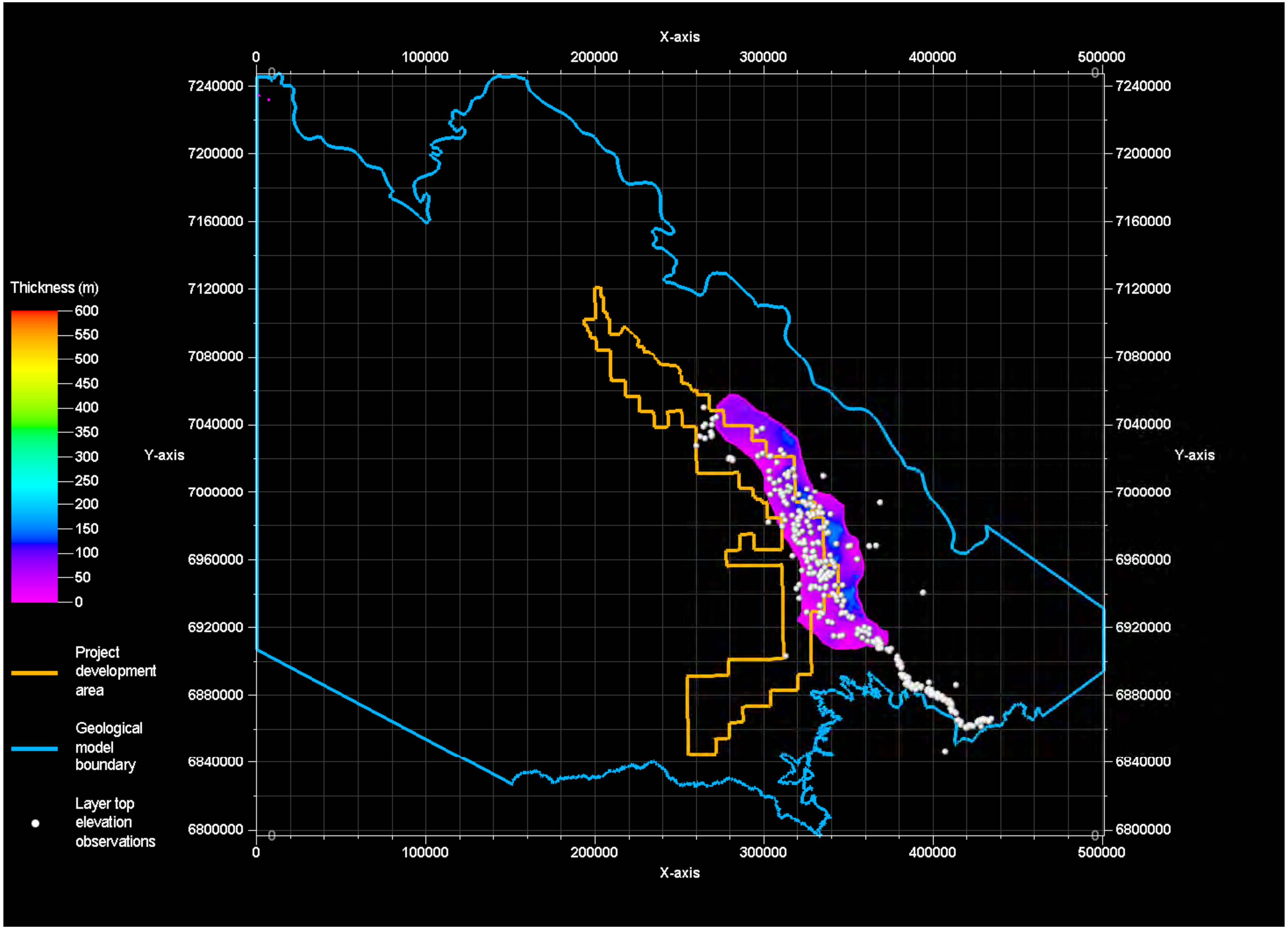

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Figure 2.7 Condamine Alluvium extent and thickness

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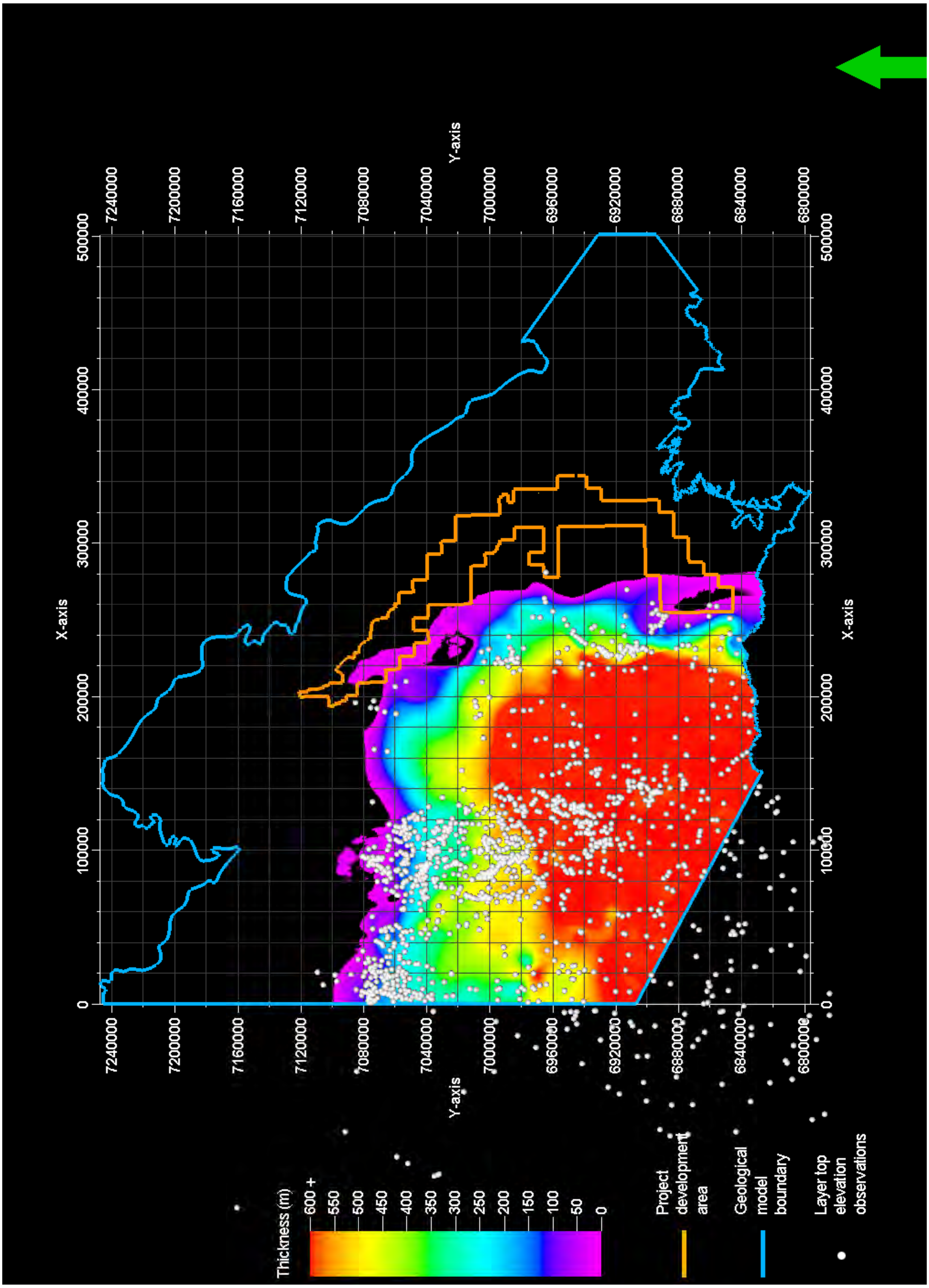
Figure 2.8 Lower Cretaceous sequence extent and thickness



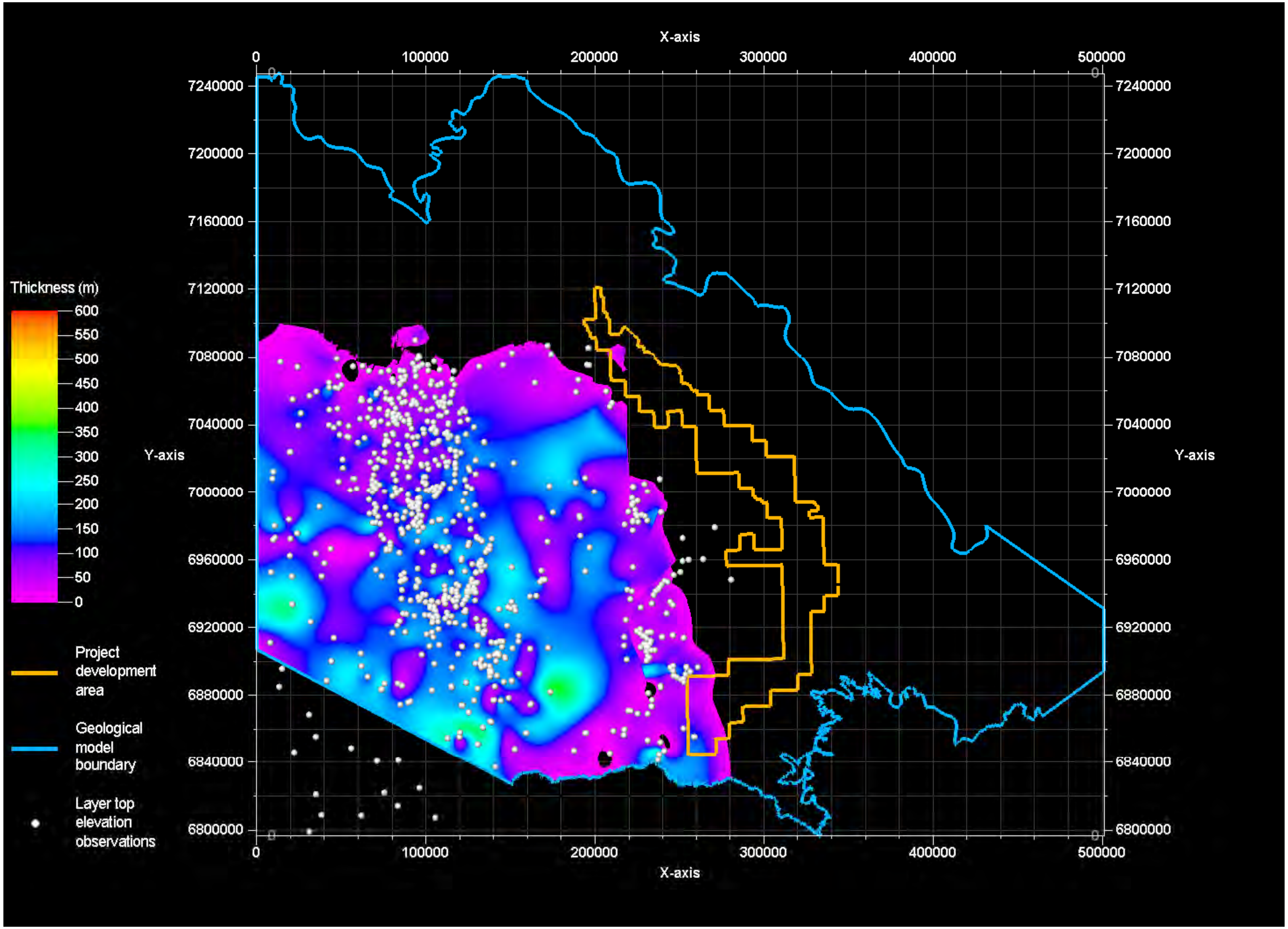


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Figure 2.9 Mooga Sandstone extent and thickness

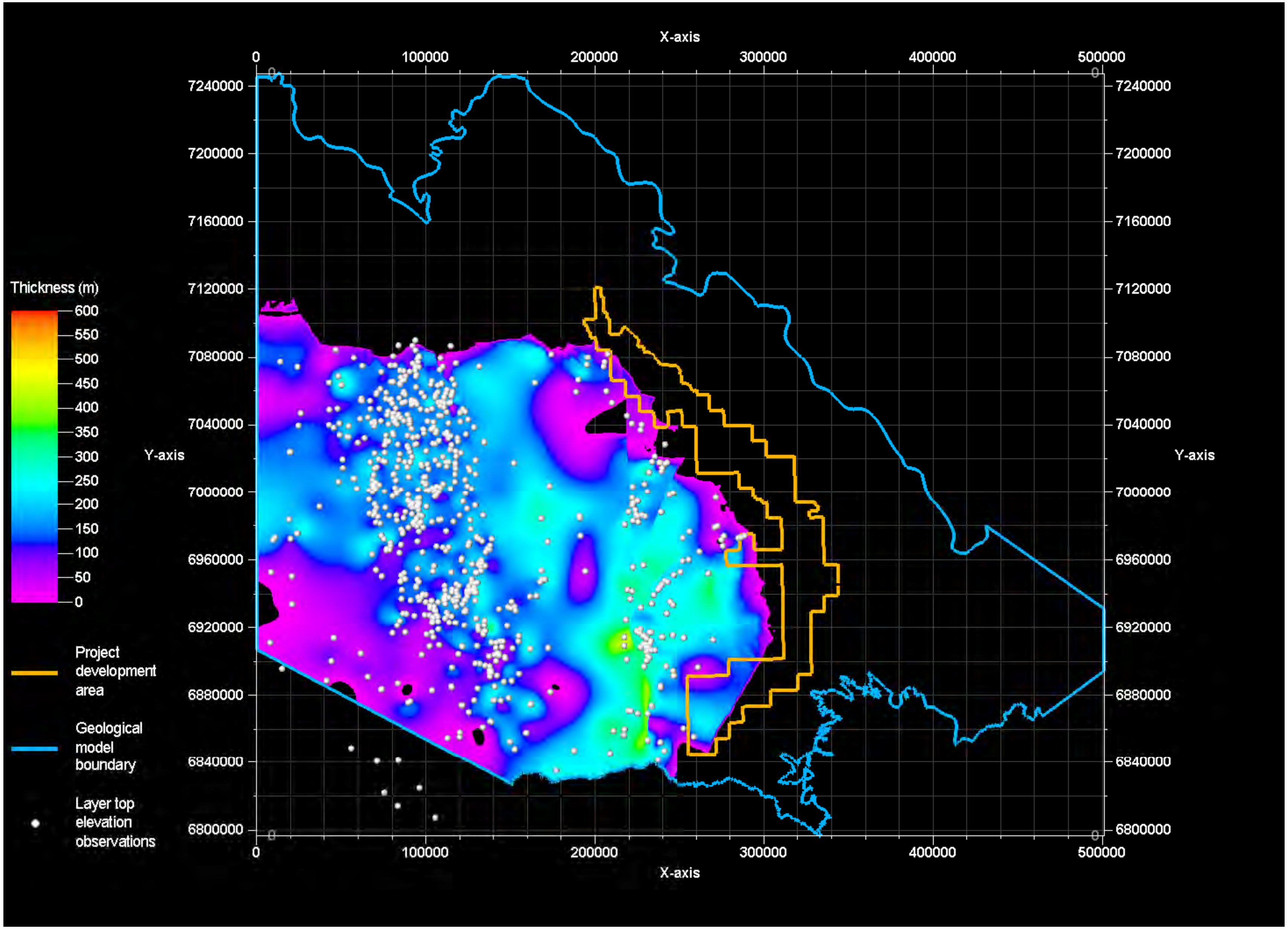

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Figure 2.10 Orallo Formation extent and thickness

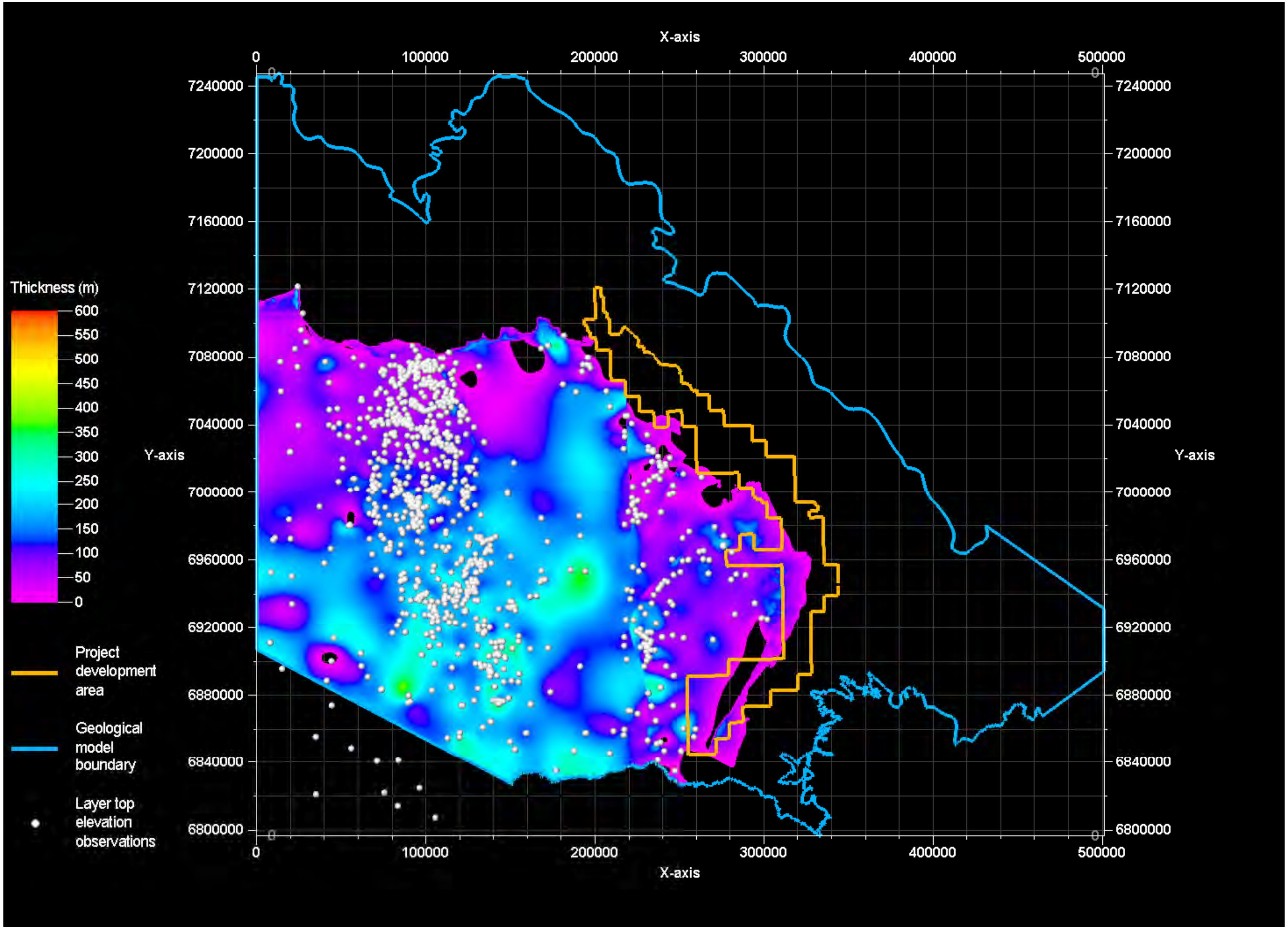

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Figure 2.11 Gubberamunda Sandstone extent and thickness

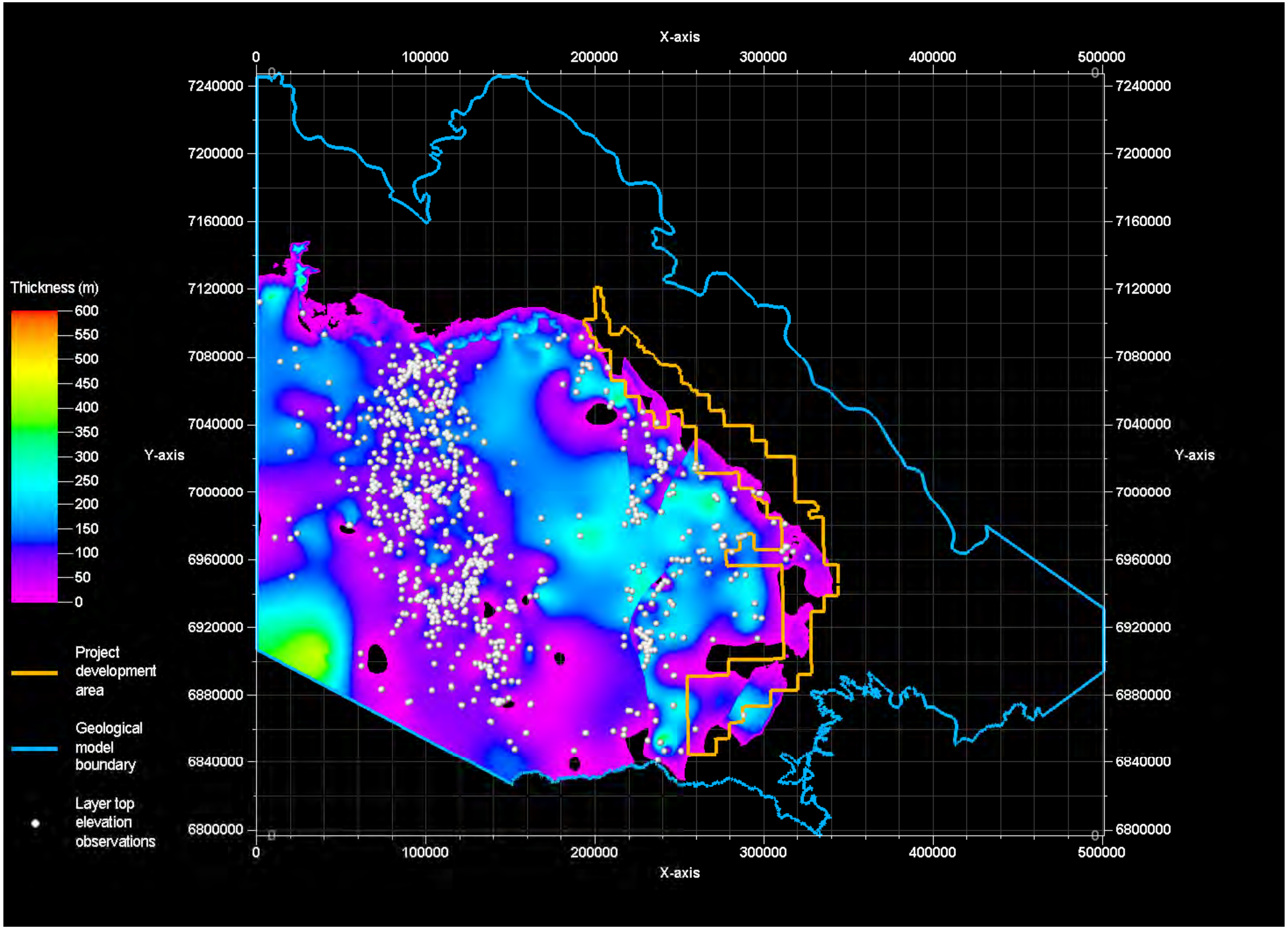

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Figure 2.12 Westbourne Formation extent and thickness

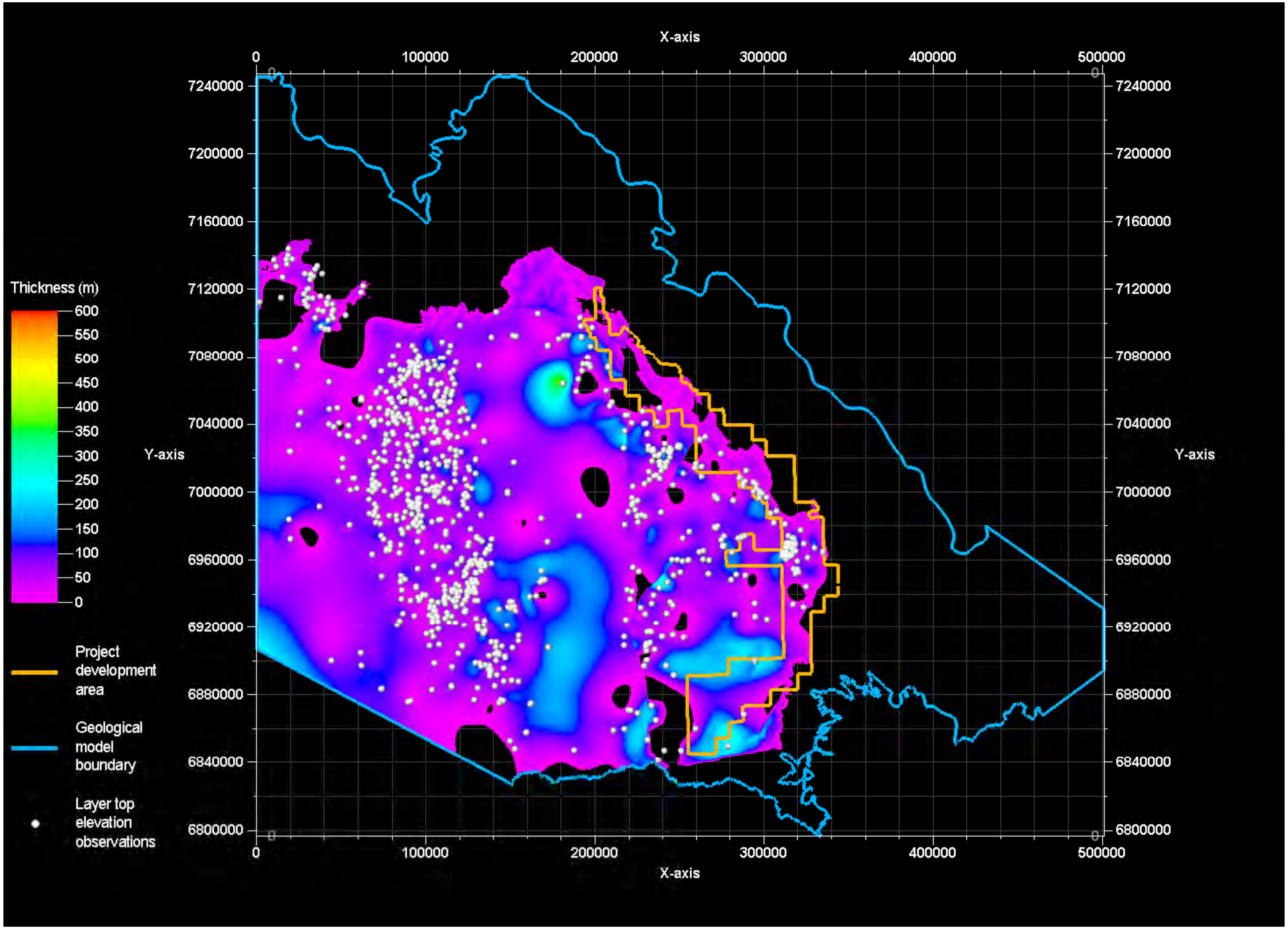

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Figure 2.13 Springbok Formation extent and thickness

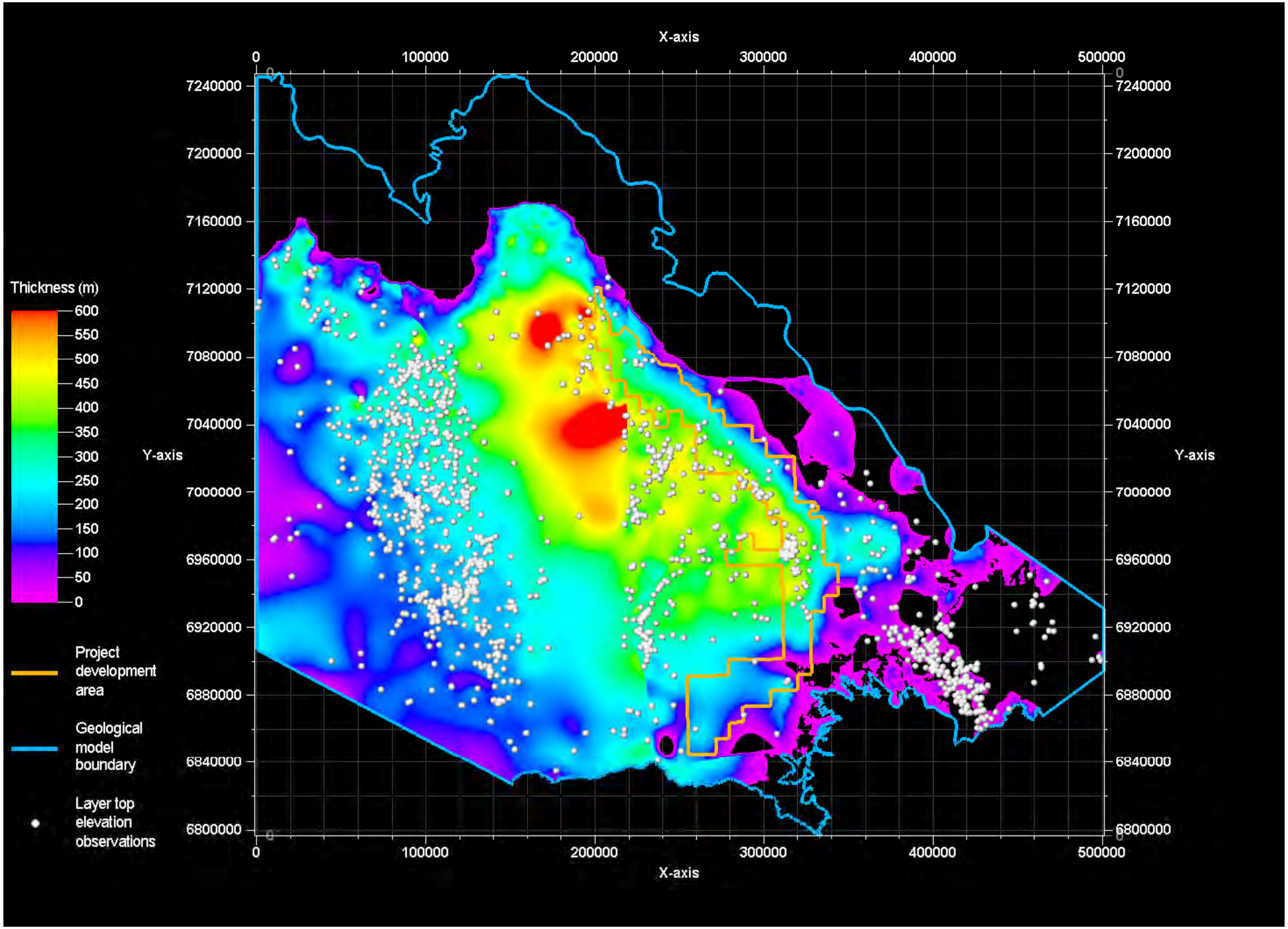

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Figure 2.14 Walloon Subgroup extent and thickness

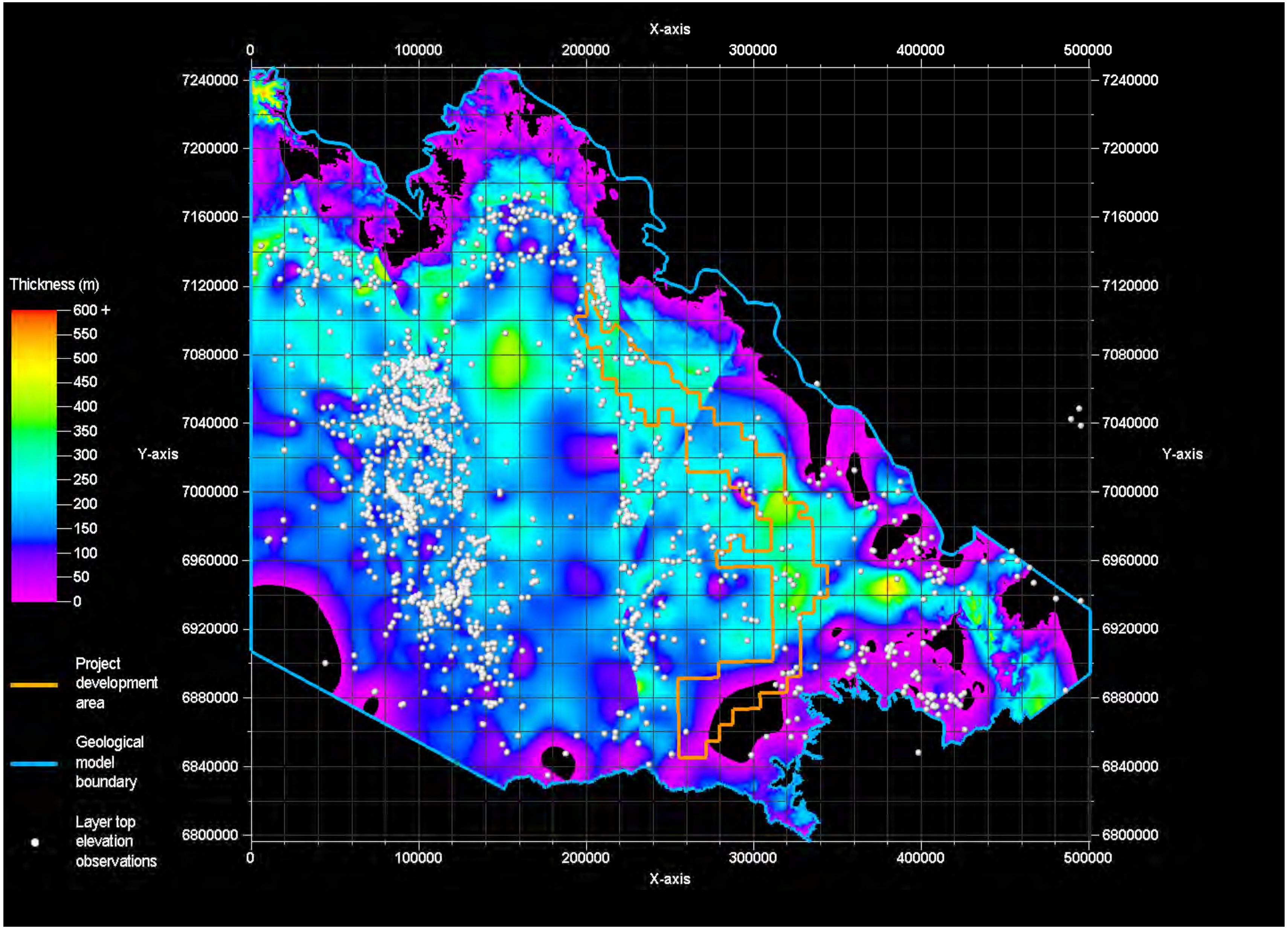

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Figure 2.15 Hutton Sandstone extent and thickness

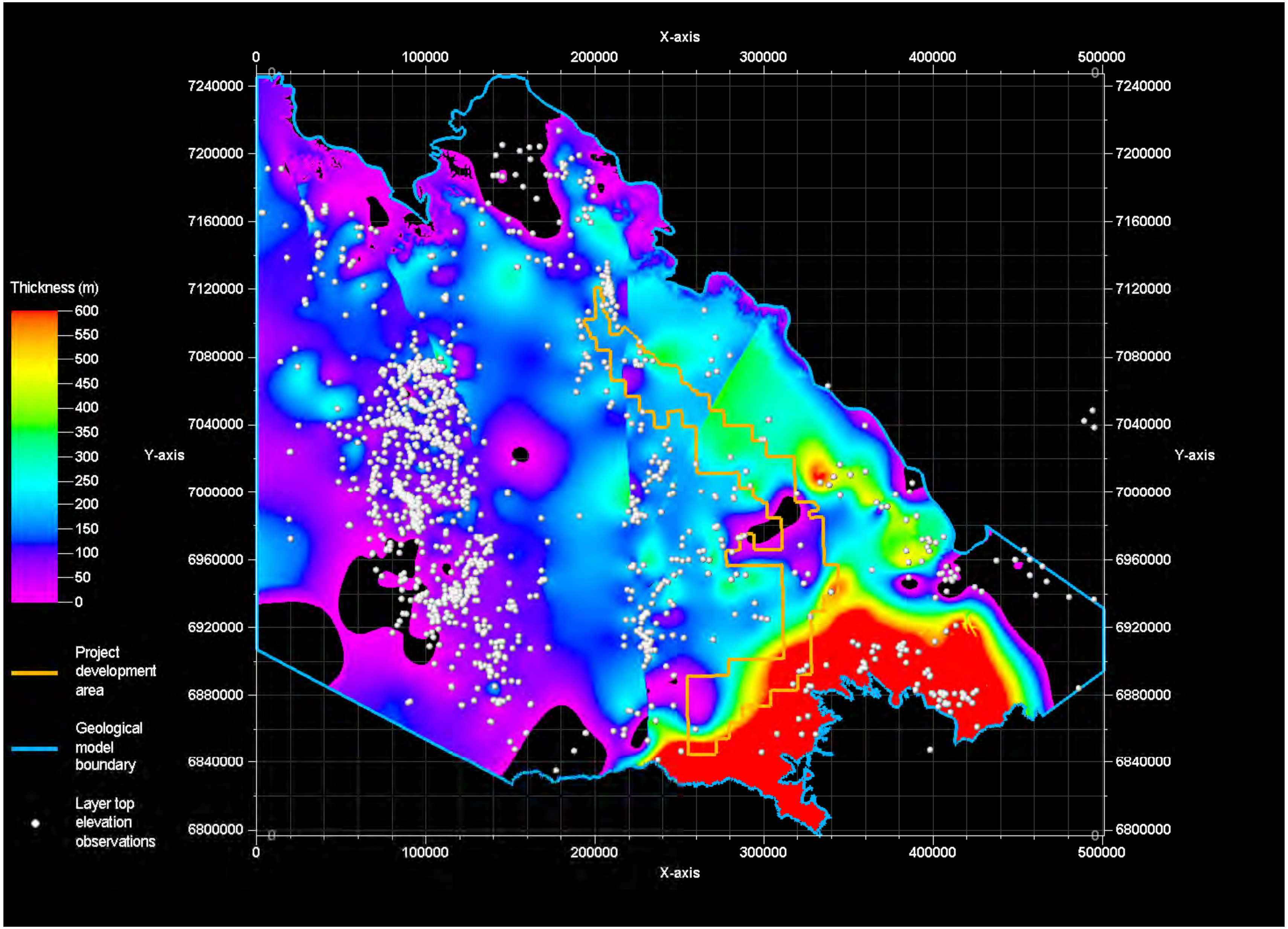

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Figure 2.16 Evergreen Formation extent and thickness

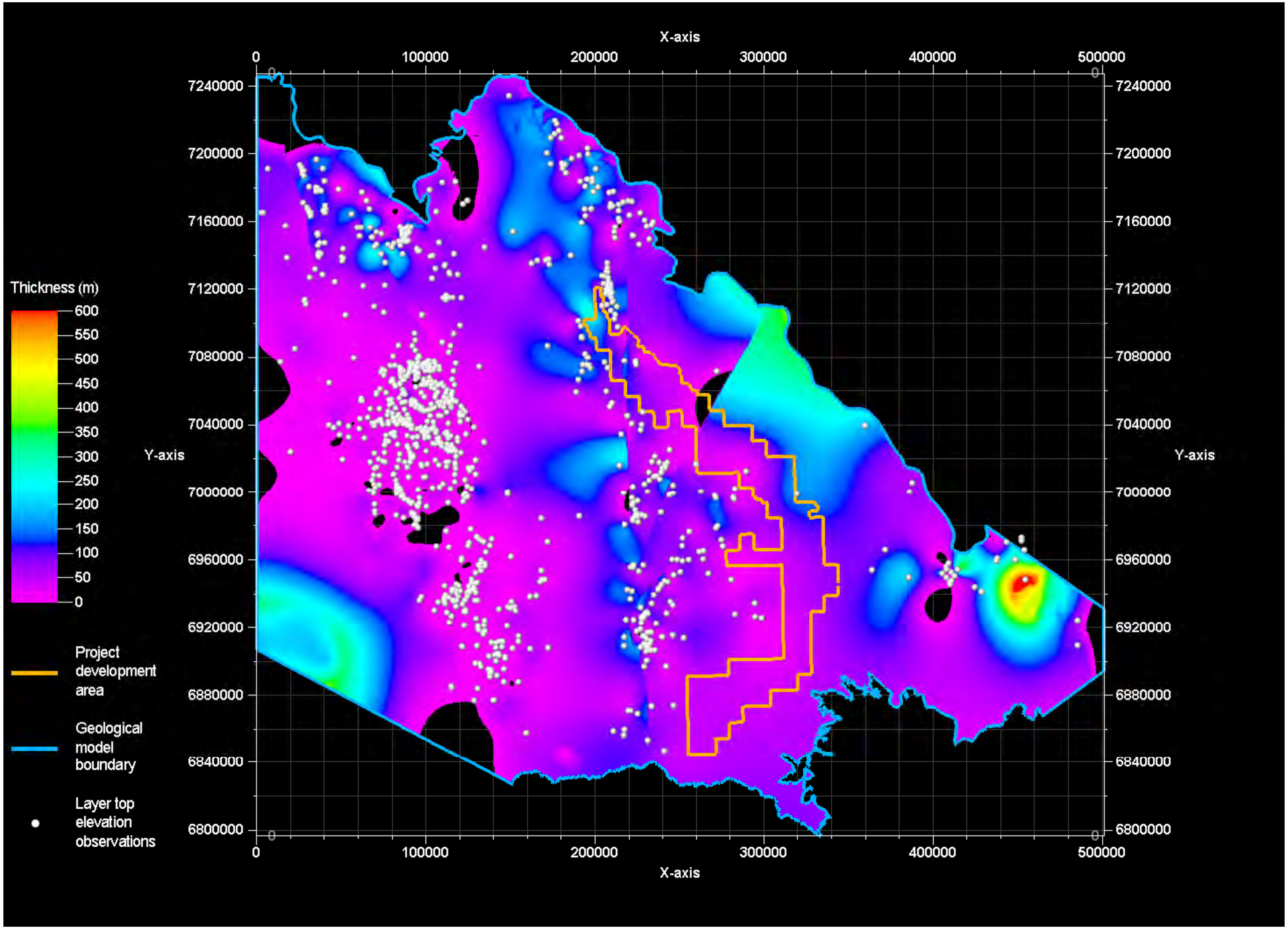

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Figure 2.17 Precipice Sandstone extent and thickness

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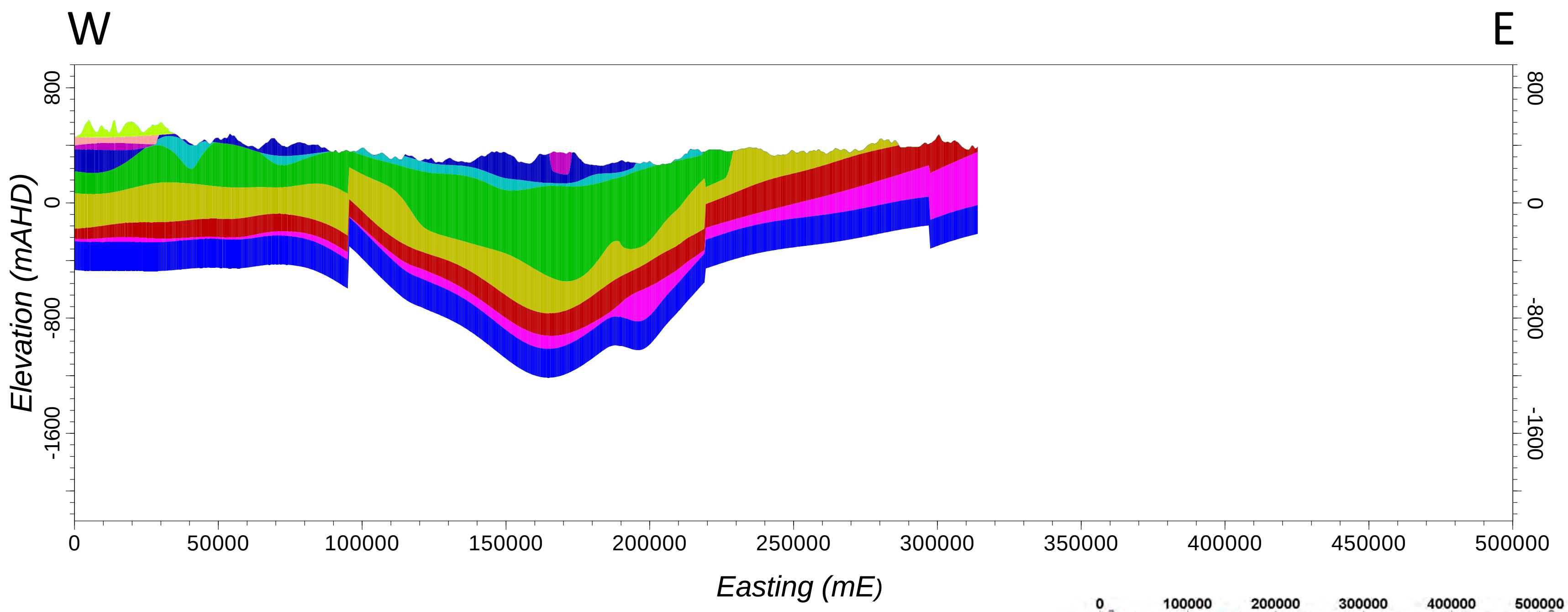
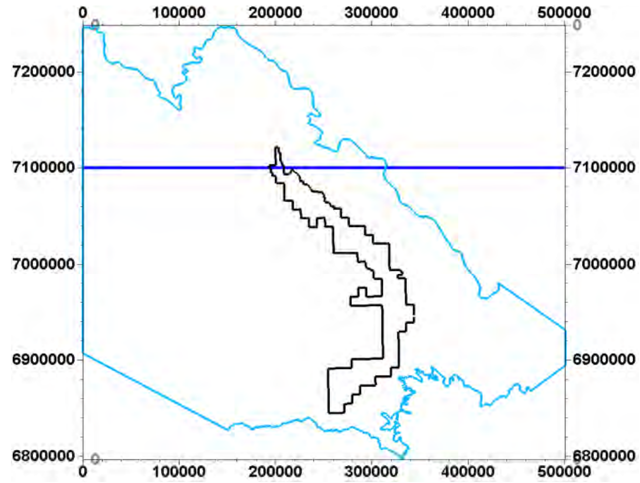


Legend

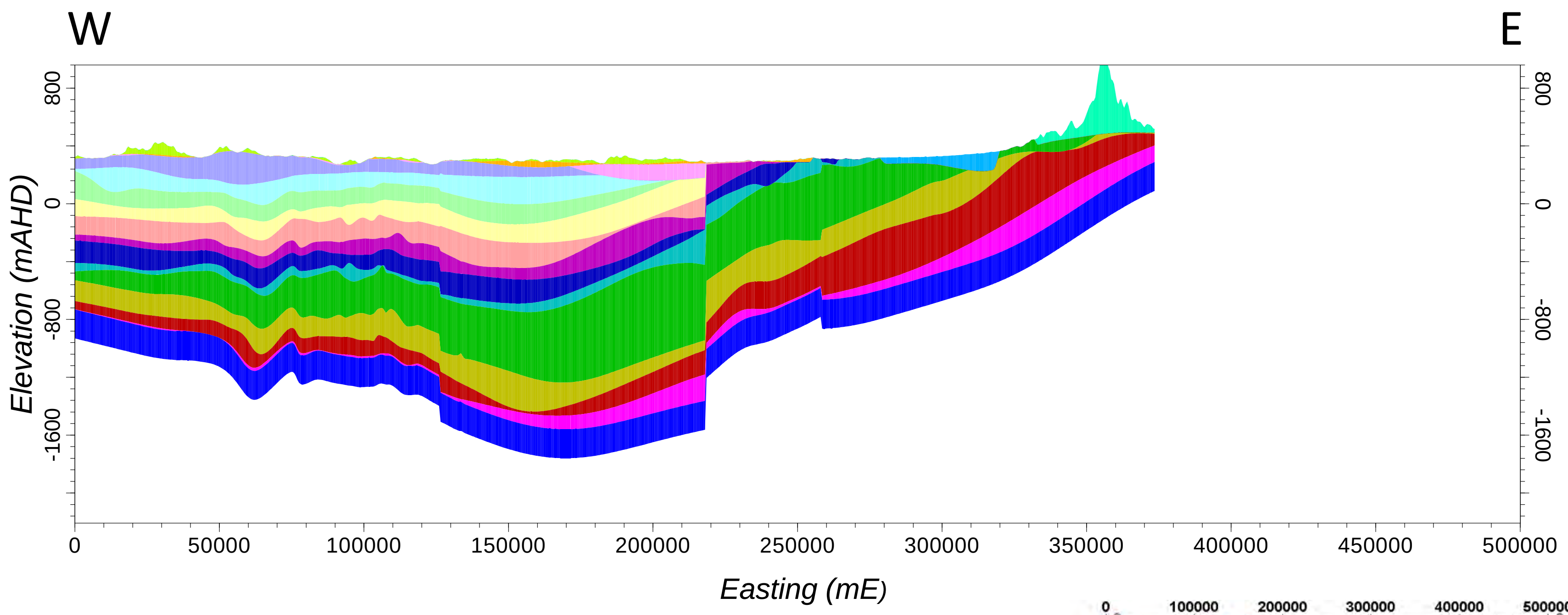
- Condamine Alluvium
- Main Range Volcanics
- Undifferentiated
- Griman Roma
- Surat Siltstone
- Coreena
- Doncaster
- Bungil
- Mooga
- Orallo
- Gubberamunda
- Westbourne
- Springbok
- Waloon
- Hutton + Marburg
- Evergreen
- Precipice + Helidon
- Triassic



Map projection: Transverse Mercator, GDA94 MGA Zone 56

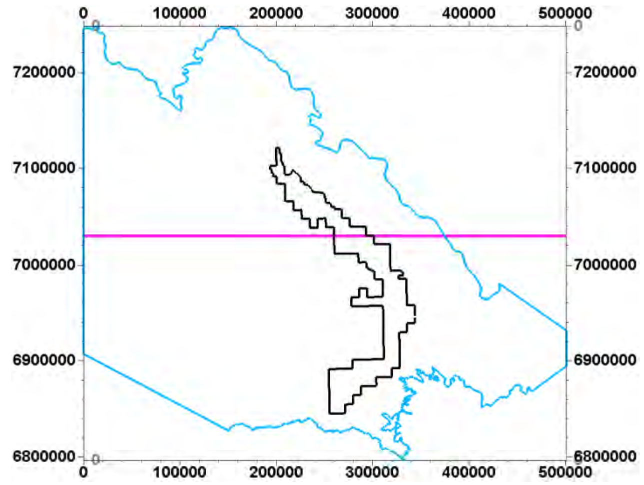
Vertical exaggeration: 50x

Figure 2.18 East-west geological model cross section 1



Legend

Condamine Alluvium	Doncaster	Springbok
Main Range Volcanics	Bungil	Waloon
Undifferentiated	Mooga	Hutton + Marburg
Griman Roma	Orallo	Evergreen
Surat Siltstone	Gubberamunda	Precipice + Helidon
Coreena	Westbourne	Triassic



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Vertical exaggeration: 50x

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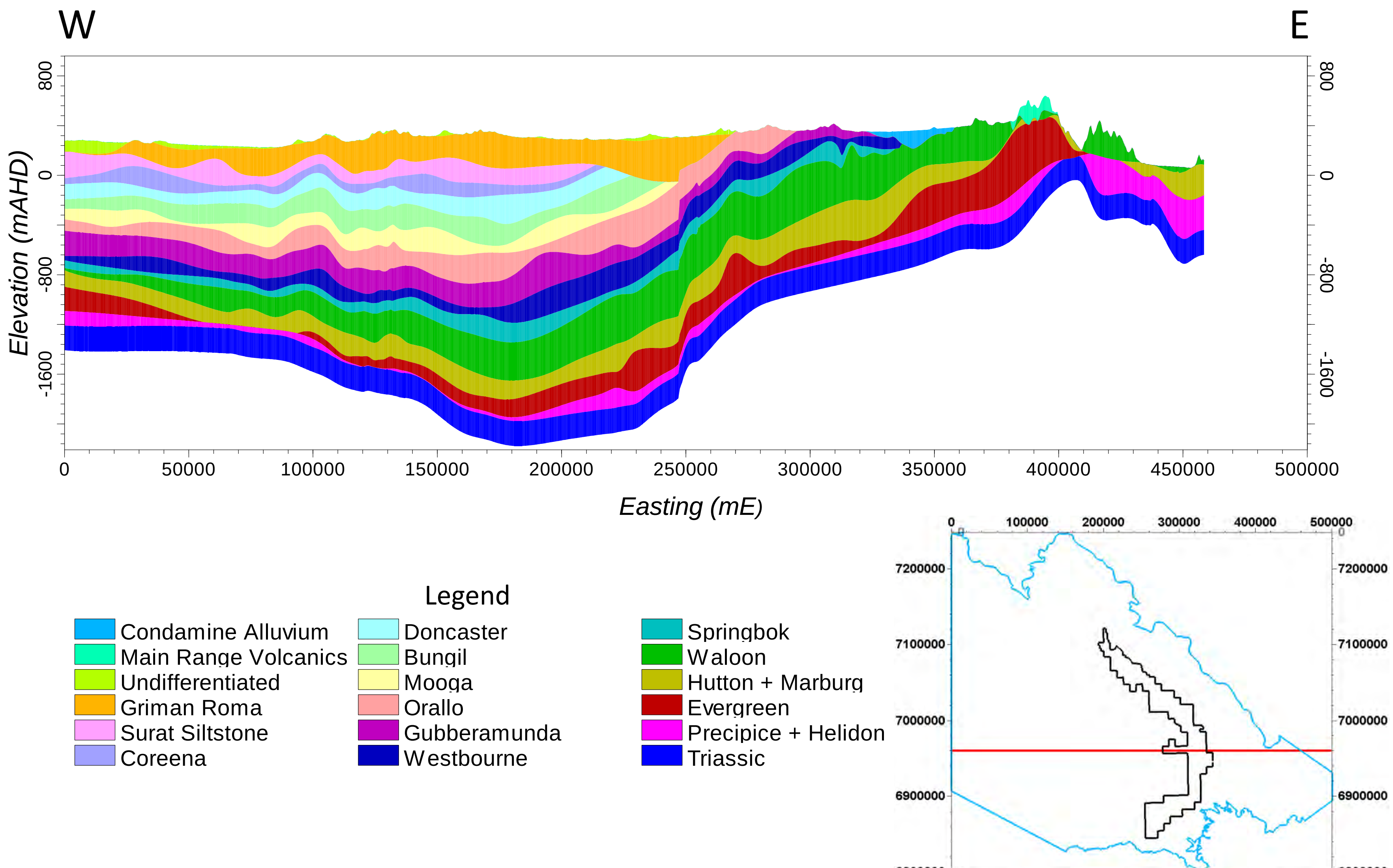
Figure 2.19 East-west geological model cross section 2



Map projection: Transverse Mercator, GDA94 MGA Zone 56

Vertical exaggeration: 50x

Figure 2.20 East–west geological model cross section 3

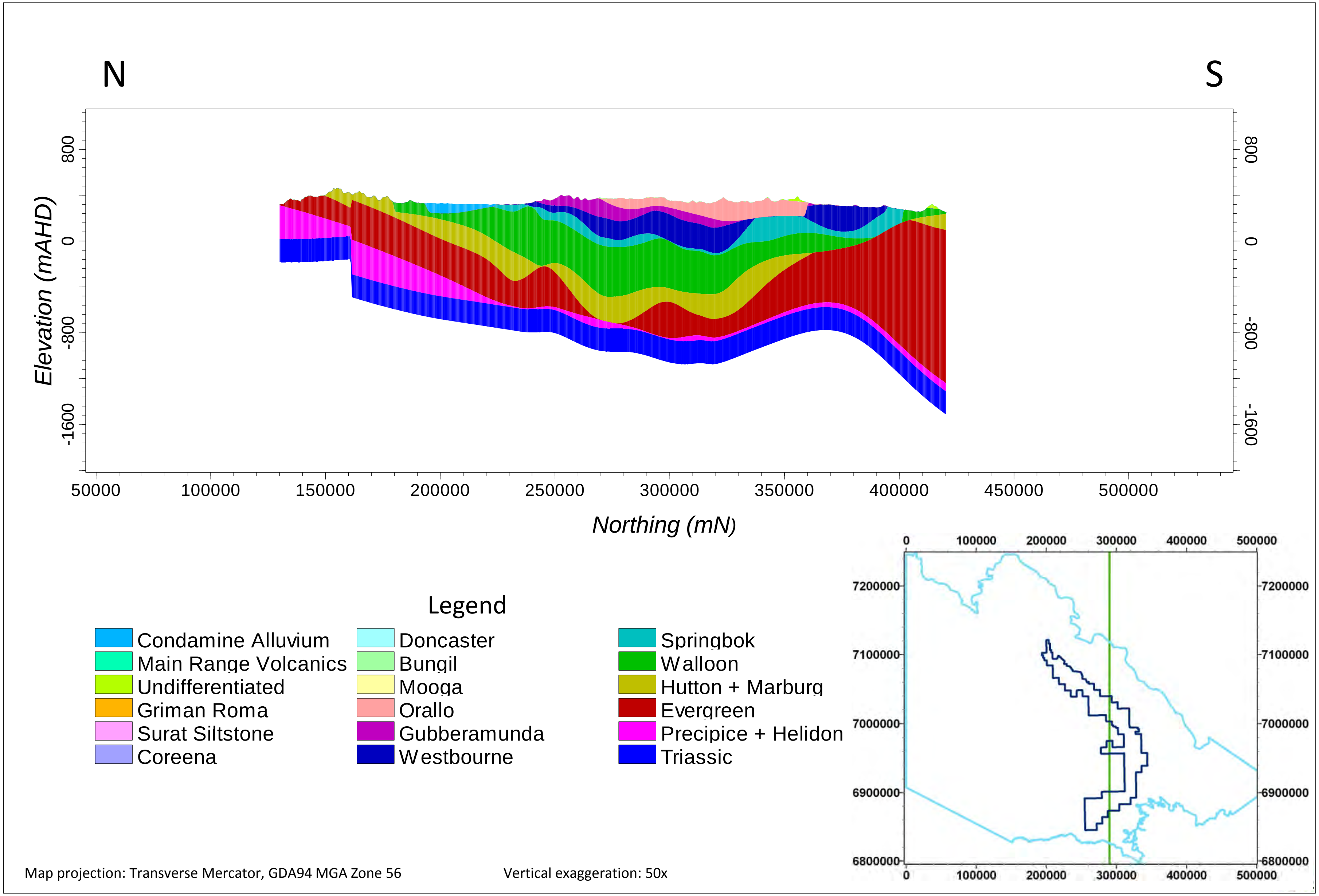


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Figure 2.21 North-south geological model cross section

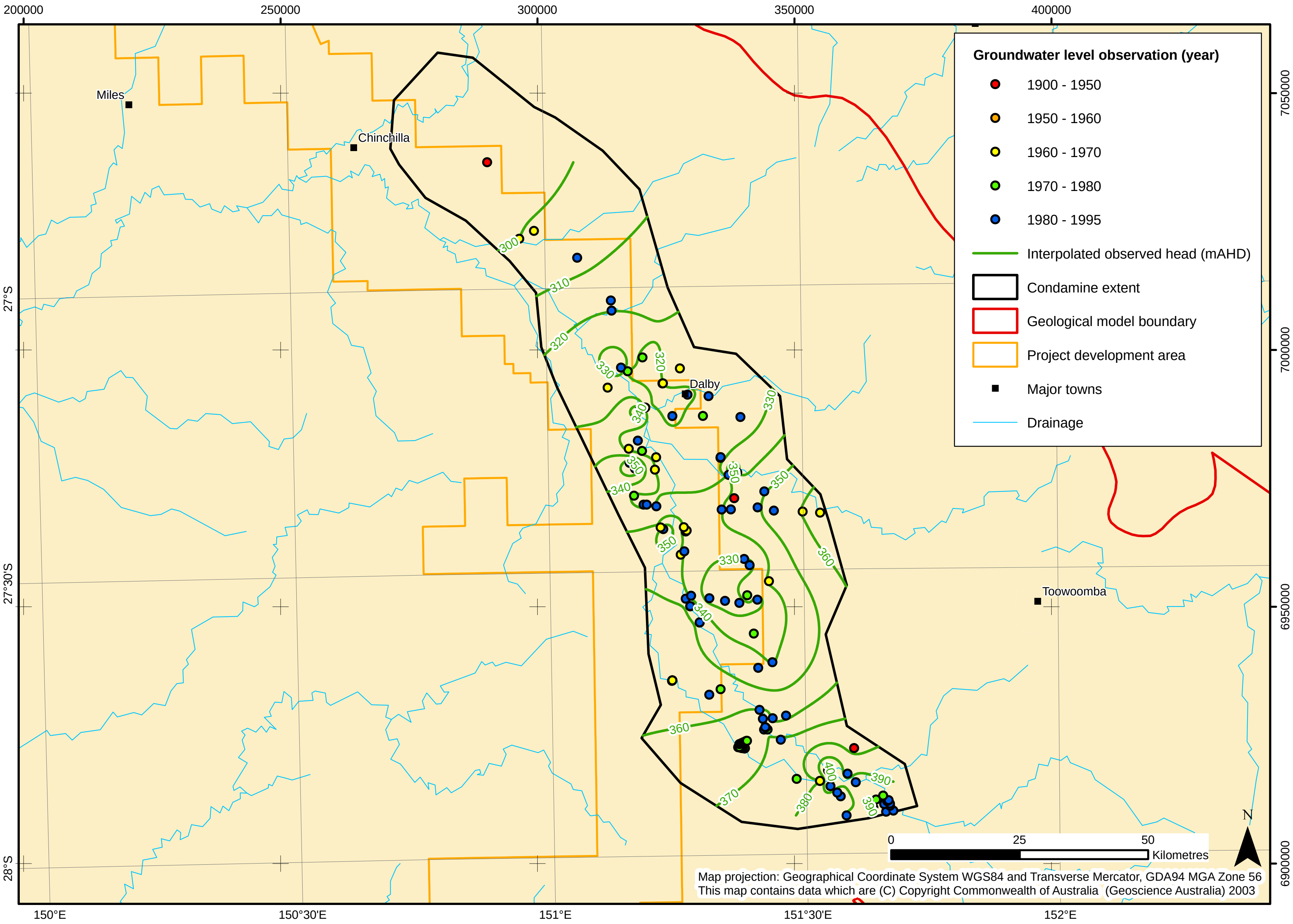

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Figure 2.22 Groundwater level observations and interpolated "pre 1995" contours in the Condamine Alluvium

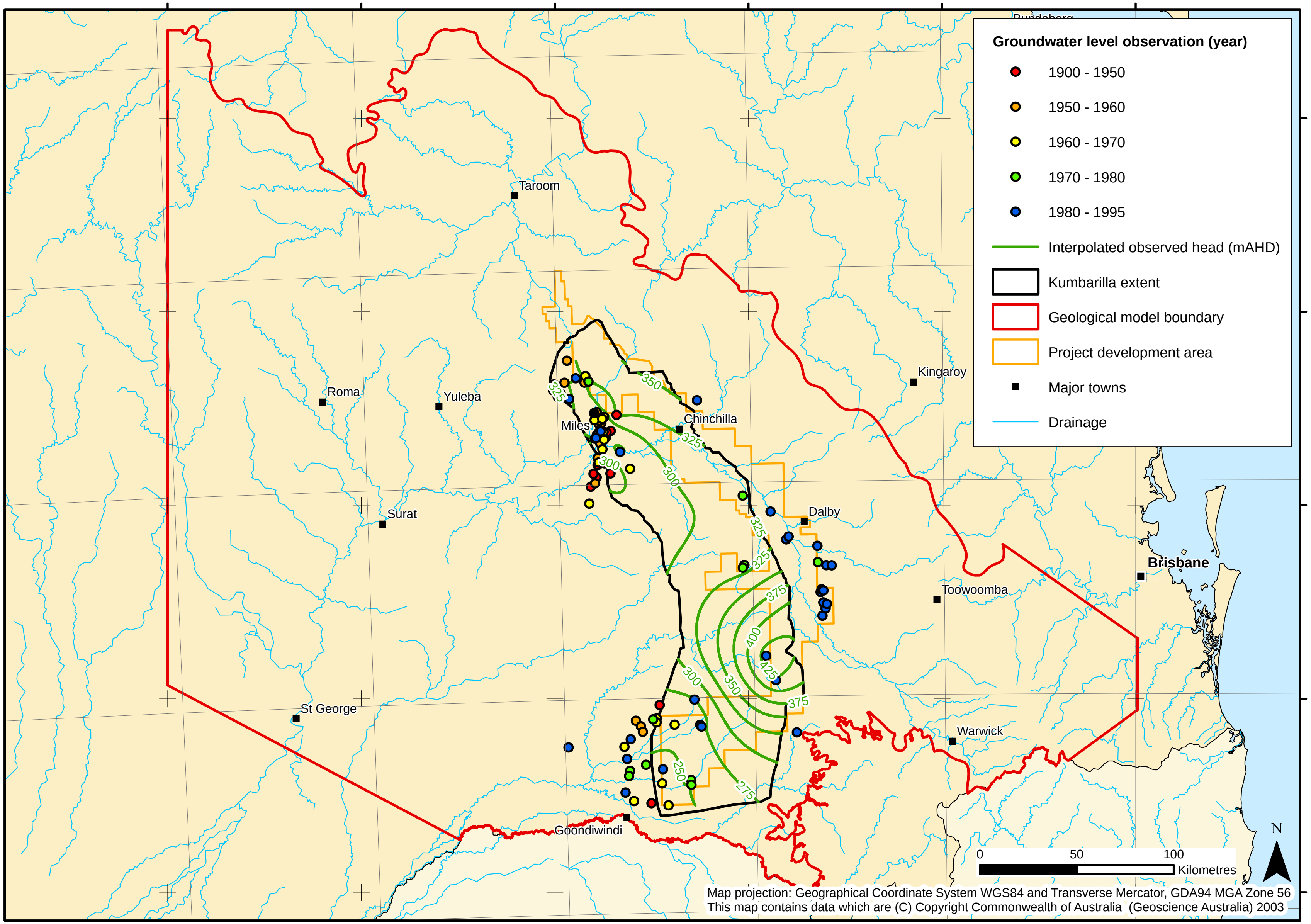

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Figure 2.23 Groundwater level observations and interpolated "pre 1995" contours in the Kumbarilla Beds

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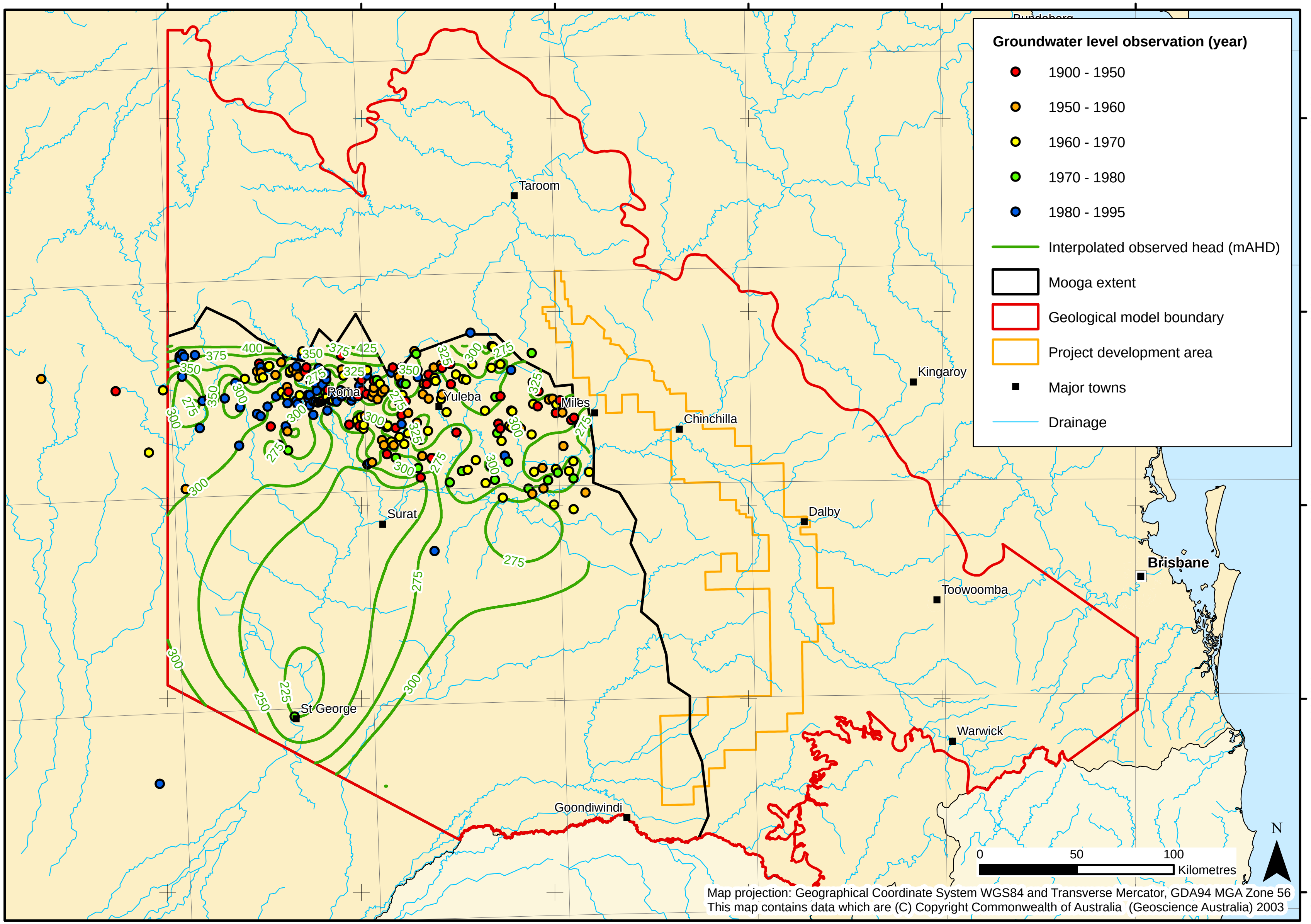

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Figure 2.24 Groundwater level observations and interpolated "pre 1995" contours in the Mooga Sandstone

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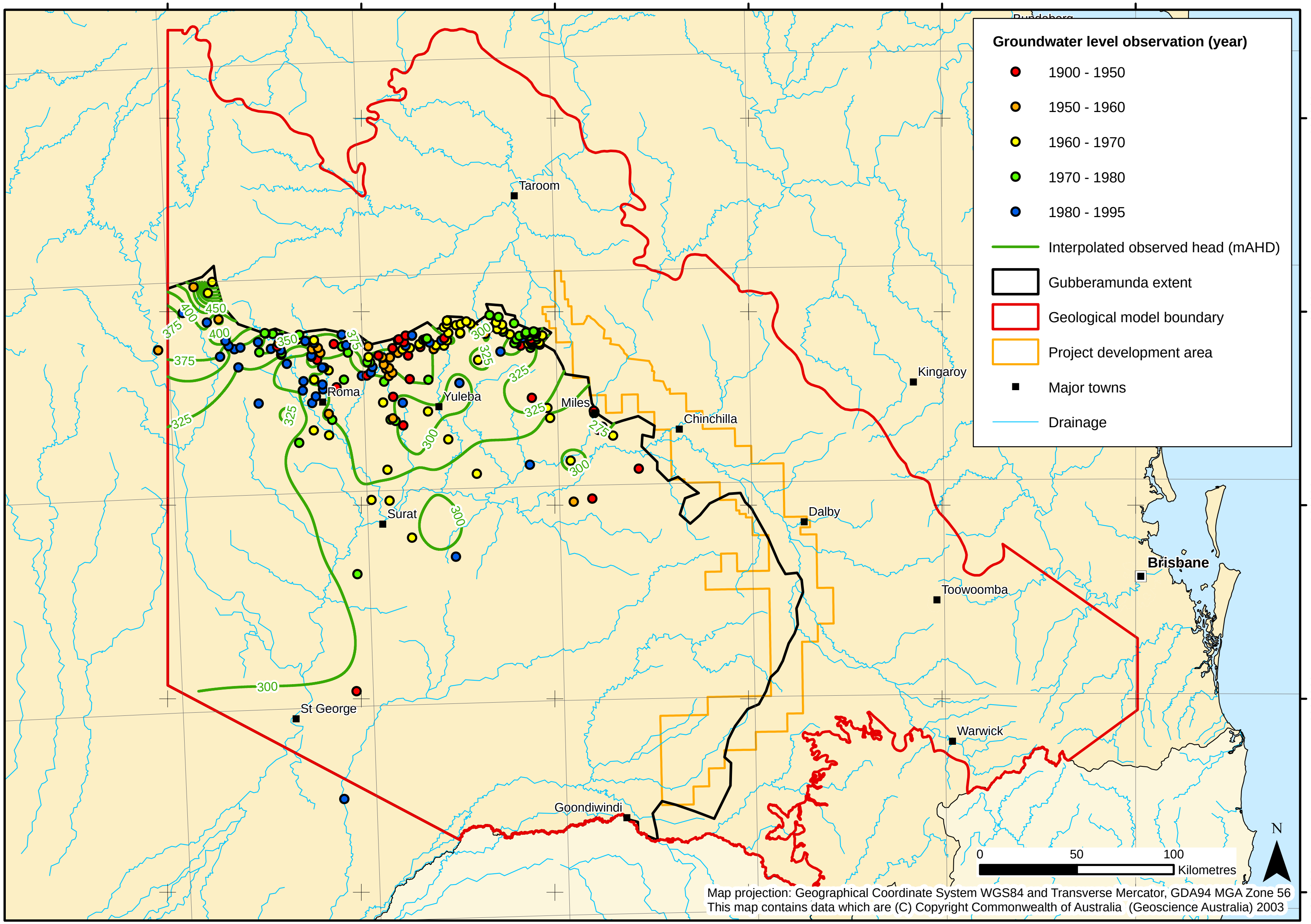

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Figure 2.25 Groundwater level observations and interpolated "pre 1995" contours in the Gubberamunda Sandstone

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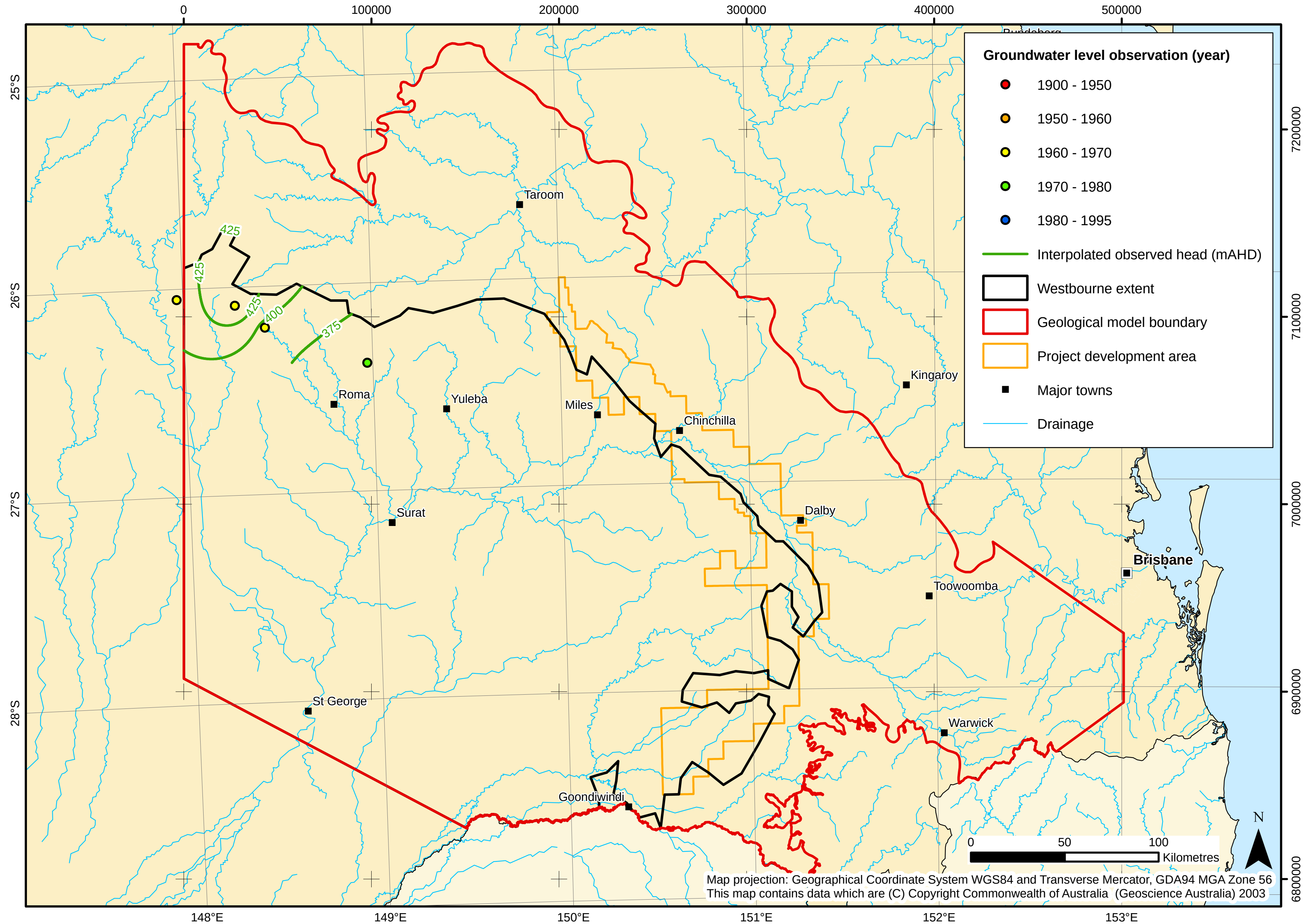

Figure 2.26 Groundwater level observations and interpolated "pre 1995" contours in the Westbourne Formation

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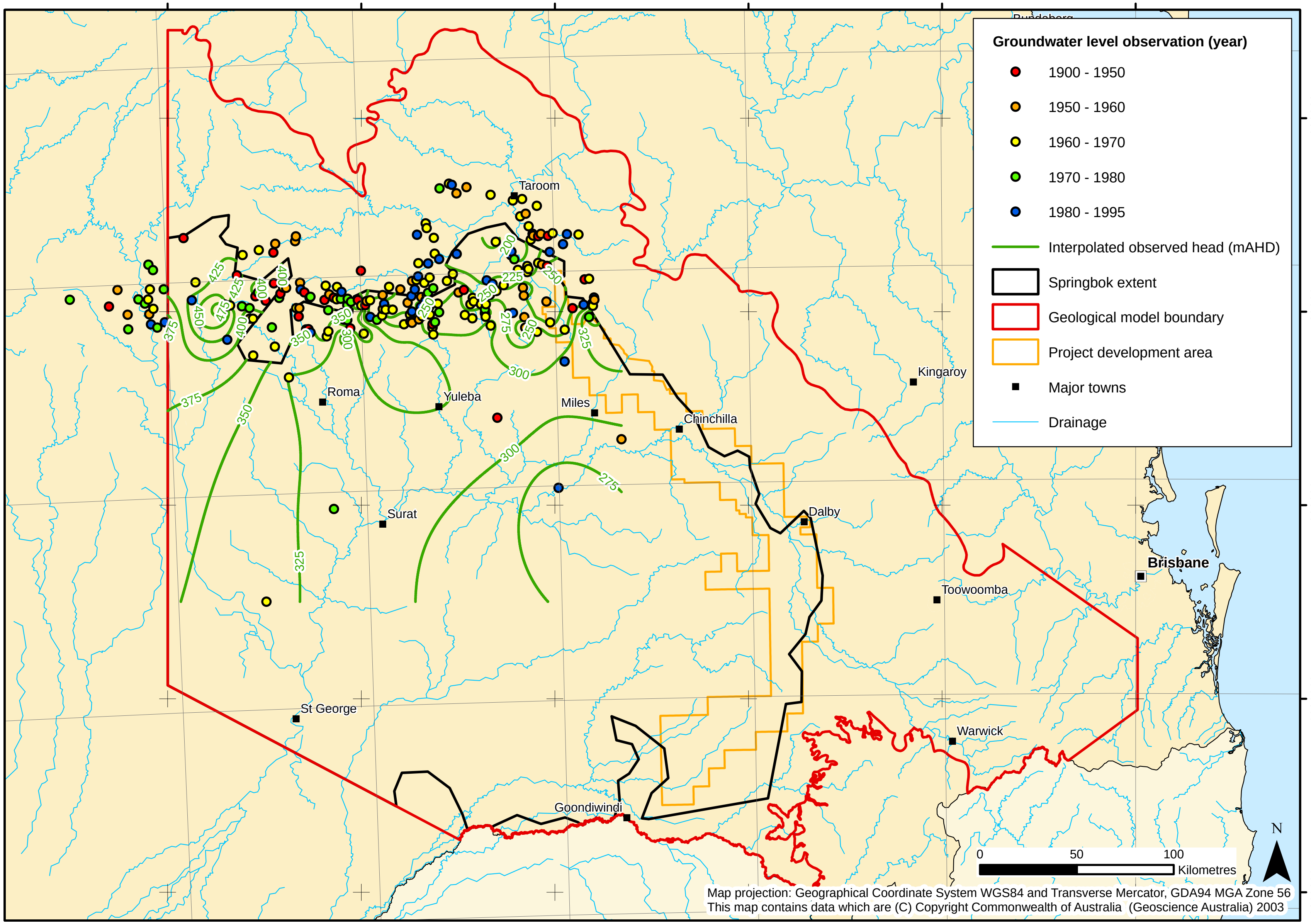

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Figure 2.27 Groundwater level observations and interpolated "pre 1995" contours in the Springbok Formation

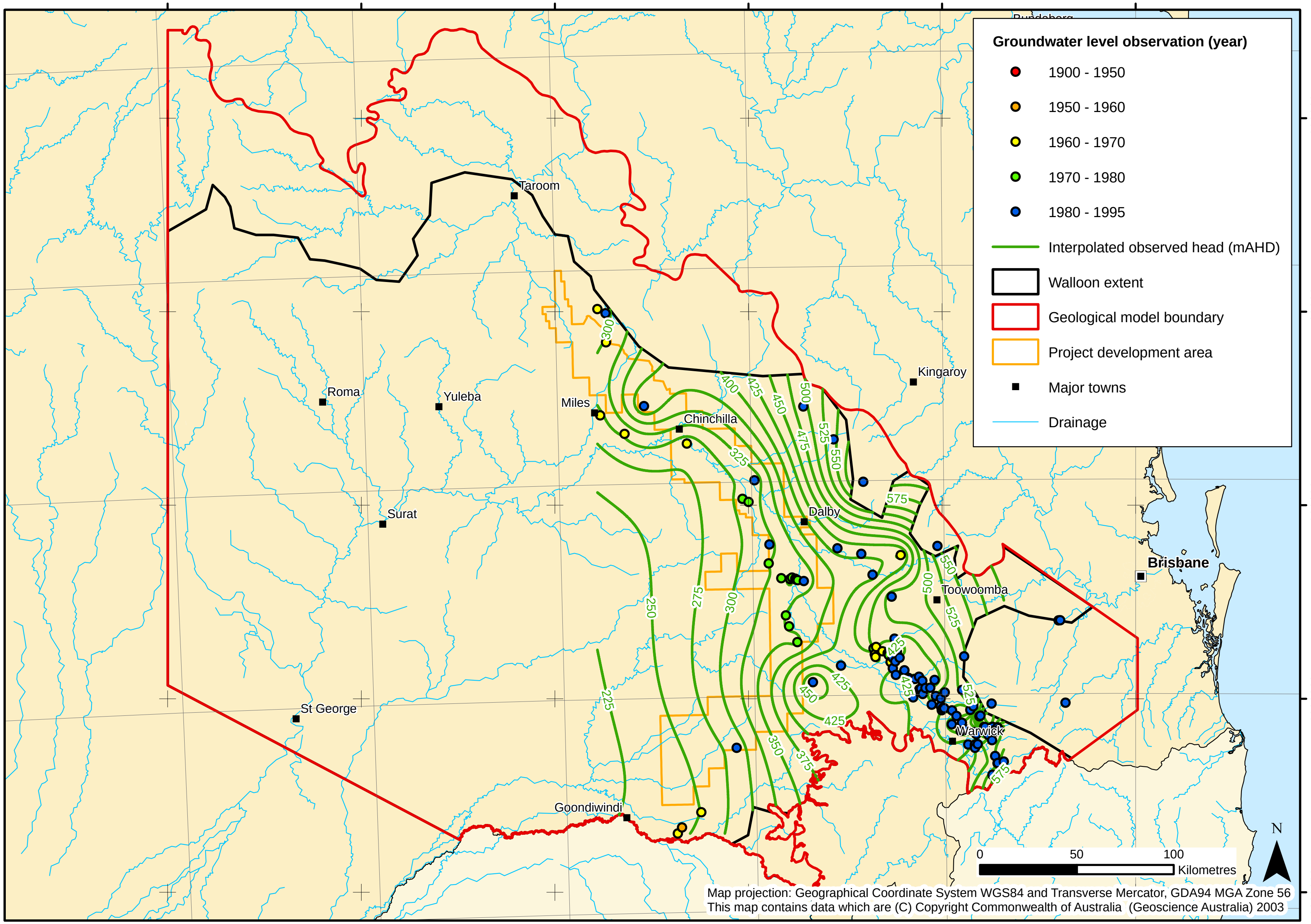

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Figure 2.28 Groundwater level observations and interpolated "pre 1995" contours in the Walloon Subgroup

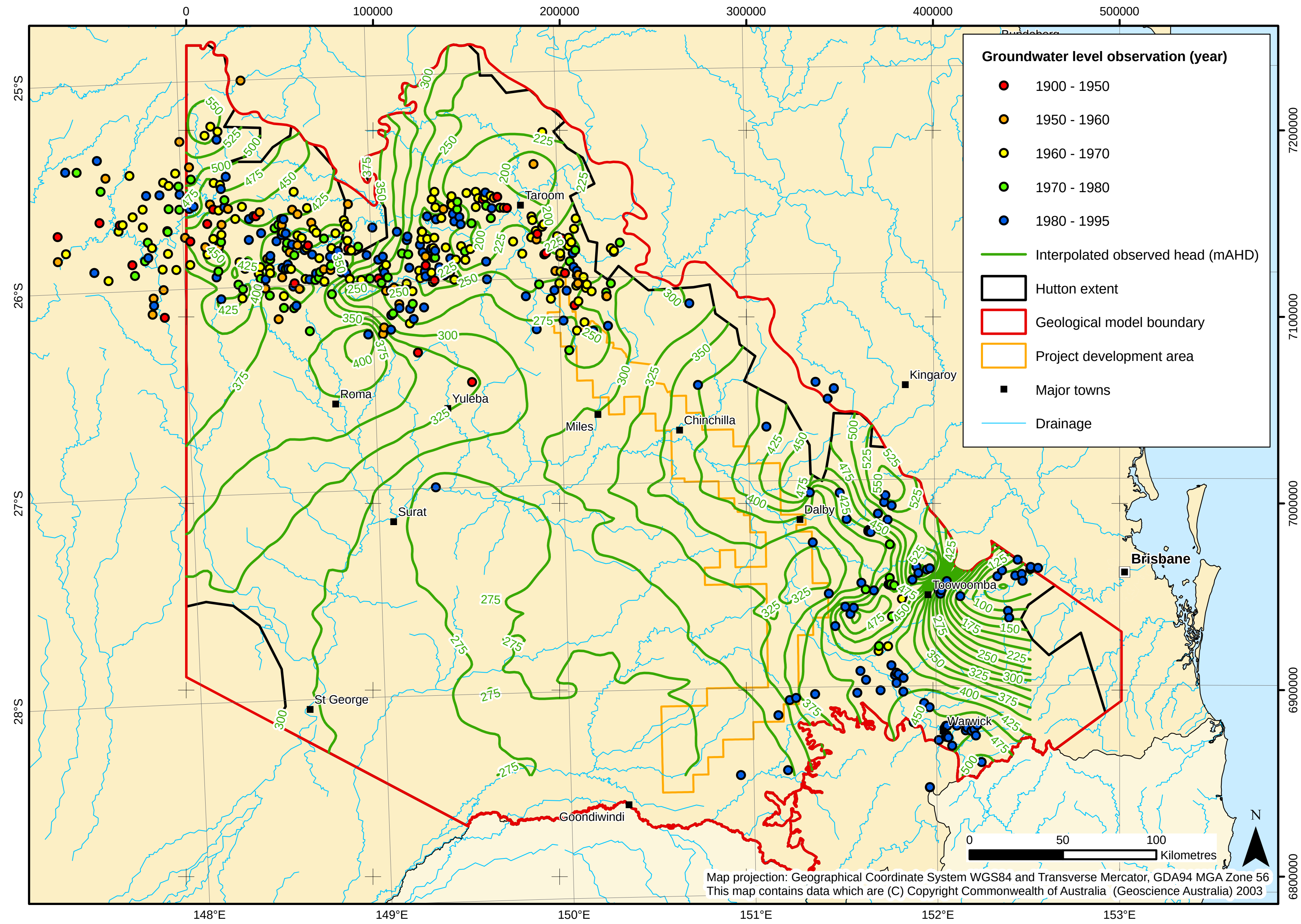

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Figure 2.29 Groundwater level observations and interpolated "pre 1995" contours in the Hutton and Marburg Sandstones

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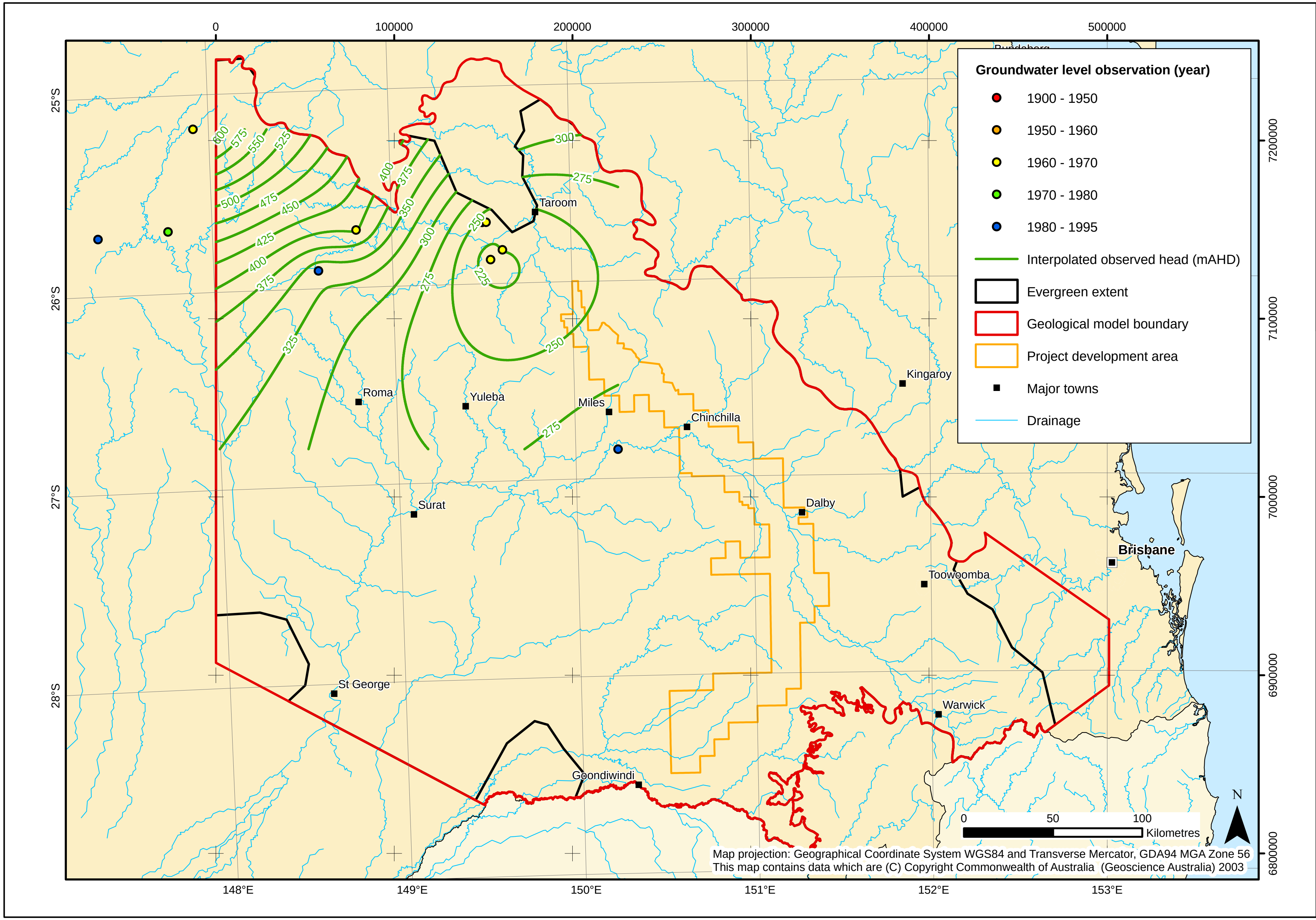

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Figure 2.30 Groundwater level observations and interpolated "pre 1995" contours in the Evergreen Formation

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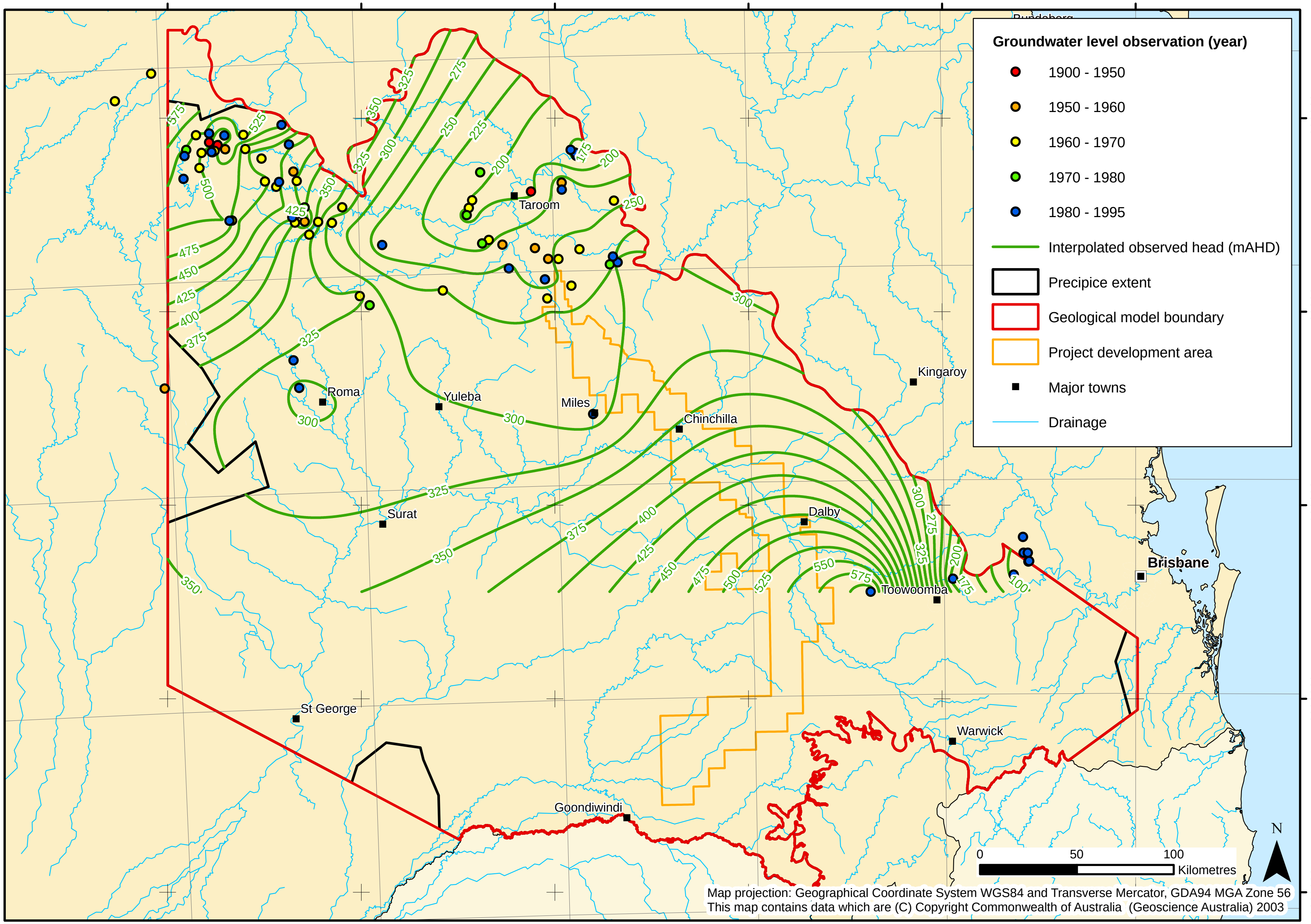

Figure 2.31 Groundwater level observations and interpolated "pre 1995" contours in the Precipice and Helidon Sandstones

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Figure 2.32 Observed groundwater level drawdown at Arrow monitoring bores

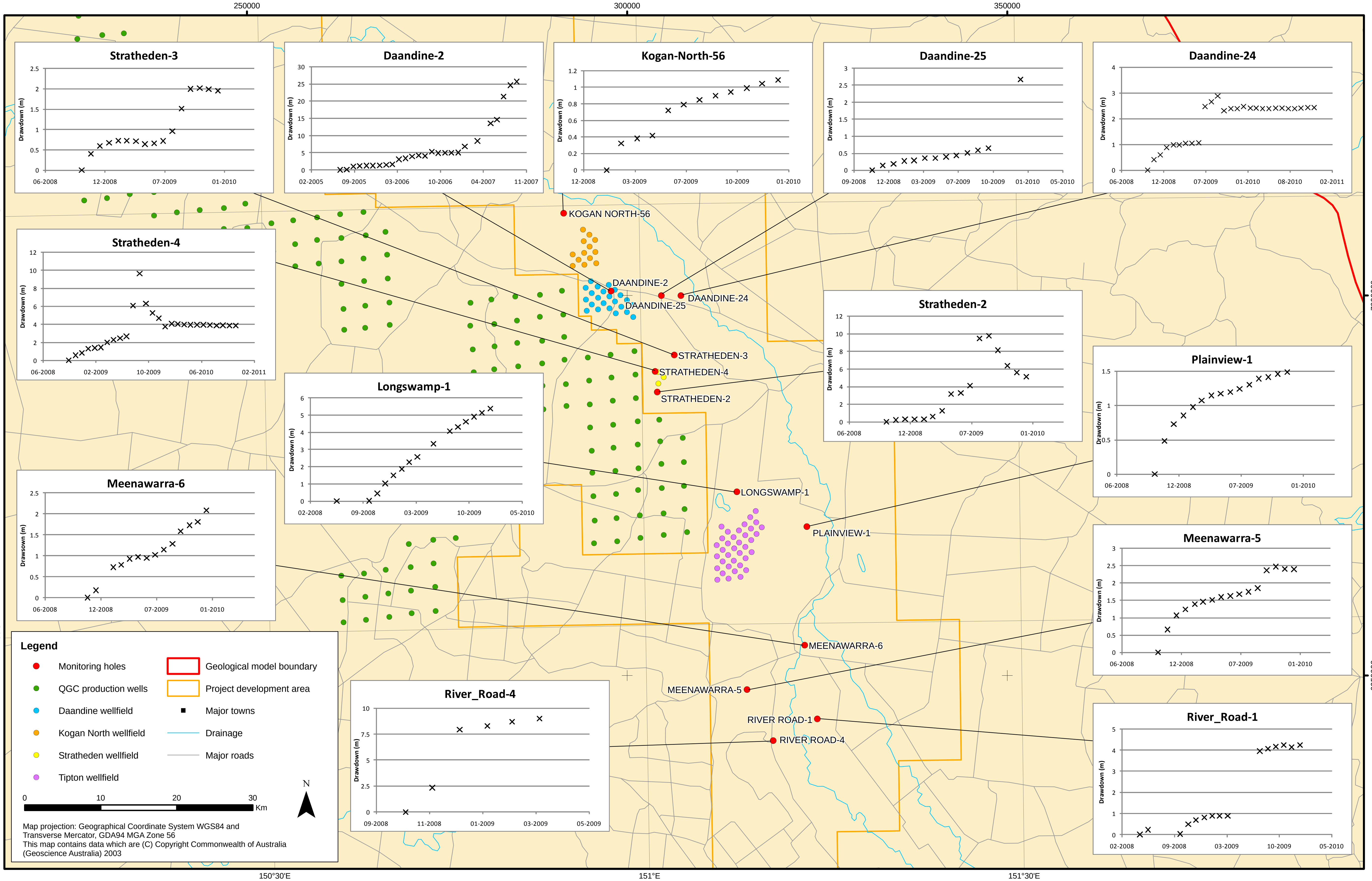
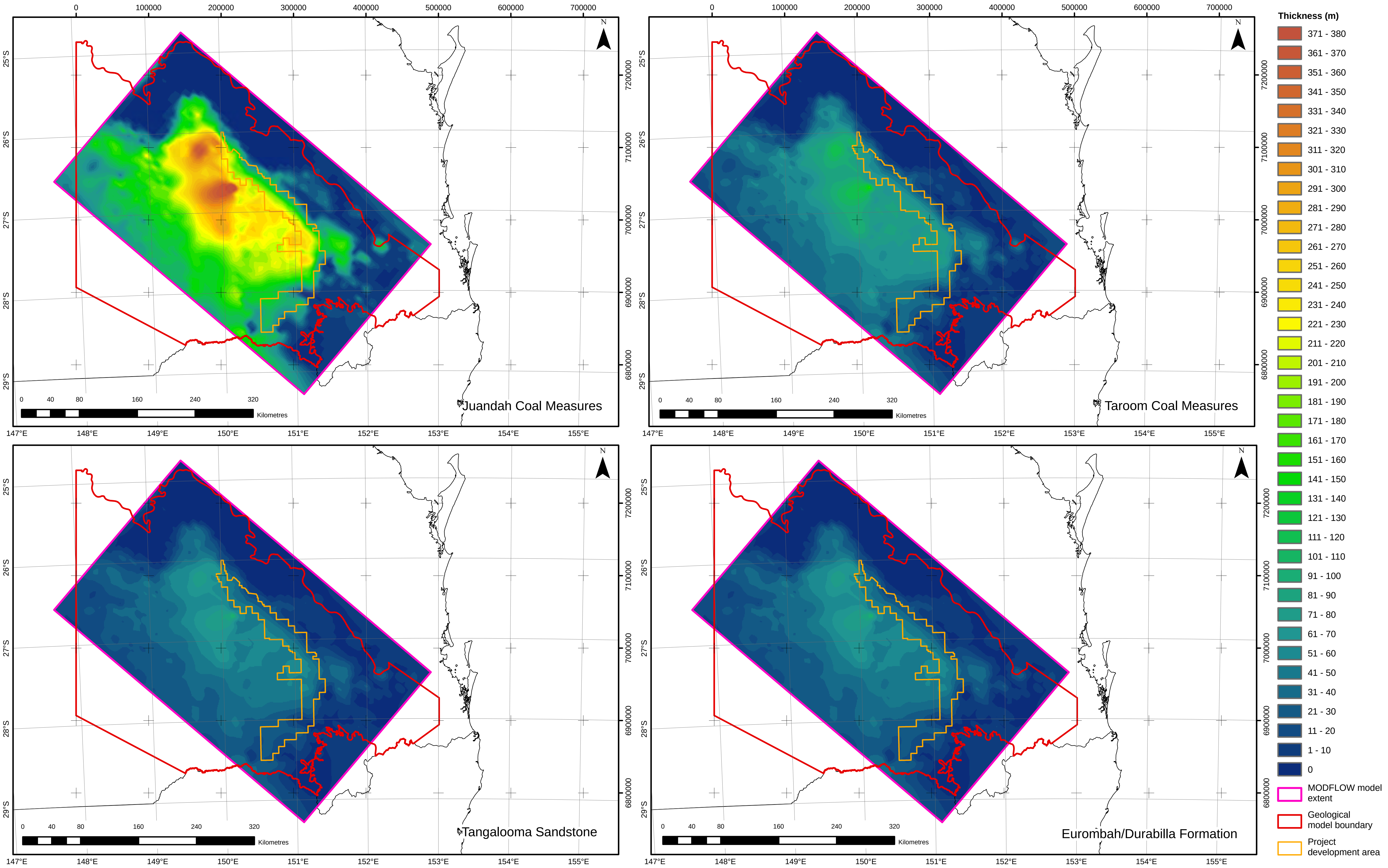


Figure 2.33 Thickness of Walloon Subgroup units used in the model



Map projection: Geographical Coordinate System WGS84 and Transverse Mercator, GDA94 MGA Zone 56

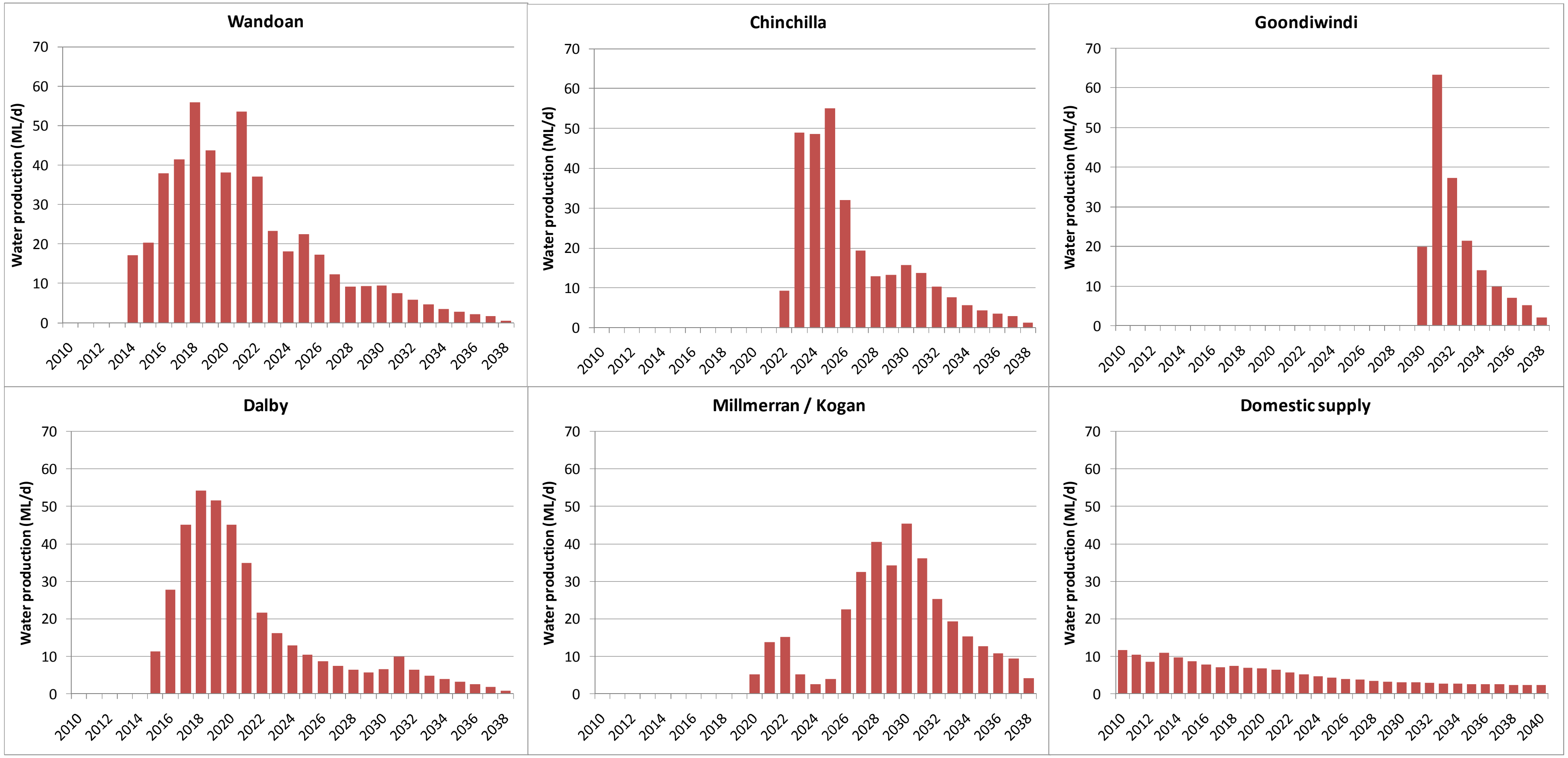
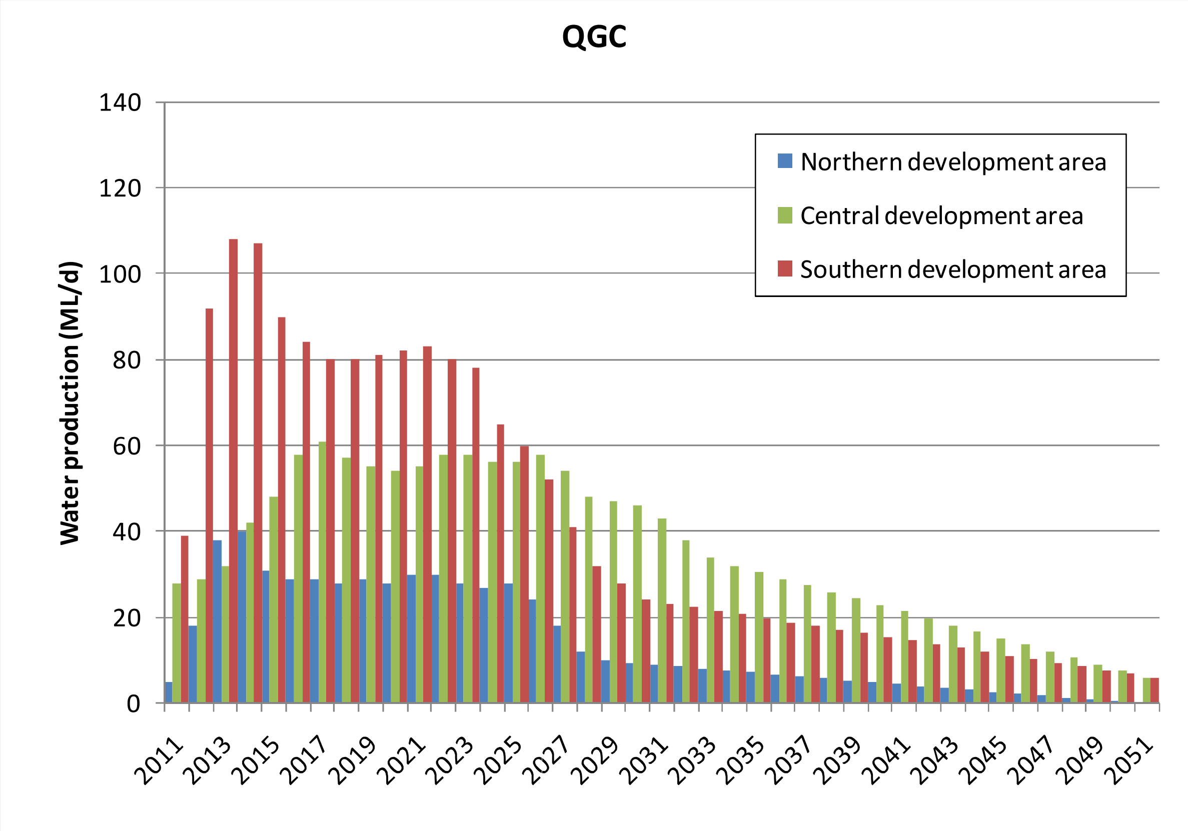
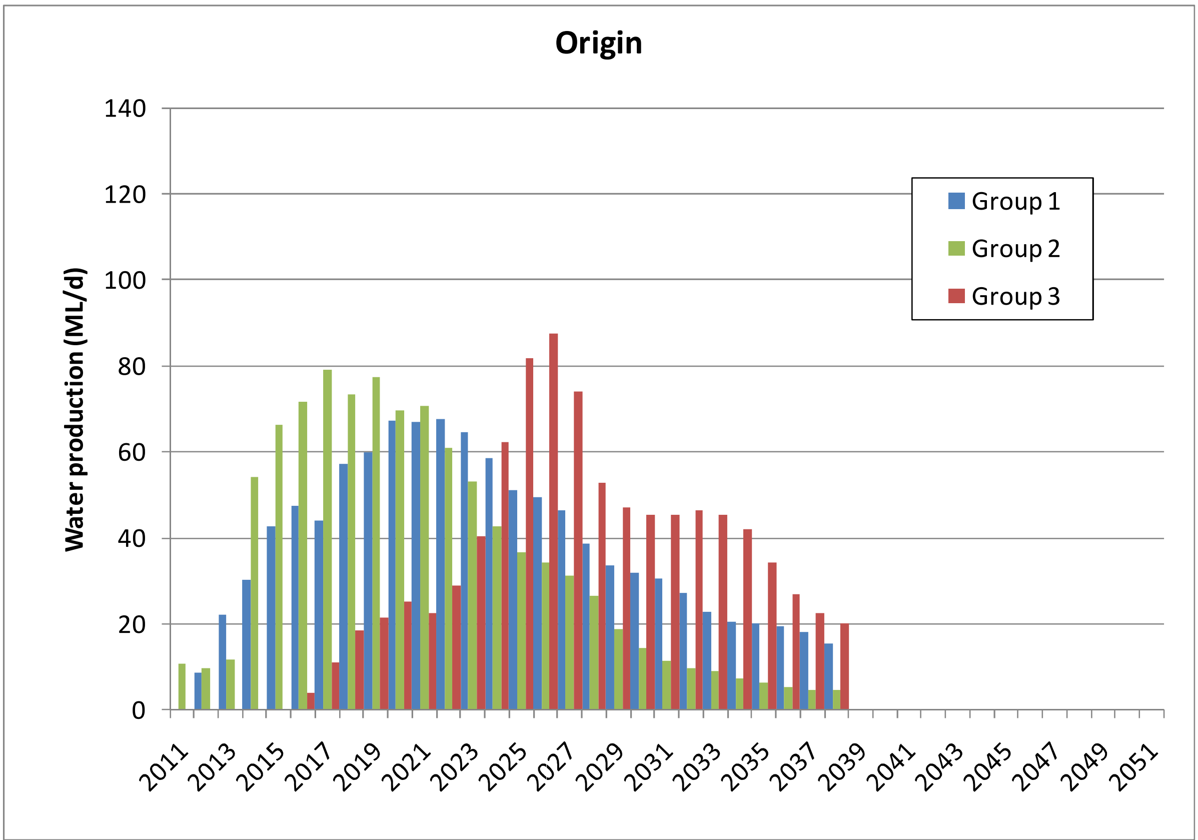


Figure 2.34. Arrow projected associated water production (by development area)

Figure 2.35 QGC and Origin projected associated water production (by development area)





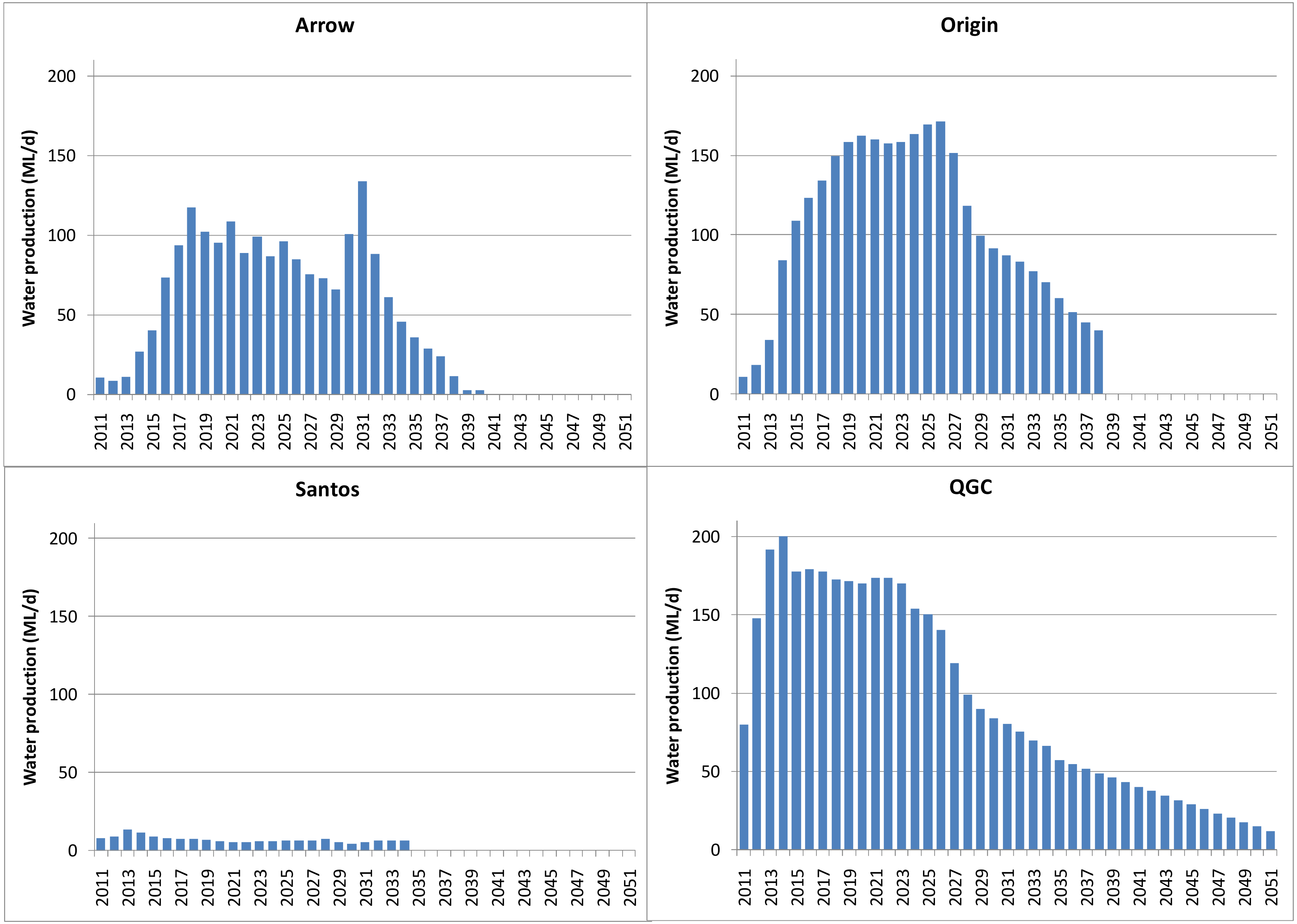


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Figure 2.36 Surat Basin CSG operators total projected associated water production

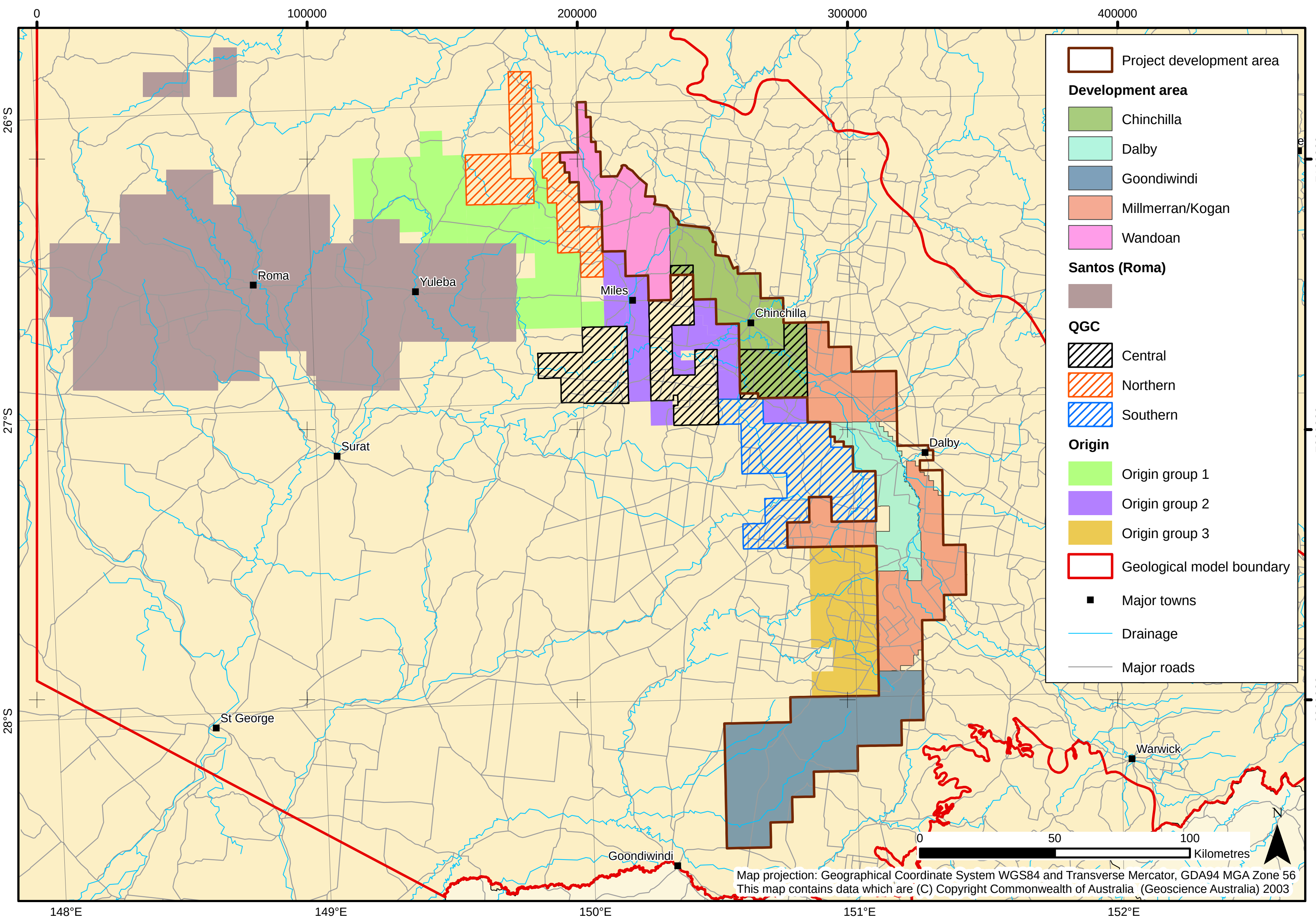

Figure 2.37 Surat Basin CSG operations

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3 NUMERICAL GROUNDWATER MODEL

3.1 Strategy overview

The numerical model is required to provide estimates of drawdown in response to the abstraction of groundwater associated with CSG activities in the Surat Basin. The design of the numerical model has been shaped by the following factors:

- The Surat Basin covers an area of roughly 400 by 300 km
- Impacts may be seen in the uppermost stratigraphy (e.g. the unconfined aquifers) to the deepest stratigraphy (greater than 2,000 m depth)
- Depending on the proximity to abstraction, predicted drawdown will likely range from over a hundred metres (within the coal seams) to less than a metre (in the unconfined units and at great depth)
- The vertical stratigraphic sequence of interest includes ten primary units, without taking into account the major members of the Walloon Subgroup
- Historical groundwater abstraction from these aquifers commenced in the 19th Century
- CSG related abstraction will occur via many thousands of wells
- An assessment of the sensitivity of predictions to key parameter values is required

The result is a highly detailed numerical model that explicitly represents the complex system of confining layers and aquifers within the Surat Basin, and that is calibrated to both regional scale data (throughout the Surat Basin) and local scale data (within the coal seams themselves).

3.2 Numerical code and software

The MODFLOW 2000 numerical code (Harbaugh et al, 2000) along with the user interface Groundwater Vistas, Version 5 (ESI, 2007) is used to simulate groundwater flow. MODFLOW is a widely adopted groundwater flow code and, through its flexibility and rapid set-up and run times, provides an appropriate basis for the simulation of abstraction of groundwater from the Walloon Subgroup.

The modelling has been undertaken assuming saturated, single phase, temperature independent and single density groundwater flow.

3.3 Model domain and discretisation

A rectangular model grid, rotated by 49.72 degrees (clockwise from north) to align with the Basin morphology, is adopted (Figure 3.1).

The model layers are provided by the geological model described in Section 2.2. To add refinement to the Walloon Subgroup this layer was divided into 5 individual layers as described in Section 2.4. The model therefore has 15 layers in total.

The specific model properties are detailed below:

- The model origin is at 314,653E, 6,759,641N (MGA Zone 56, GDA1994)
- The model extends 453 km to the NW and 270 km to the NE
- The model cell size 1,000 m by 1,000 m, (453 rows and 270 columns)
- Each model layer is composed of 122,310 cells, resulting in a total number of cells for the model of 1,834,650.

3.4 Layering

Table 3.1 correlates the model layers and stratigraphy. The extent, top and base of each layer has been sourced directly from the Petrel geological model. Figures 3.2 and 3.3 show the layering along two cross sections through the MODFLOW model. Due to requirements of MODFLOW (specifically that model layers are not allowed to be discontinuous) where geological model layers outcrop then disappear, they are continued in the MODFLOW model at a thickness of 1 metre and are assigned the parameters of the layer directly below them. Where the Springbok Sandstone outcrops for example, in the MODFLOW model it is overlain by model layers that in other areas represent the full thickness of the Westbourne Formation, Gubberamunda Sandstone, Orallo Formation, Mooga Sandstone, Lower Cretaceous Units and the Condamine Alluvium. To accommodate this situation all of these layers are assigned a thickness of 1 metre, and the properties of the Springbok Sandstone.

As previously noted, the Kumbarilla Beds do not represent a standalone unit within the Surat Basin, rather a collection of lithologies in a certain area. The Kumbarilla Beds are therefore not allocated a model layer of their own, but where the Springbok Sandstone, Westbourne Formation, Gubberamunda Sandstone, Orallo Formation and Mooga Sandstone cross into the area designated as Kumbarilla Beds, they are all allocated the Kumbarilla Bed hydraulic parameters (Figure 3.4).

All layers have been set as confined in the MODFLOW model, apart from the upper layer which is defined as unconfined. This has the following implications:

- Specific yield (Sy) is only used as a storage parameter in Layer 1 (the Condamine Alluvium). Only the Specific Storage (Ss) parameter is used in model Layers 2 to 15, even where they are, or become, unconfined
- Transmissivity (the product of Kh and saturated layer thickness) will vary with the position of the water table in Layer 1, but will not vary in the unconfined portions of the other units
- Unconfined portions of units other than the Condamine Alluvium are therefore not optimally represented. Drawdown in response to abstraction will be overestimated in these instances.

This approach ensures that the representation of the hydraulic system in the Condamine Alluvium is as close to the natural state as possible and that the representation of the underlying and adjacent systems remains conservative.

Table 3.1 MODFLOW model layers

Model Layer	Equivalent stratigraphy
Layer 1	Condamine Alluvium
Layer 2	Lower Cretaceous sequence
Layer 3	Mooga Sandstone
Layer 4	Orallo Formation
Layer 5	Gubberamunda Sandstone
Layer 6	Westbourne Formation
Layer 7	Springbok Sandstone
Layer 8	10 m thick shale
Layer 9	Juandah Coal Measures
Layer 10	Tangalooma Sandstone
Layer 11	Taroom Coal Measures
Layer 12	Durabilla / Eurombah Formation
Layer 13	Hutton Sandstone
Layer 14	Evergreen Formation
Layer 15	Precipice Sandstone

3.5 Boundary conditions

3.5.1 Abstraction

Introduction

All simulated abstractions are represented in the model using the MODFLOW "Multi-Node Well" (MNW) package (Halford and Hanson, 2002). This allows for the simulation of wells that are screened (or open) over multiple hydrogeological units, and assigns a proportion of the total abstraction to each unit based on the transmissivity of, and the calculated head in, the unit. This is relevant to the CSG wells as they are generally open through the Juandah, Tangalooma and Taroom layers of the numerical model.

There are no abstractions simulated in the steady state model.

Time variant historical

The methodology behind the location of the wells for each CSG producer is described below and the locations of the simulated wells are displayed in Figure 3.5:

- All historically active Arrow CSG abstraction bores have been included in the model. These include wells from the following fields; Daandine, Kogan North, Tipton and Stratheden.
- Queensland Gas Company (QGC) historical abstraction has been distributed across QGC Petroleum Lease (PL) blocks with representative wells spaced at 2.7 km intervals (actual locations are unknown and the interval was chosen to reduce the number of simulated wells to a manageable amount). Abstraction rates are divided into Central, Northern and Southern QGC development areas.
- Santos historical abstraction in the Roma Field is derived from coal seams within the Surat Basin. Actual well positions are not known, and, due to the large size of the field, representative wells have been located along a line roughly through the centre (coincident with the Warrego Highway). These wells are also spaced at 2.7 km intervals.

Abstraction associated with all CSG activities has been notionally allocated to the Juandah and Taroom Coal Measures and the Tangalooma Sandstone between them.

Monthly abstraction volumes were provided by Coffey for the Arrow historical operations and these have been averaged into six monthly periods (either 182 or 183 days) for inclusion in the model, apart from the first (151 days) and last (214 days).

3.5.2 Boundary fluxes

Constant Heads (steady state, time variant historical)

Constant head boundary conditions were set based upon the pre 1995 steady state water level contour data and the conceptual understanding of the Surat Basin. All boundaries are active throughout the steady state and time variant models. Constant head boundaries were applied in the following 3 areas (Figure 3.6):

- Western border (discharge). Constant heads were applied to the entire length of the western border in model Layers 2 to 15. The heads are variable along the border and the gradient is based on the contoured steady state groundwater level in the Gubberamunda Sandstone.
- Southeast border (discharge). A constant head of 120 mAHD is applied to model Layers 9 to 15 to represent discharge to the adjacent watershed. Constant heads were not applied when the bottom of the cell was higher than 120 mAHD.
- Northeast border (discharge). A constant head of 200 mAHD was assigned to Layer 15 to represent discharge towards the lower elevations to the northeast of the model.

Drain cells (steady state, time variant historical)

Drain cells have been used to provide a mechanism to control the water table surface, especially in the steady state model (Figure 3.6). They have been assigned to model Layer 1 for all the major surface drainages. Drain elevation equates to the topographic level minus 1 metre (to represent a nominal base of the drainage channel). Conductance was initially defined based on cell size, conductivity and estimated drainage area, but was refined during calibration to 100 m^2/day. These drain cells are active in all model variants.

Rainfall recharge (steady state, time variant historical)

A typical range of recharge between 0 – 3 mm/yr is reported in the Surat Basin by Kellett et al. (2003). Rates of 10 mm/yr are reported in localised areas, however, for the purposes of steady state calibration a rate of 1 mm/yr is considered to be consistent and representative of the intake beds of the Surat Basin. The recharge boundary condition was used in the model and applied to the uppermost active layer. A blanket rate of 1 mm/yr was used and assigned only to areas of outcrop for aquifers. Where confining layers (e.g. Westbourne Formation and Evergreen Formation) outcrop at surface, no recharge was applied.

To achieve a better calibration, an enhanced zone of recharge (5 mm/yr) was applied to the footprint of the Main Range Volcanics. The Main Range Volcanics are reported to have a high recharge rate and it is considered that conceptually this unit would provide an element of subsurface leakage to the Hutton and Walloon Coal Measures where it overlies them. Therefore this greater recharge rate has been applied to account for this.

Recharge is applied to the highest active layer in the model. Therefore, in areas of Layer 1 that are “dry” (and therefore inactive), the recharge is applied to the layer beneath.

The calibrated recharge distribution is illustrated in Figure 3.7. The recharge distribution and rates are unchanged for all the model variants.

3.6 Simulation period and time stepping

Two model variants were required for calibration; a steady state and a time variant historical. Together these models allow for the simulation of historical conditions.

The steady state model has no time component.

The time variant historical model runs from the 1st June 2005 to 1st January 2011. This period is split into 11 stress periods. The length of the stress periods is based on the division of historical CSG abstraction into 6 monthly averages. The first and last stress periods, however, are shorter (151 days) and longer (214 days) respectively. The first 10 stress periods are divided into 36 time steps of equal length (time step multiplier of 1) and the last into 40 (again of equal length).

The steady state model groundwater levels are used as the initial groundwater levels in the time variant historical model.

3.7 Solver parameters

The Preconditioned Conjugate-Gradient (PCG2) package was used to solve the finite difference equations in MODFLOW. The settings are defined in Table 3.2.

Table 3.2 PCG solver settings

Parameter	**Value**
Maximum outer iterations	10,000
Maximum inner iterations	2,000
Head change criteria	0.01 (m)
Residual criterion for convergence	0.2 (m^3/d)
Relaxation parameter	1
Damping factor	1 (no damping)

3.8 Calibration

3.8.1 Methodology

Calibration of the numerical model was undertaken by manually varying parameters (within the ranges quoted in Table 2.7) in order to improve the match between simulated and observed groundwater levels. The focus of the calibration in the steady state and time variant models is distinct and each is described below:

- The steady state calibration will be most sensitive to the recharge rates and the K of the upper layers and layers at outcrop. The boundary conditions (constant heads and drains cells) will provide outflow and will control the regional gradients. Storage parameters do not contribute to the steady state flow equations and, therefore, do not influence the calibration. Hydraulic conductivity was varied within the ranges described in Section 2.5.3 to provide the best fit between observed and simulated heads at the monitoring points and the best fit to the regional gradients. As noted in Section 3.5.2, recharge was also varied during this process. The constant heads were set based on the contouring of observed historical groundwater levels, and were not adjusted further during calibration.

- The time variant calibration was focussed on the Walloon Subgroup where abstraction from the Arrow CSG operations has been monitored and groundwater level observations are available. Boundary conditions were not varied, but K and storage parameters were (where possible within the ranges described in Section 2.5.3). Any changes to K required the re-running of the steady state model to provide the correct initial conditions for the time variant model.

The predicted groundwater levels and the relevant calibration statistics from the steady state and time variant calibration models are described below. The calibrated parameter values are also presented.

3.8.2 Mass Balance

The mass balance for the steady state model is provided in Table 3.3. This shows that about 75% of the water entering the model as rainfall recharge discharges from the system via the drain cells in Layer 1 of the model. The remaining 25% discharges via the constant heads set around the boundary of the model. The mass balance error is less than 0.001%.

Figure 3.8 displays the steady state mass balance for each model layer, including the boundary condition flows and the flows between adjacent layers. These graphs show that the Hutton Sandstone, Juandah Coal Measures and Kumbarilla Beds receive the majority of recharge (61 ML/d, 56 ML/d and 39 ML/d respectively). The Hutton Sandstone also receives the majority of inflow from constant head boundary conditions (0.5 ML/d), although the volume is significantly less than the other flow components. Flow out of the model via constant heads is far more significant and the majority of this occurs from the Precipice Sandstone (30 ML/d).

Flow out of the model via drain boundary conditions is most significant from the Hutton Sandstone (42 ML/d), Juandah Coal Measures (31 ML/d), Kumbarilla Beds (27 ML/d) and Condamine Alluvium (26 ML/d). It is important to note however that this boundary condition provides a gross simplification of stream flows and the interaction between streams and groundwater. Additionally, drain cells (streams) that are simulated within the non alluvial systems are further simplified as they are, in reality, unlikely to be connected directly to these hydrostratigraphic units as they are overlain by younger Cainozoic sediments (which are not included in the model).

Flow into the Condamine Alluvium is roughly equal from recharge (14 ML/d) and from inflow from adjacent layers (10 ML/d from the Juandah Coal Measures and 2 ML/d from the Kumbarilla Beds). Total inflow to the Condamine is, therefore, about 26 ML/d in the steady state model.

The time variant mass balance for the historical model is displayed in Figure 3.9. The graph shows that the main inputs and outputs of water to the model remain constant through the simulation period. These are recharge, constant head inflow and drain outflow. The graph also shows how flow out of the model via abstraction wells ("MNW out") increases gradually through the simulation period and forms a major component of the water balance by the end of the simulation.

Analysis of the performance of the model MNW wells reveals that the division between the amount of water abstracted from the Juandah vs Taroom Coal Measures is about 63 : 37. This is in line with their relative thicknesses (75% : 25%). Virtually no water is taken from the Tangalooma Sandstone due to the low transmissivity (a function of K and saturated thickness) of this unit in the model.

3.8.3 Pre-1995 (steady state)

Scatter plots of the observed and simulated groundwater levels used in the steady state calibration are provided in Figures 3.10 and 3.11. These show that in general and in all layers of the model, where observed heads are greater than approximately 380 mAHD, the steady state model underestimates the observed levels. However, observations below 380 mAHD tend to be replicated more accurately by the model and this is the range in the areas where the Surat Gas Project is located and which is, therefore, the main focus of the modelling. The plots also display several observations which are notably higher or lower than others in the vicinity and are, therefore, probably erroneous or unrepresentative of the stratigraphy. This occurs frequently in data assigned to Layers 13, 14 and 15 (the Hutton and Precipice Sandstones and the Evergreen Formation).

Figures 3.12 to 3.19 display the calibrated steady state groundwater levels by stratigraphic unit. These show a general agreement with the contours of interpolated observed water levels described in Section 2.3.2.

Statistical analysis of the "performance" of the steady state calibration has been undertaken using methods summarised by Middlemis (2000) which considers the Root Mean Square (RMS) and SRMS (Scaled RMS). These were derived using the formulas below (where h and H are the simulated and observed groundwater elevations respectively) using the Microsoft Excel software.

$$RMS = \sqrt{\frac{1}{n}\sum\left[Wi(hi - Hi)\right]^{2}}$$

$$SRMS = \frac{100.RMS}{\Delta H}$$

The RMS and SRMS for the calibrated steady state model are 43.7 m and 6.8% respectively. Given the exploratory nature of the modelling exercise, the scale of the model and the uncertainties associated with the calibration data, this is considered to be an acceptable result in terms of this calibration performance measure.

Table 3.3 Steady state mass balance

	Constant Head	Drains	Recharge	Total
		ML/d		
In	1.6	0	199.5	201.1
Out	51.6	149.5	0	201.1

3.8.4 1995-2009 (time variant historical)

Figure 3.20 displays the observed and simulated hydrographs at the 13 Arrow monitoring locations. The initial observation of drawdown has been adjusted to match the simulated value at the same time. Whilst the two would not necessarily match, this acknowledges the fact that drawdown may well have occurred prior to the first reading at the monitoring bore, and allows for a more relevant comparison of observed and simulated drawdown at each location.

The figures show that observed drawdown is simulated very well by the model at the following bores:

- Kogan North 56. About 1 metre of drawdown, originating from the Kogan North wellfield, is observed and simulated at this location. The model suggests that the actual drawdown at this location, from the commencement of CSG production to the 1st January 2011, is in the order of 4.5 metres.
- Daandine 2, Daandine 24 and Daandine 25. Daandine 2 is in the centre of the Daandine wellfield and returns the greatest observed (about 25 m) and simulated drawdown. Daandine 24 is located furthest from the wellfield but returns a higher drawdown (3 metres) than Daandine 25. The model shows, however, that the total historical drawdown from CSG production at Daandine 24 is likely to be about 8 metres, but at Daandine 25, it is likely to be about 12 metres.
- Stratheden 3. This monitoring bore is located just to the north of the Stratheden wellfield and records about 1.5 metres of drawdown (over 1 year). The model does not simulate the fine detail particularly well over this period (possibly due to the 6 month time step) but does reproduce the gross value. It also suggests that up to 6 metres of drawdown may have been produced at this location over the full life of this wellfield.
- Longswamp 1. This monitoring hole is located a few kilometres to the north of the Tipton wellfield and records about 5 metres of drawdown between October 2008 and January 2010. The model slightly over predicts drawdown over this period, but does suggest that up to 25 metres of drawdown may have been experienced here over the life of the Tipton wellfield.
- Meenawarra 5 and Meenawarra 6. These holes are located 10 to 15 kilometres to the south of the Tipton wellfield. Considering this distance, both holes record a significant amount of drawdown (1.5 and 3.0 metres respectively). In both cases the model replicates this well.

The observed drawdown at Stratheden 2 and 4 is simulated accurately between October 2008 and July 2009. Roughly 4 metres of drawdown is observed at both locations during this time. From July 2009 to January 2010, both locations also observe an additional and rapid increase of drawdown in the order of 6 metres, and a similarly rapid recovery of about 5 metres. This response is not simulated by the model.

Drawdown at Plainview 1 (to the east of the Tipton wellfield) is overpredicted by the model. Observed drawdown between October 2008 and January 2010 amounts to about 2 metres, but the model returns about 6 metres.

Drawdown at River Road 1 and River Road 4 (about 20 km to the south of the Tipton wellfield) is underpredicted by the model. The observed drawdown is about 4 metres and 9 metres respectively at these locations. Due to their distance from the wellfields the predicted drawdown is significantly lower than this and only begins to increase above 0.5 m at the end of the historical simulation (December 2010). It is unlikely that the drawdown observed at these locations is derived from associated water abstraction further north (which would suggest a much higher transmissivity and connectivity of the coal seams than currently simulated). It is probably the case that the drawdown has been generated from an abstraction local to these holes, such as a CSG pilot test. As this data has not been incorporated into the model, the observed drawdown cannot be reproduced.

The discrepancy between observed and simulated drawdown at Stratheden 2, Stratheden 4 and Plainview 1 could be derived from any one of, or a combination of, the following factors:

- Abstraction data has been assigned evenly between the wells for each wellfield. This averaging means that very local system responses caused by variations in abstraction at individual wells will not be reproduced.
- Abstraction data has been averaged to 6 monthly periods. This means that system responses to variations in abstraction occurring at shorter time intervals will not be simulated by the model.
- The hydraulic parameter distribution for all layers is homogeneous throughout their extent. This is justified given the amount of (time variant) calibration data available, but is unlikely to be valid throughout the model and at particularly local scales. Hydraulic boundaries may also be present at a local scale but have not been investigated (by hydraulic testing) at this stage.
- There is significant variation in the completion of the boreholes. Unless they are open to the full extent of only, or all of, the Juandah, Tangalooma and Juandah units, they have been completed to a finer scale (in terms of vertical sequence) than the model layering can match.

Given the constraints mentioned above, the calibration to the time variant Arrow groundwater monitoring data is very good. Furthermore there are no obvious differences in either simulated or observed responses to abstraction in holes open to the Juandah Coal Measures only, or those open throughout the Walloons. This suggests that the bulk hydraulic parameters assigned to the Juandah and Taroom Coal Measures and the method of representation of associated water abstraction are suitable for the purposes of this modelling study.

The successful calibration of the model to this observational dataset supports the chosen representation of the coal measures (thickness and parameters) and the representation of CSG abstraction wells using the MNW package.

The RMS and SRMS for the calibrated time variant model are 2.3 m and 8.8% respectively. Whilst the SRMS is higher than the steady state equivalent, this should not be taken to indicate a limitation in the time variant calibration. On the contrary, the discussion above has shown that the calibration is more than adequate in this regard.

3.8.5 Calibrated model parameters

The combination of hydraulic parameters that produce the calibration discussed above are shown in Table 3.4. These values form the "calibration basecase" for use in the predictive modelling. As discussed above, calibration effort was focussed on the key Walloon sub-divisions. As a result, only the K and storage of the Juandah Coal Measures, Tangalooma Sandstone and Taroom Coal Measures were changed from the initial values described in Section 2.5.3, and only these can be considered calibrated.

The Kh of the Juandah and Taroom Coal Measures was changed to 0.05 m/d and the specific storage to 1×10^{-6} m^{-1}. The Kv assigned to these units was also modified (reduced to $1\text{x}10^{-5}$ m/d). This means that the Kv/Kh ratio in those units is now 1:5000, significantly lower than the initial setting, but considered plausible given the numerous layers of low vertical permeability material separating the coal seams (layered heterogeneity) and the anisotropy caused by the coal seam cleats. In addition the K value assigned to the Tangalooma Sandstone was decreased significantly ($1\text{x}10^{-4}$ m/d, Kv/Kh 1:1). These adjustments resulted in a greater simulated extent and magnitude of drawdown (i.e. closer to the observed behaviour) in the Juandah and Taroom Coal Measures than was achieved with the initial values.

The K in the Condamine Alluvium was refined to align it as closely as possible to the calibrated CSIRO model (Barnett and Muller, 2008). This involved lowering the Kv to 0.001 m/d in a zone to the south and setting the remaining areas to 0.5 m/d. The adopted parameters elsewhere in the Condamine are broadly in line with the CSIRO model.

Table 3.4 Parameters used in the calibrated groundwater model

Unit	Kh (m/d)	Kv (m/d)	Ss (m^{-1}) (unless otherwise stated)
Condamine Alluvium	5	0.5 and 0.001	5%*
Lower Cretaceous units	0.001	0.00001	5×10^{-6}
Mooga	0.5	0.05	5×10^{-6}
Orallo (and Kumbarilla Beds)	0.1	0.002	5×10^{-6}
Gubberamunda	0.5	0.05	5×10^{-6}
Westbourne	0.001	0.00001	5×10^{-6}
Springbok	0.5	0.05	5×10^{-6}
10 m thick shale	0.05	0.001	5×10^{-6}
Juandah	0.05	0.00001	1×10^{-6}
Tangalooma	0.0001	0.0001	5×10^{-6}
Taroom	0.05	0.00001	1×10^{-6}
Durabilla / Eurombah	0.05	0.001	5×10^{-6}
Hutton	0.1	0.002	5×10^{-6}
Evergreen	0.001	0.00001	5×10^{-6}
Precipice	1	0.1	5×10^{-6}

* Specific yield

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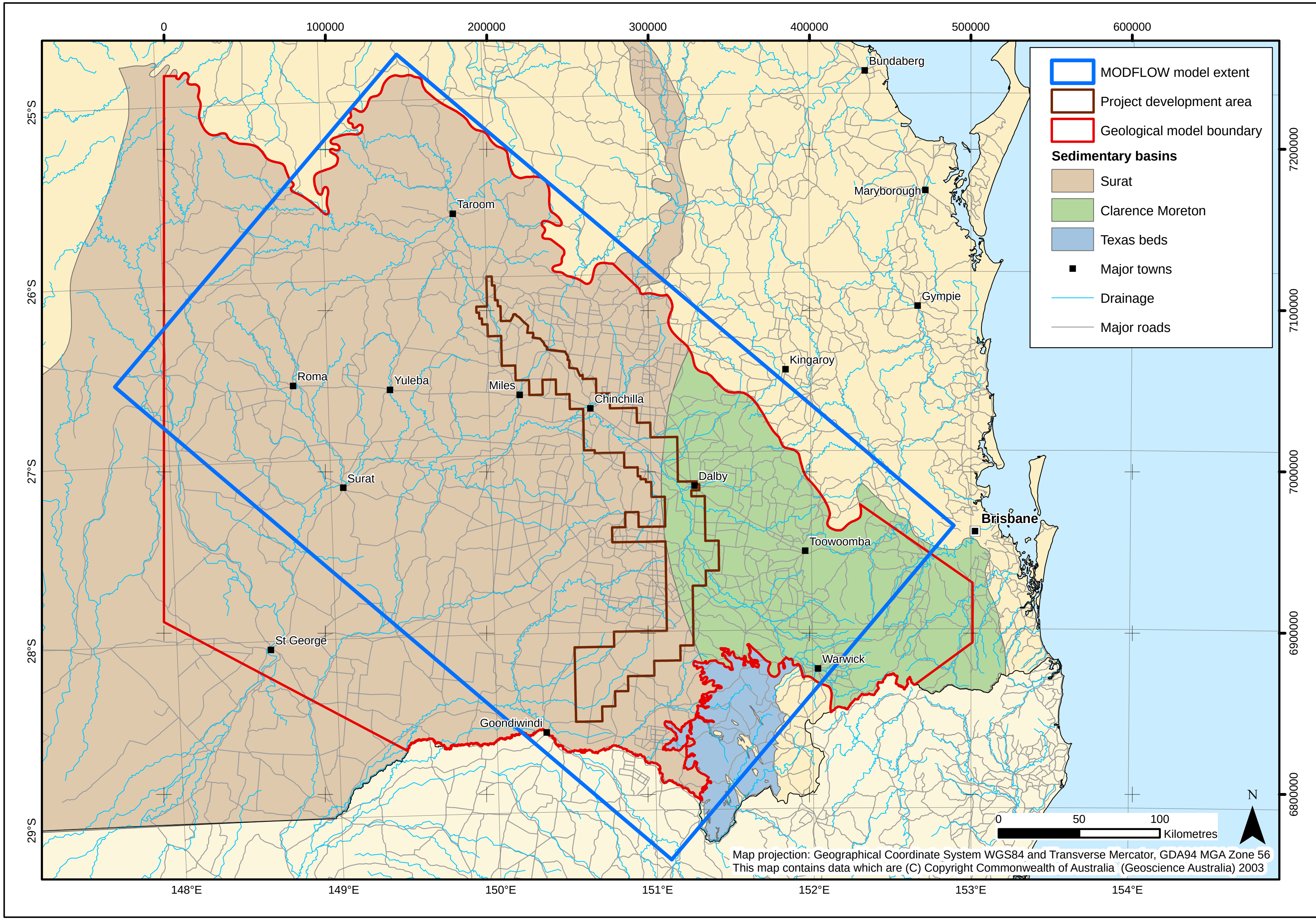

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Figure 3.1 MODFLOW model extent

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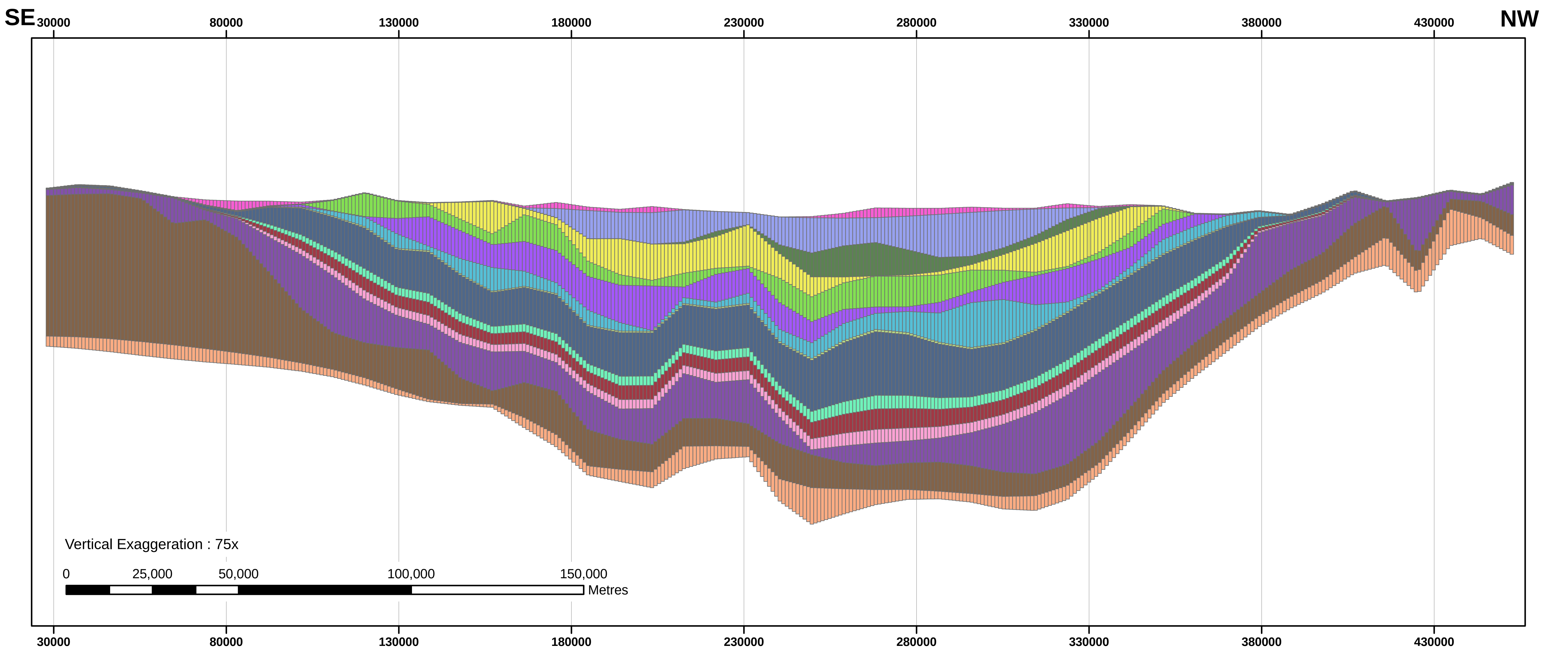
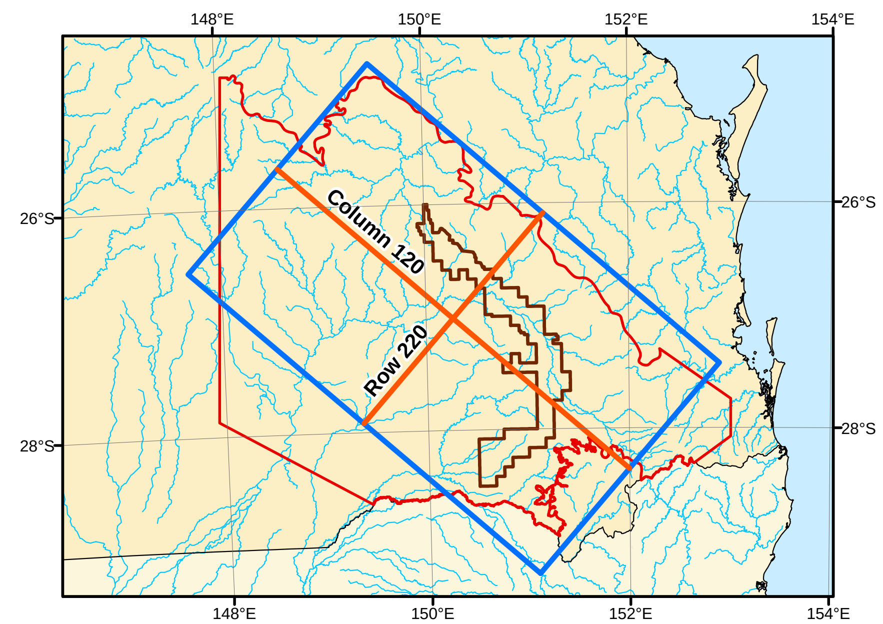
Figure 3.2 Model cross section (column 120)





- Condamine River Alluvium
- Lower Cretaceous sequence
- Mooga Sandstone
- Orallo Formation
- Gubberamunda Sandstone
- Westbourne Formation
- Springbok Sandstone
- 10 m thick shale
- Juandah Coal Measures
- Tangalooma Sandstone
- Taroom Coal Measures
- Durabilla / Eurombah Formation
- Hutton Sandstone
- Evergreen Formation
- Precipice Sandstone
- Cross sections location
- MODFLOW model extent
- Project development area
- Geological model boundary
- Drainage

Map projection: Geographical Coordinate System WGS84

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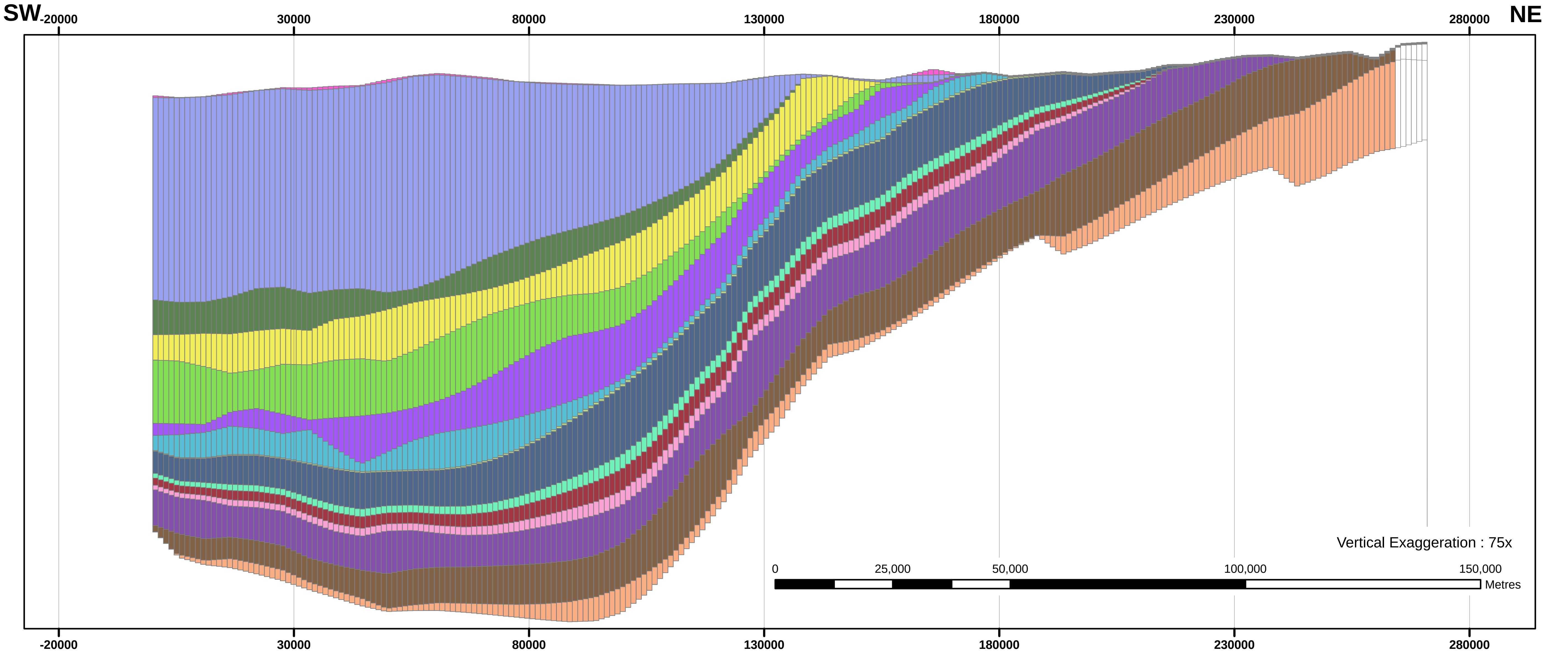
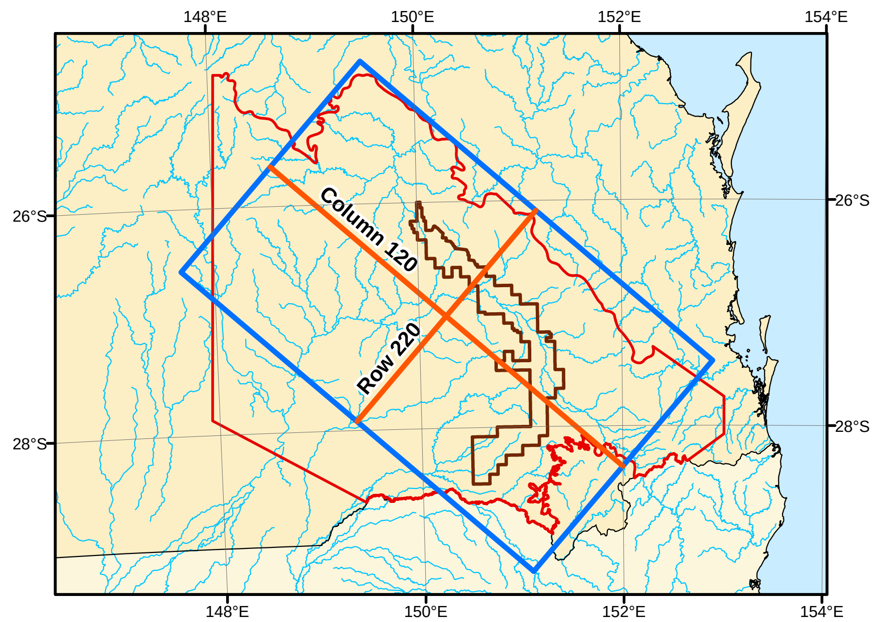
Figure 3.3 Model cross section (row 220)





Inactive cells	10 m thick shale
Condamine River Alluvium	Juandah Coal Measures
Lower Cretaceous sequence	Tangalooma Sandstone
Mooga Sandstone	Taroom Coal Measures
Orallo Formation	Durabilla / Eurombah Formation
Gubberamunda Sandstone	Hutton Sandstone
Westbourne Formation	Evergreen Formation
Springbok Sandstone	Precipice Sandstone

- Cross sections location
- MODFLOW model extent
- Project development area
- Geological model boundary
- Drainage

Map projection: Geographical Coordinate System WGS84

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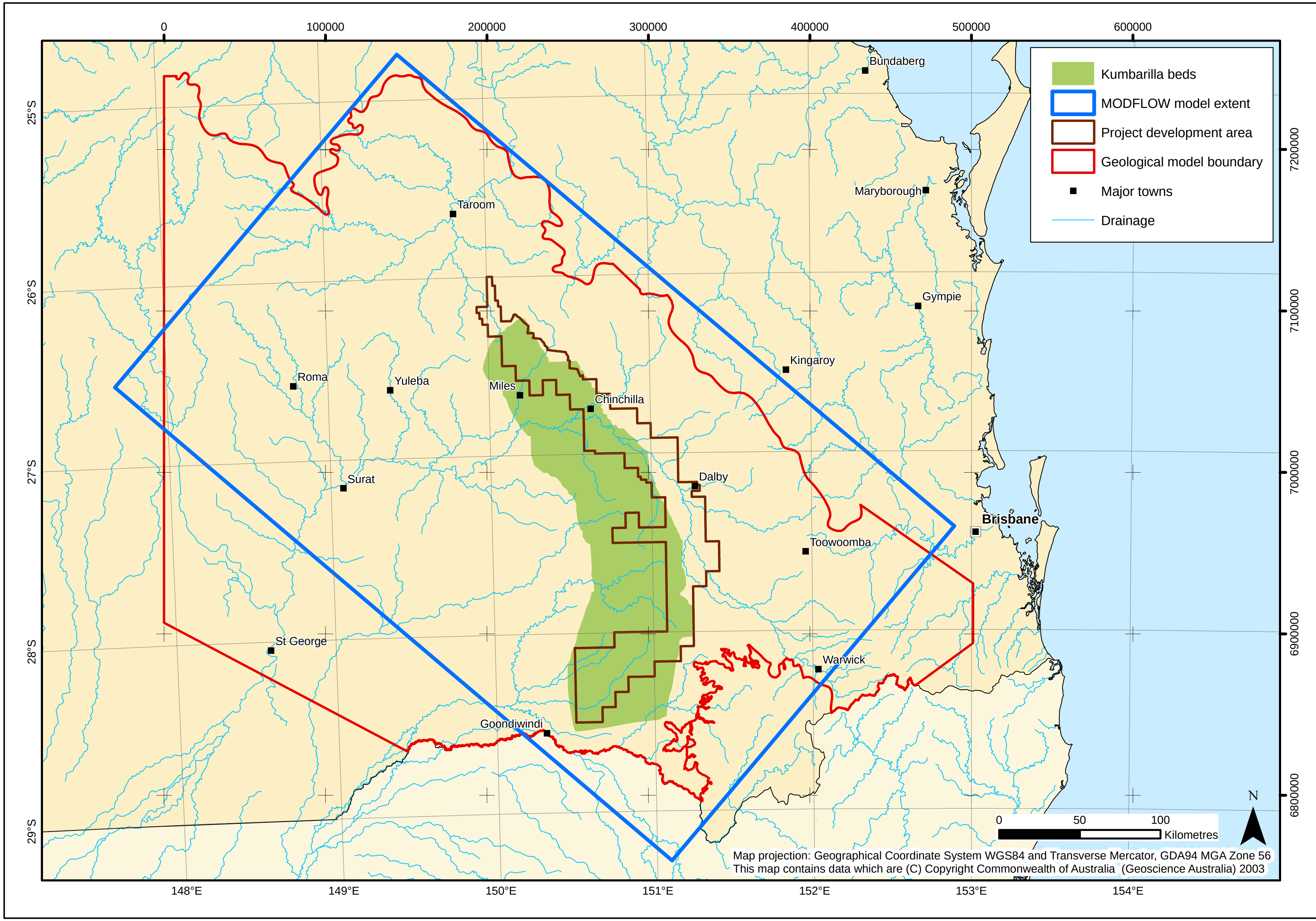

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Figure 3.4 Modelled extent of the Kumbarilla Beds

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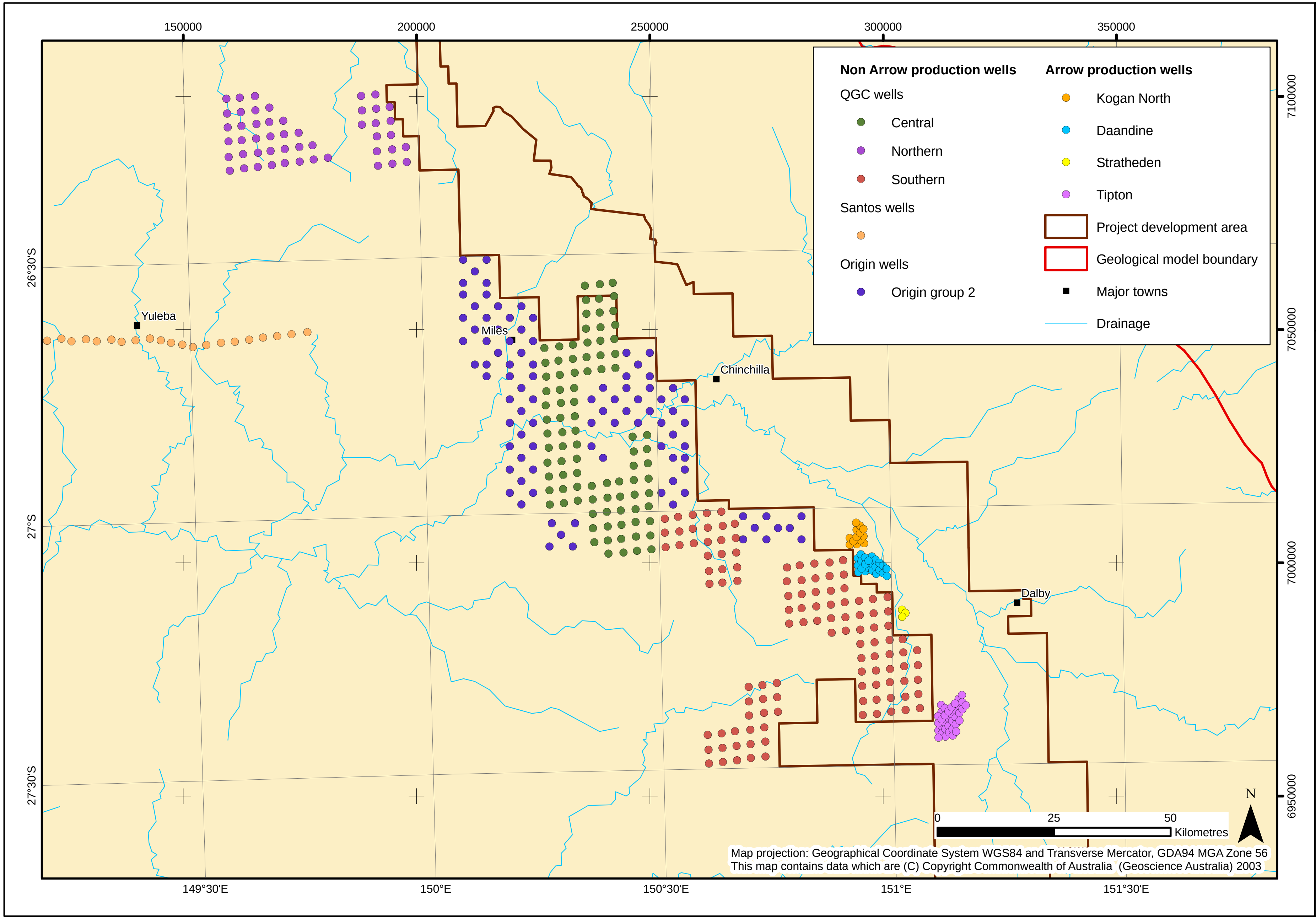

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Figure 3.5 Simulated CSG production wells (time variant historical model)

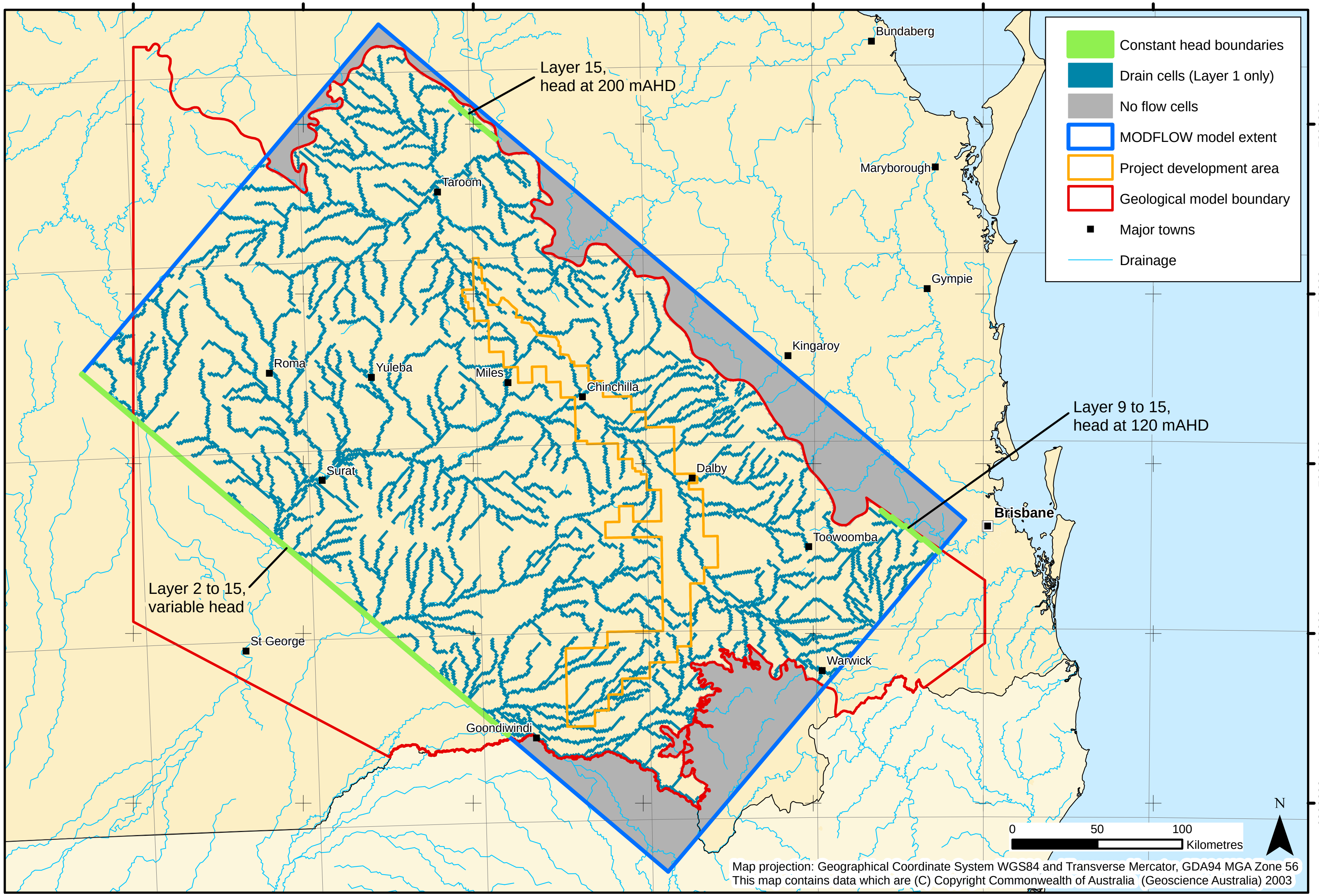

Figure 3.6 Model boundary conditions

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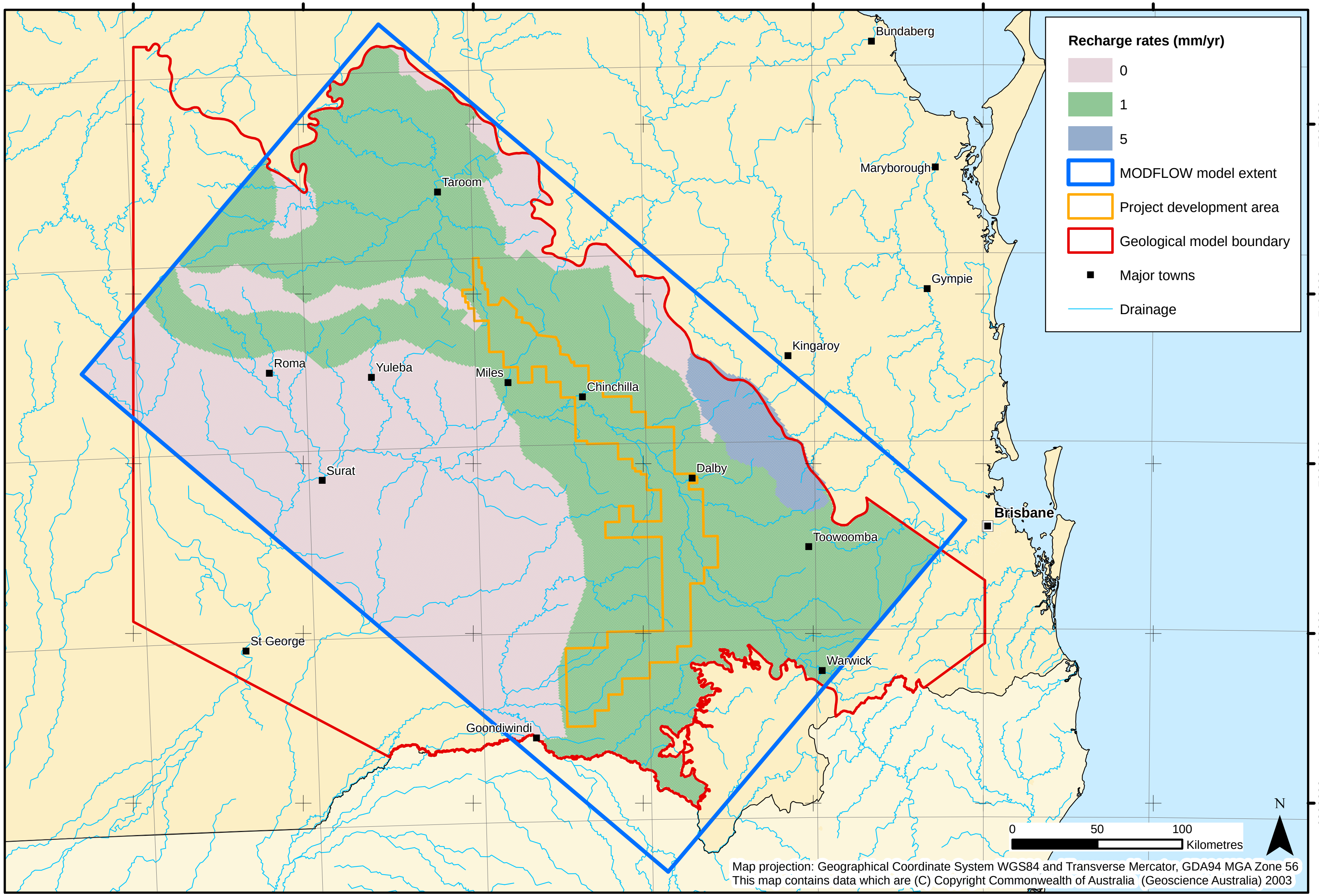

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Figure 3.7 Calibrated model recharge distribution and rates

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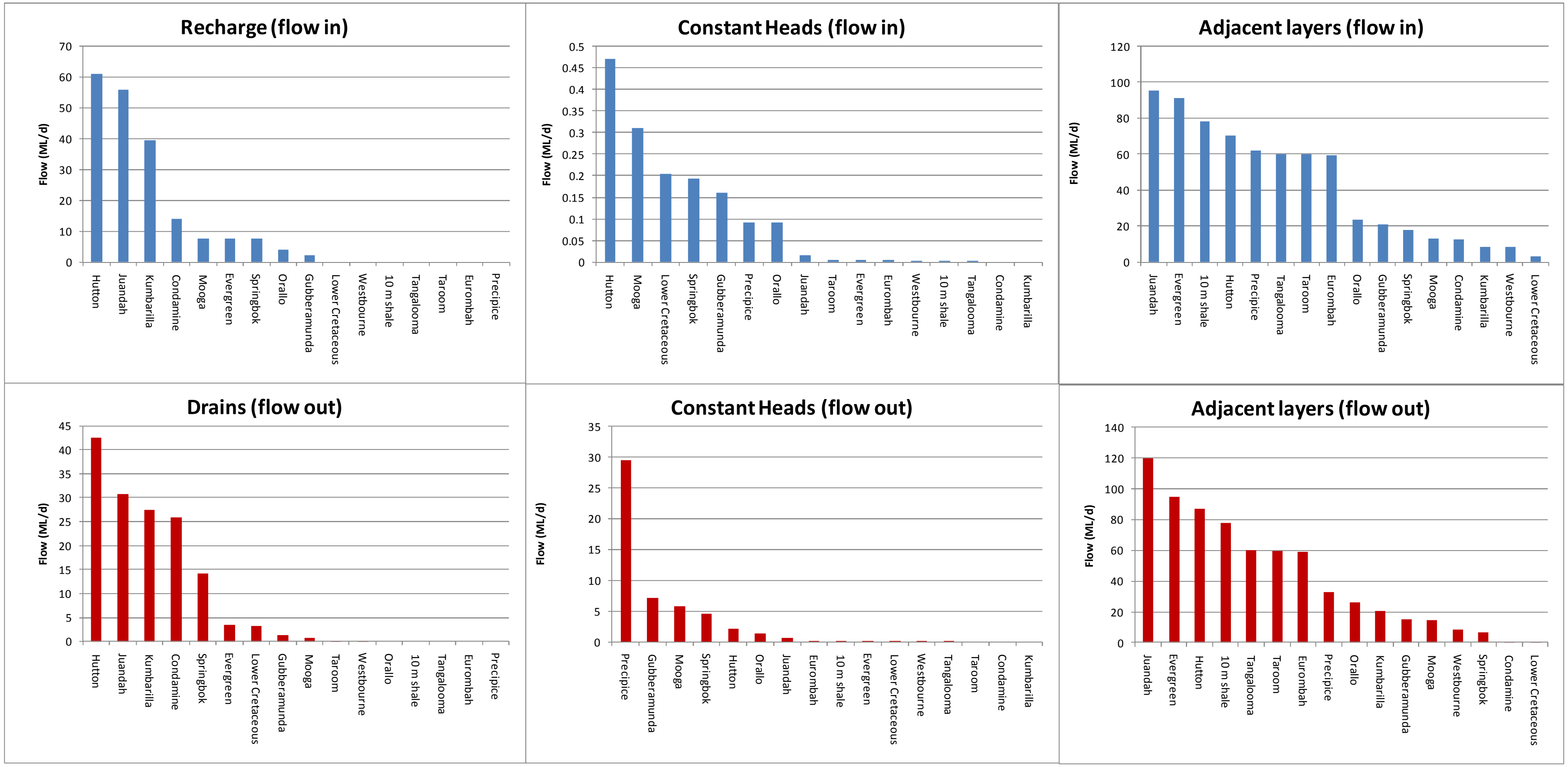

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Figure 3.8 Calibrated steady state model mass balance (by model layer)

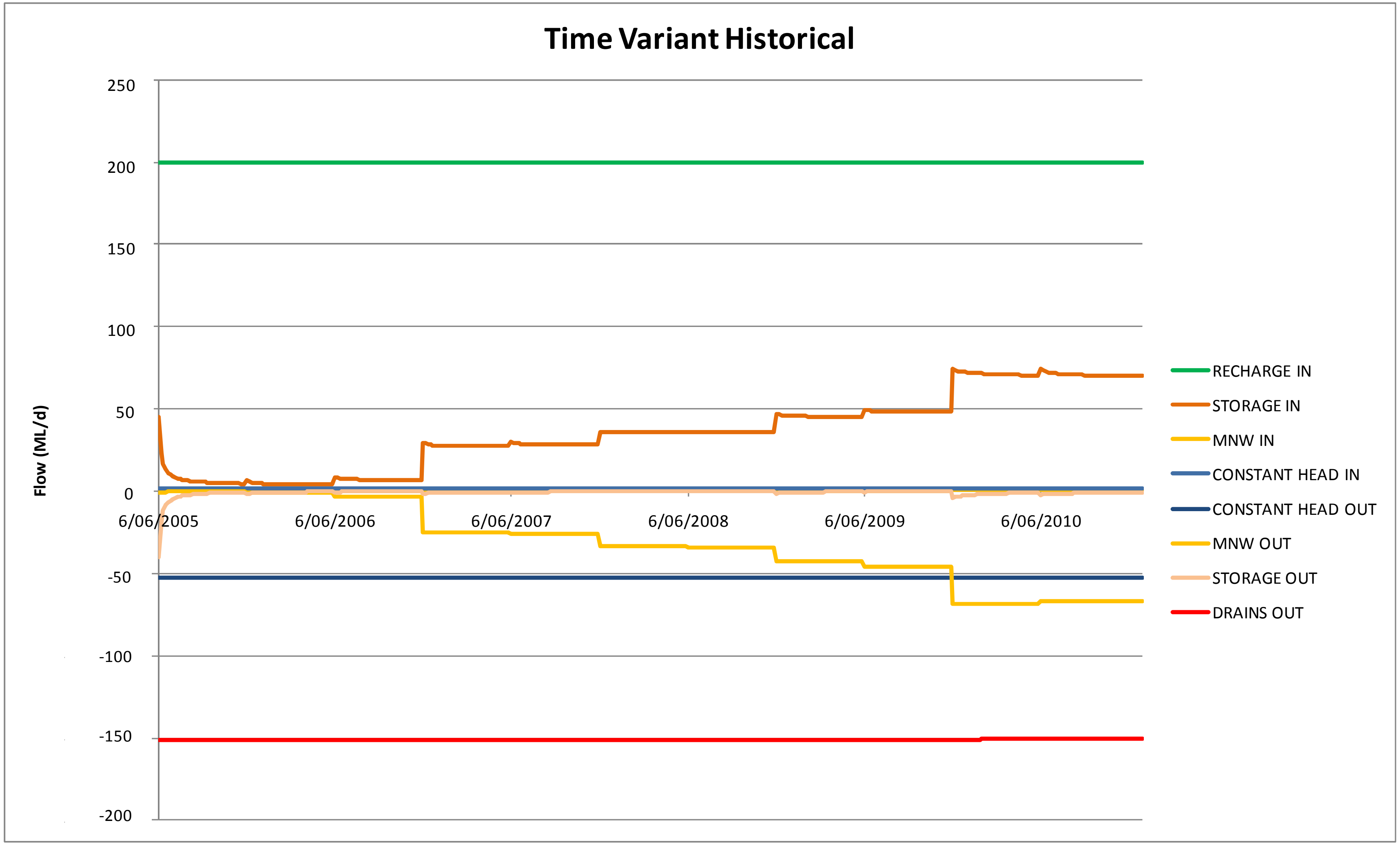

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Figure 3.9 Calibrated time variant historical model mass balance

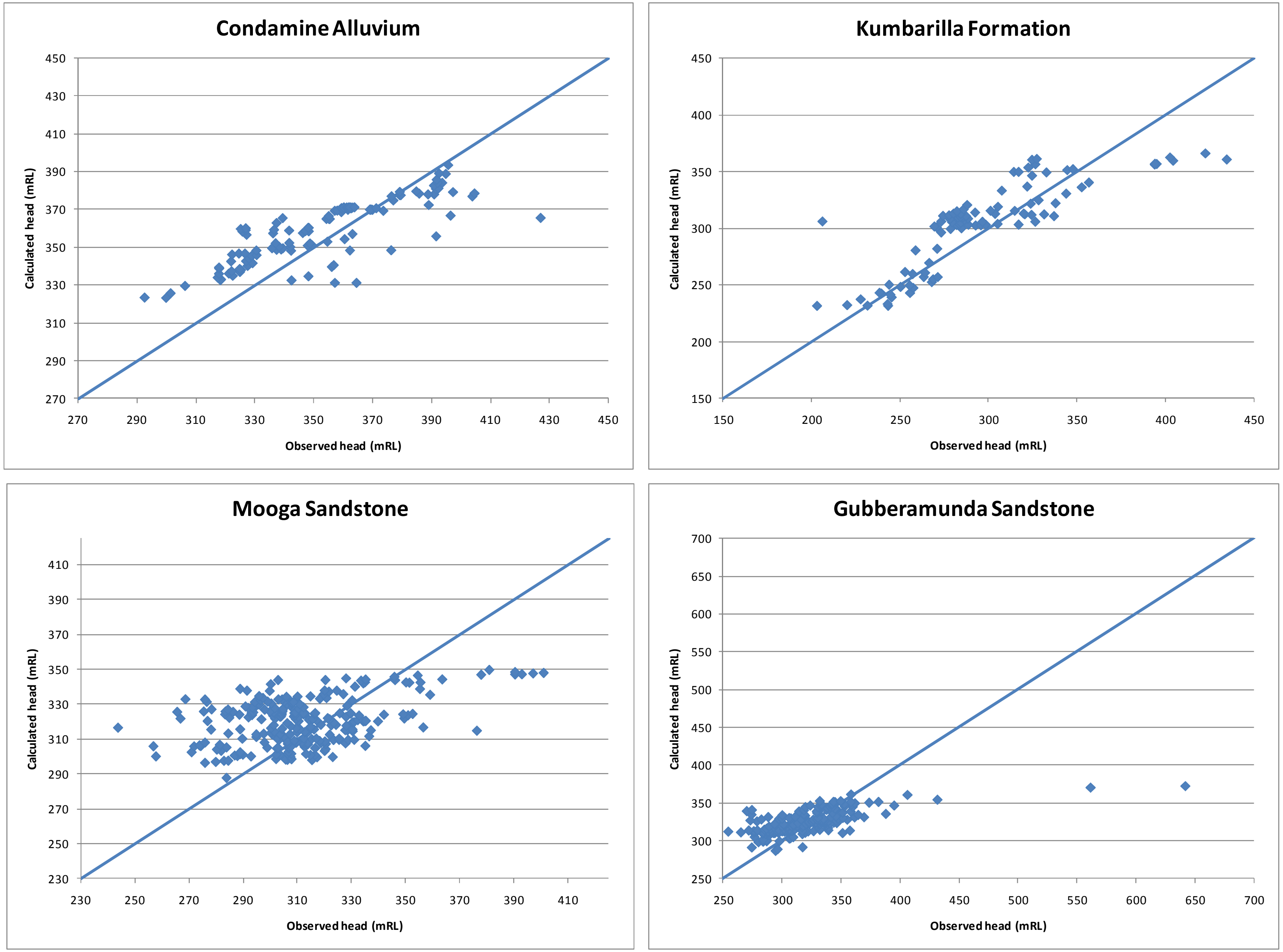

Figure 3.10 Steady state calibration plots (1)

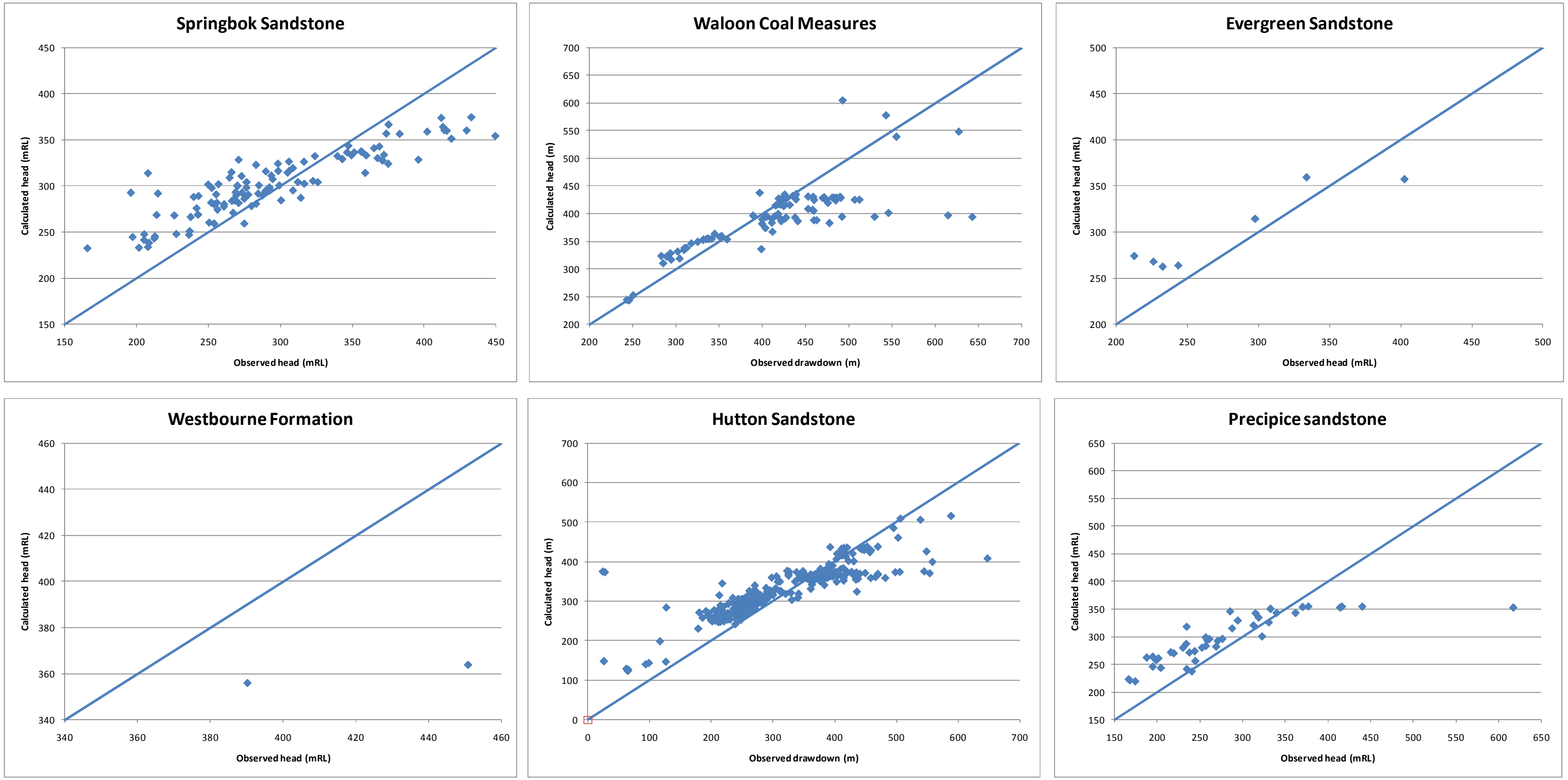

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Figure 3.11 Steady state calibration scatter plots (2)

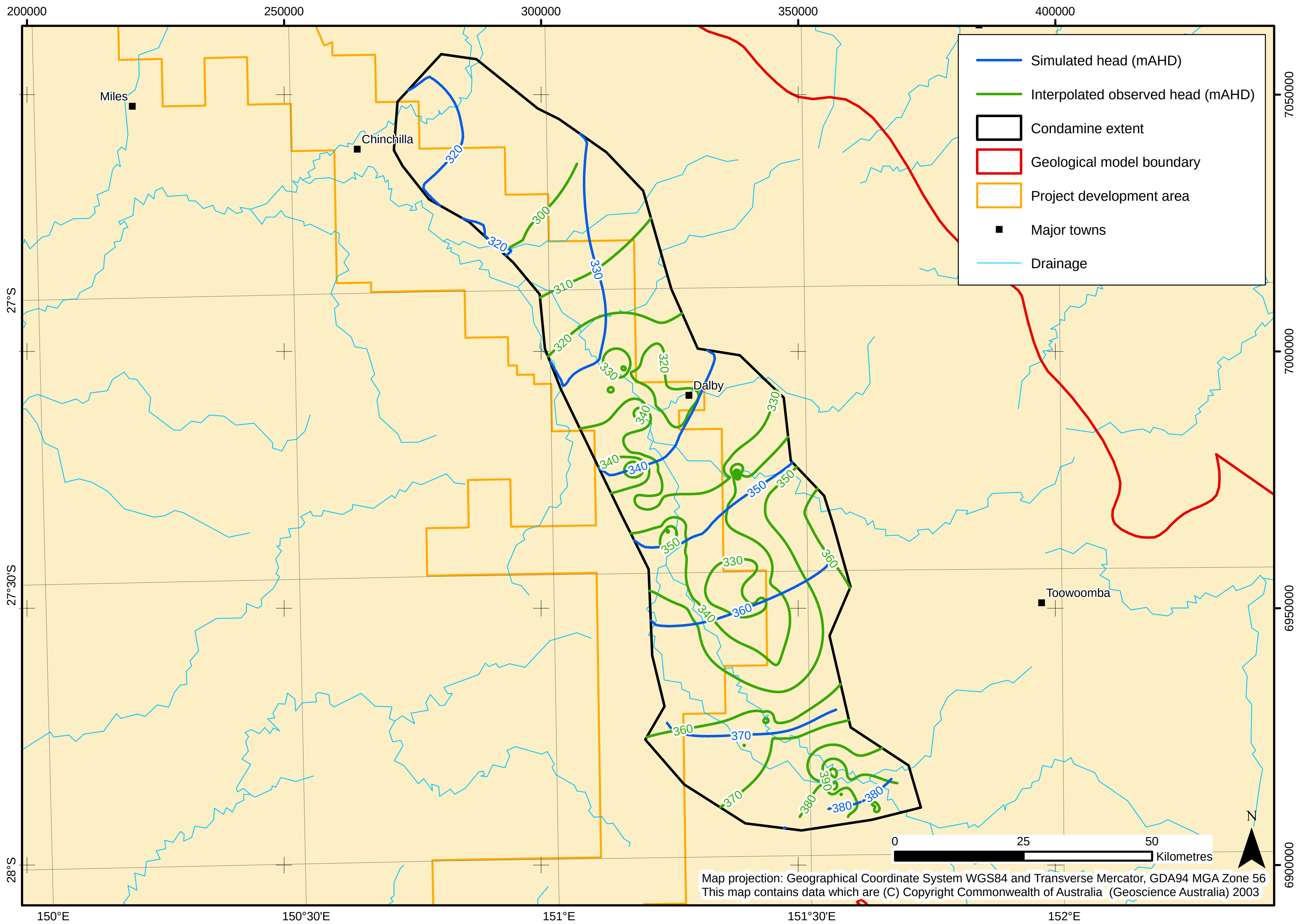

Figure 3.12 Steady state calibrated and observed groundwater levels, Condamine Alluvium

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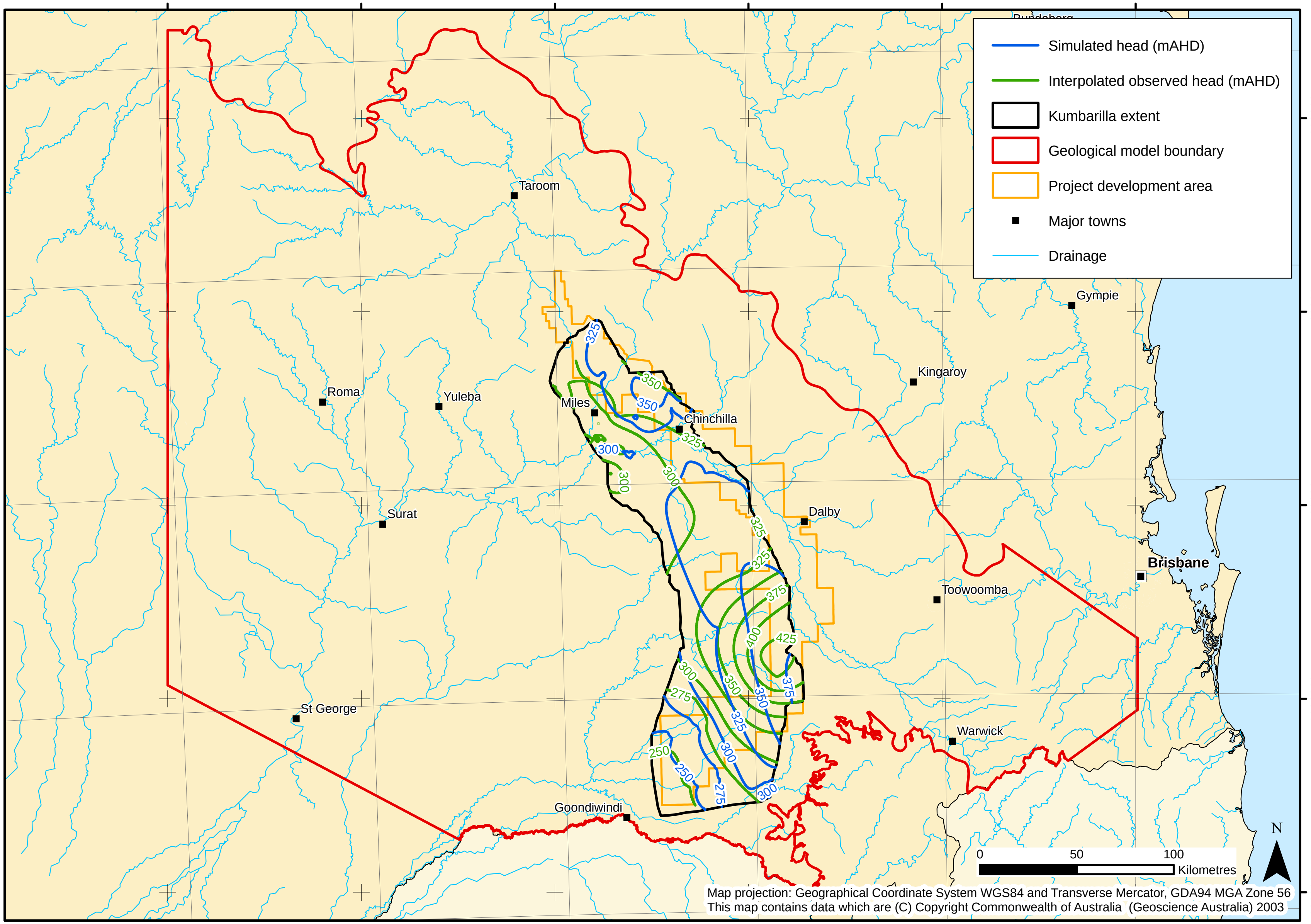

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Figure 3.13 Steady state calibrated and observed groundwater levels, Kumbarilla Beds

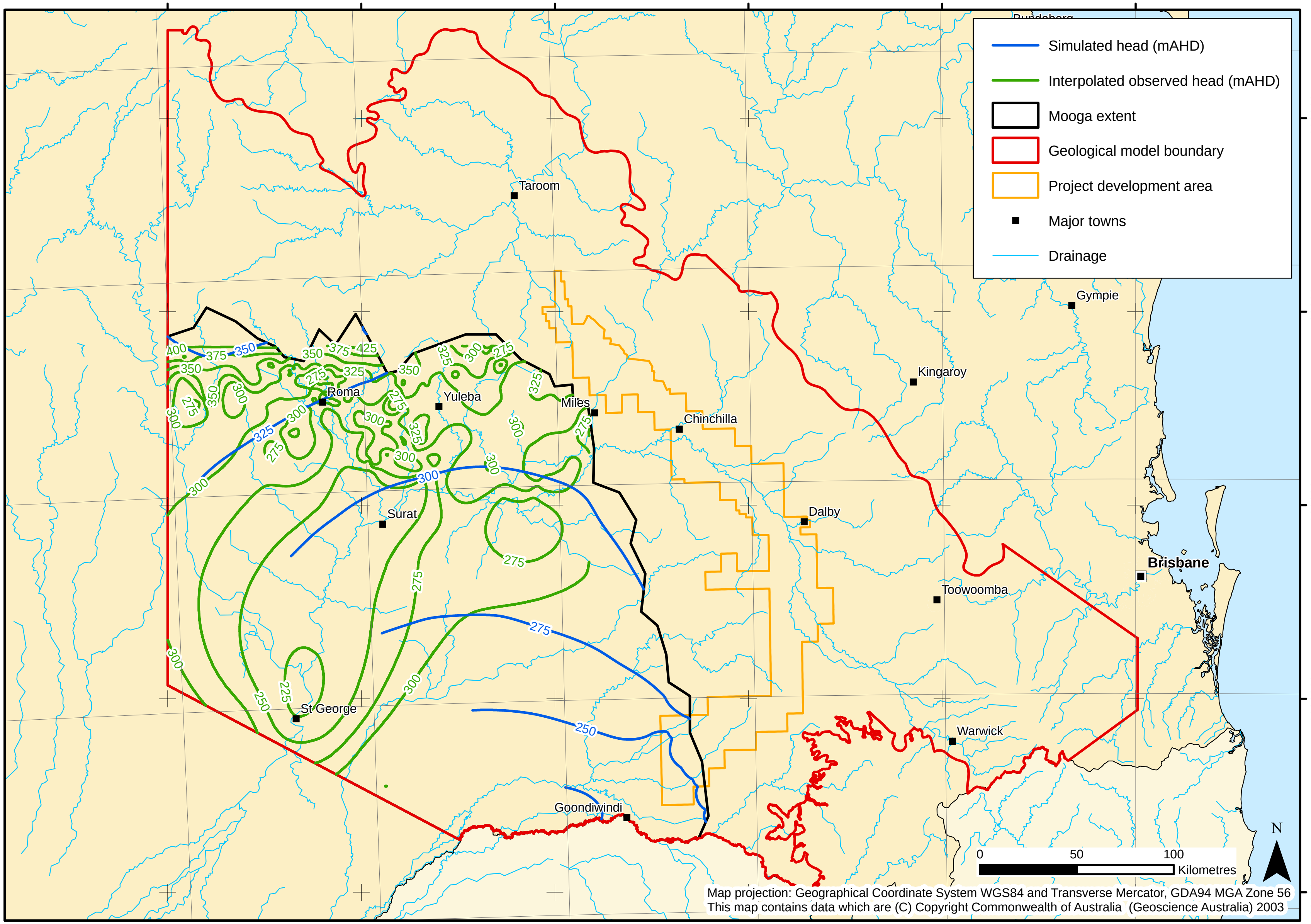

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Figure 3.14 Steady state calibrated and observed groundwater levels, Mooga Sandstone

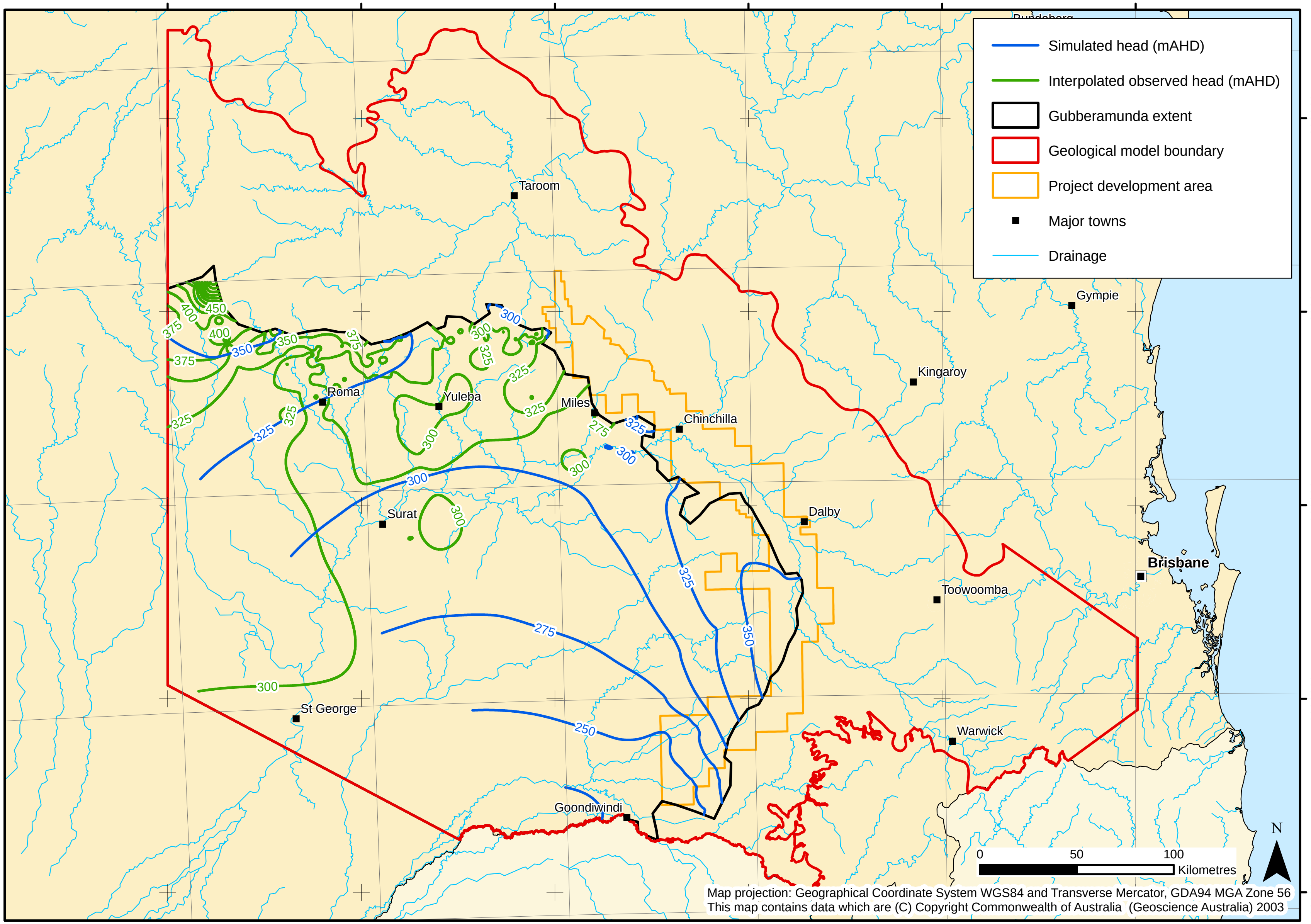

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Figure 3.15 Steady state calibrated and observed groundwater levels, Gubberamunda Sandstone

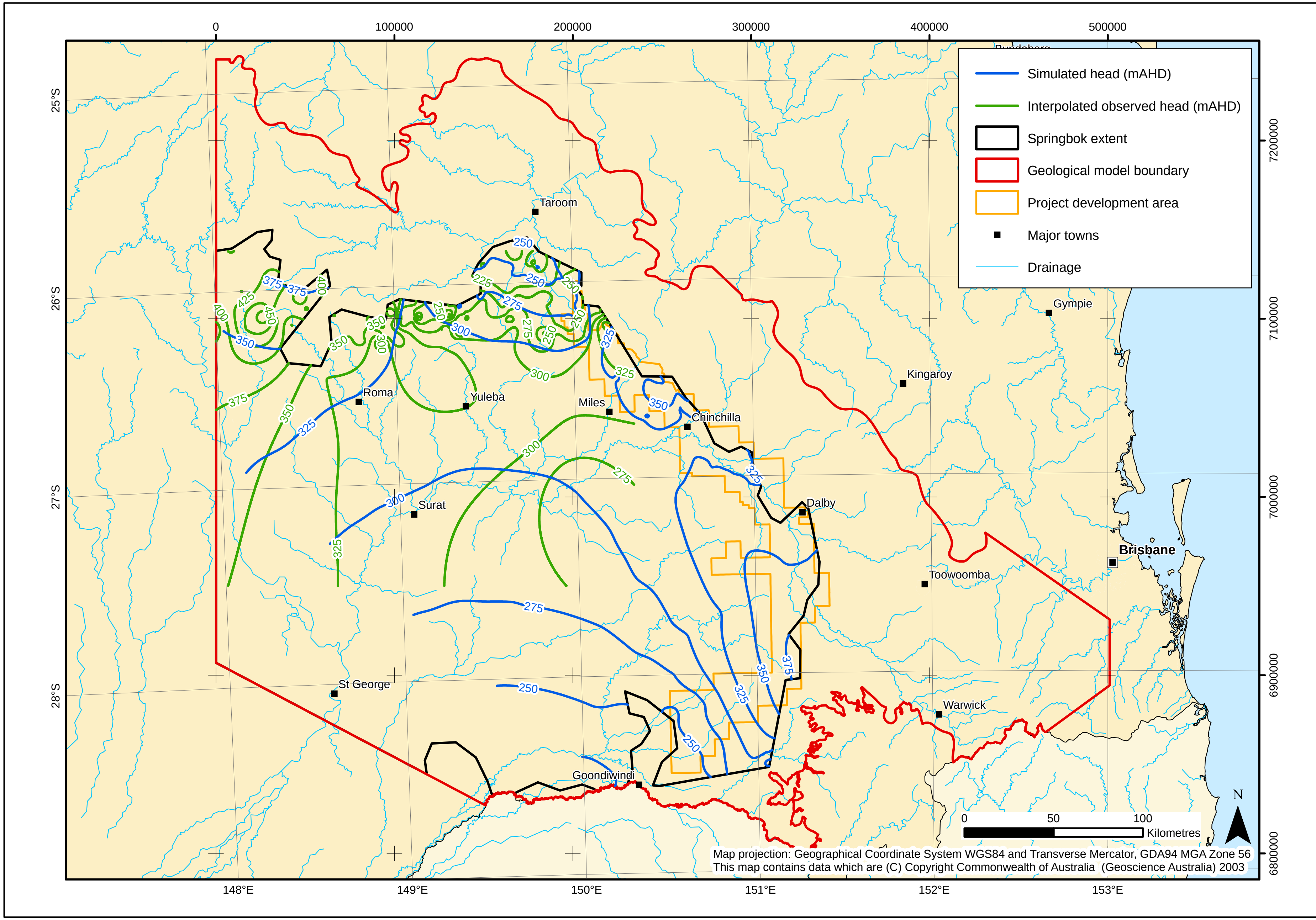

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Figure 3.16 Steady state calibrated and observed groundwater levels, Springbok Sandstone

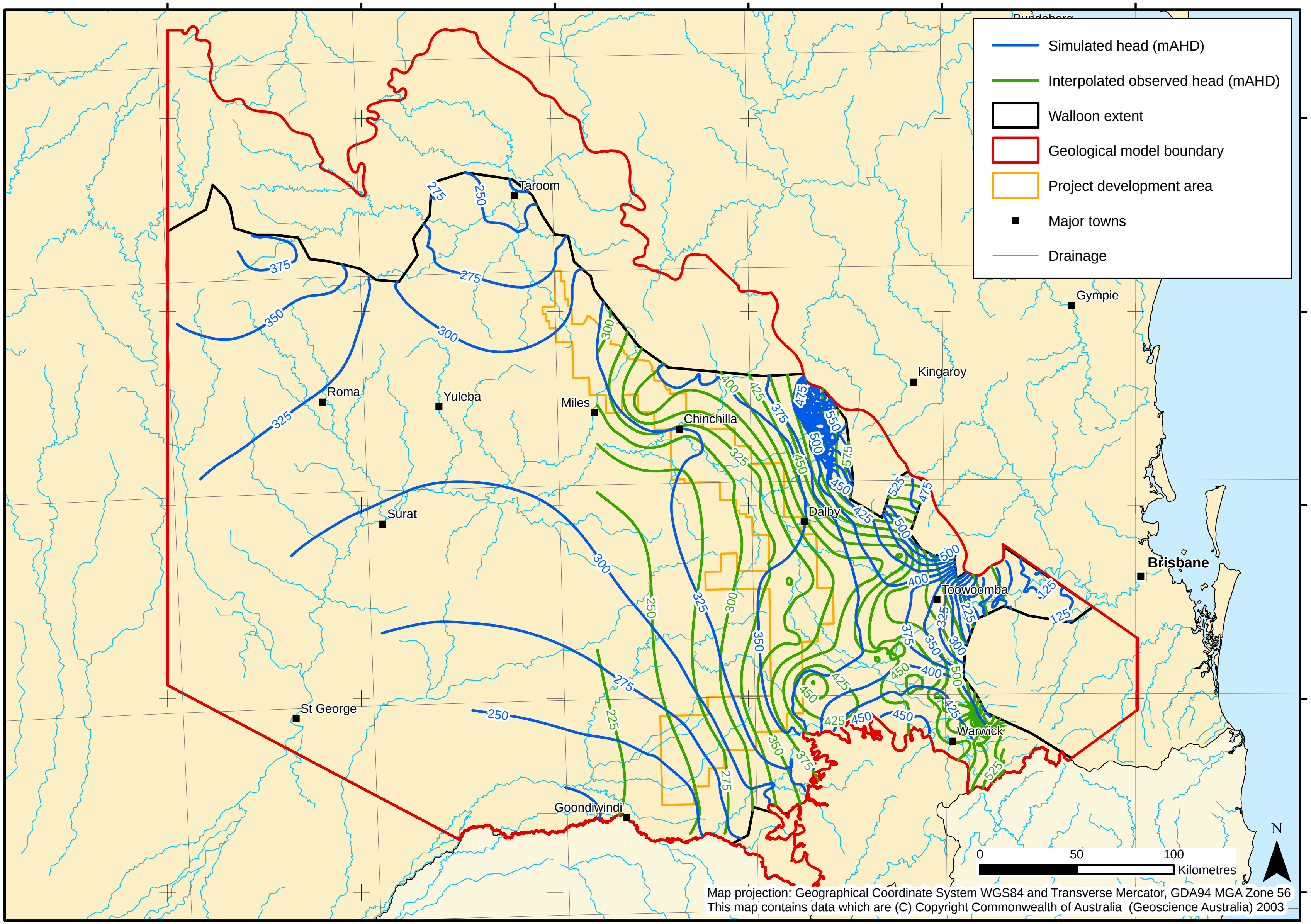

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Figure 3.17 Steady state calibrated and observed groundwater levels, Walloon Subgroup

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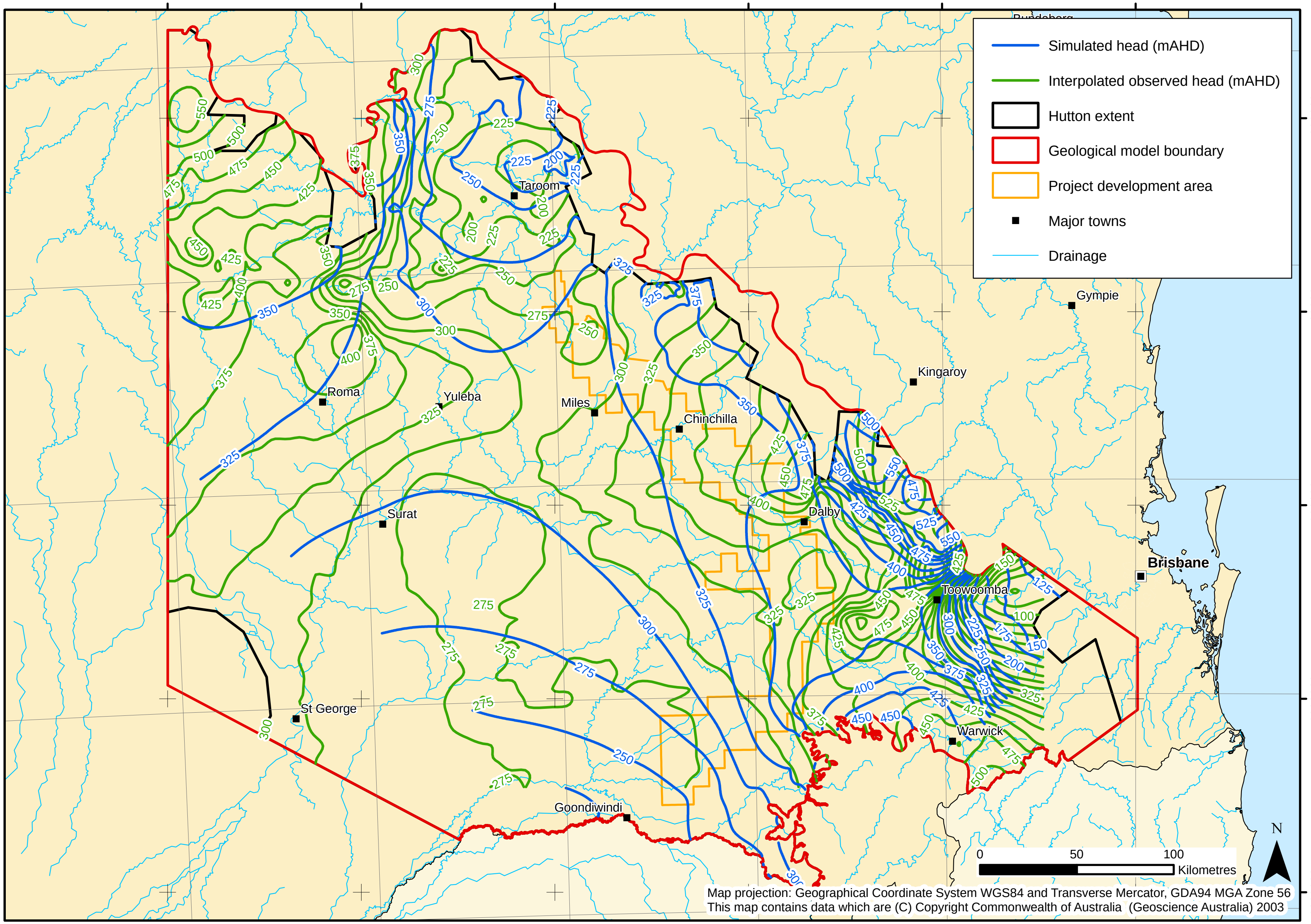

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Figure 3.18 Steady state calibrated and observed groundwater levels, Hutton and Marburg Sandstones

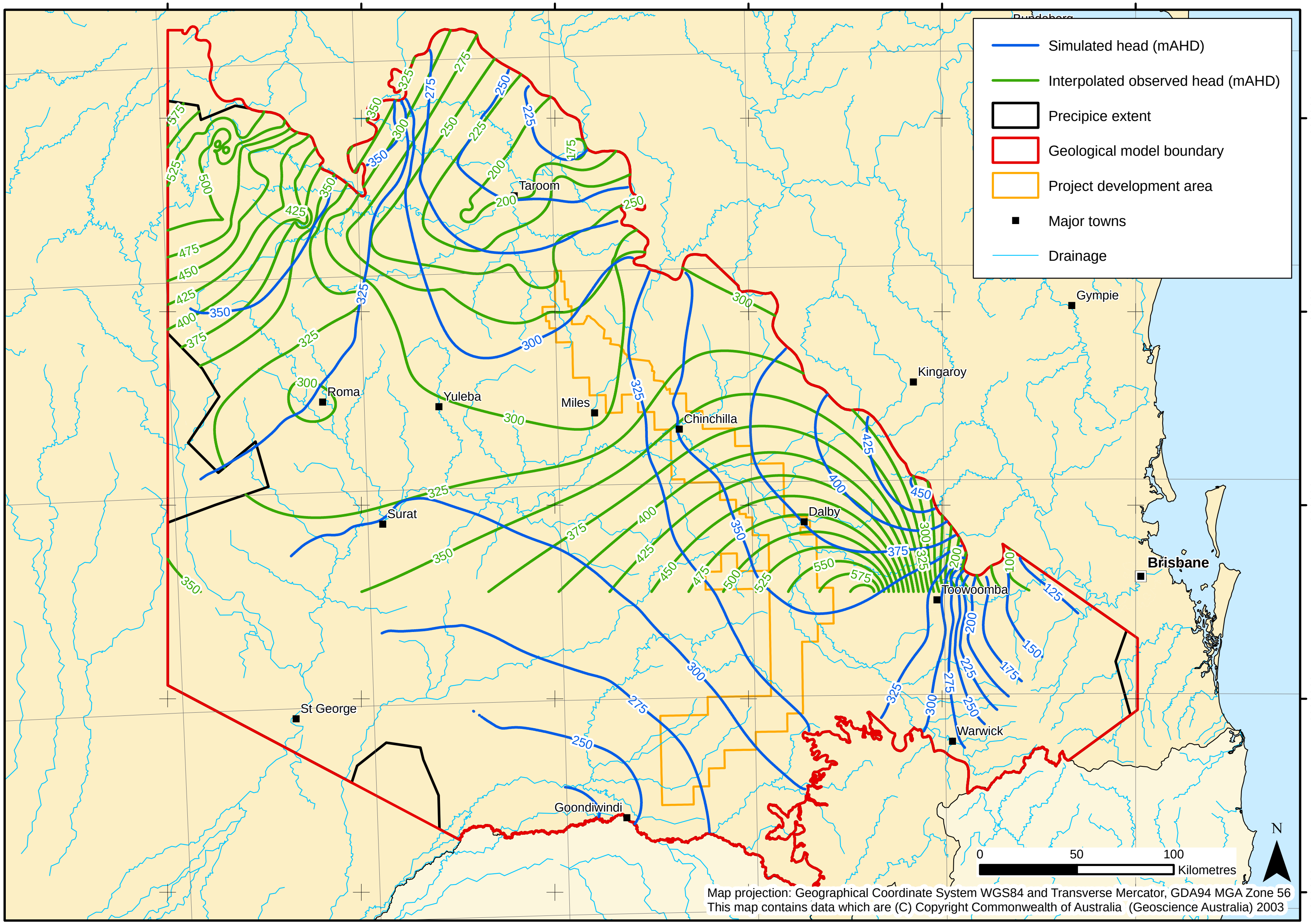

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Figure 3.19 Steady state calibrated and observed groundwater levels, Precipice and Helidon Sandstones

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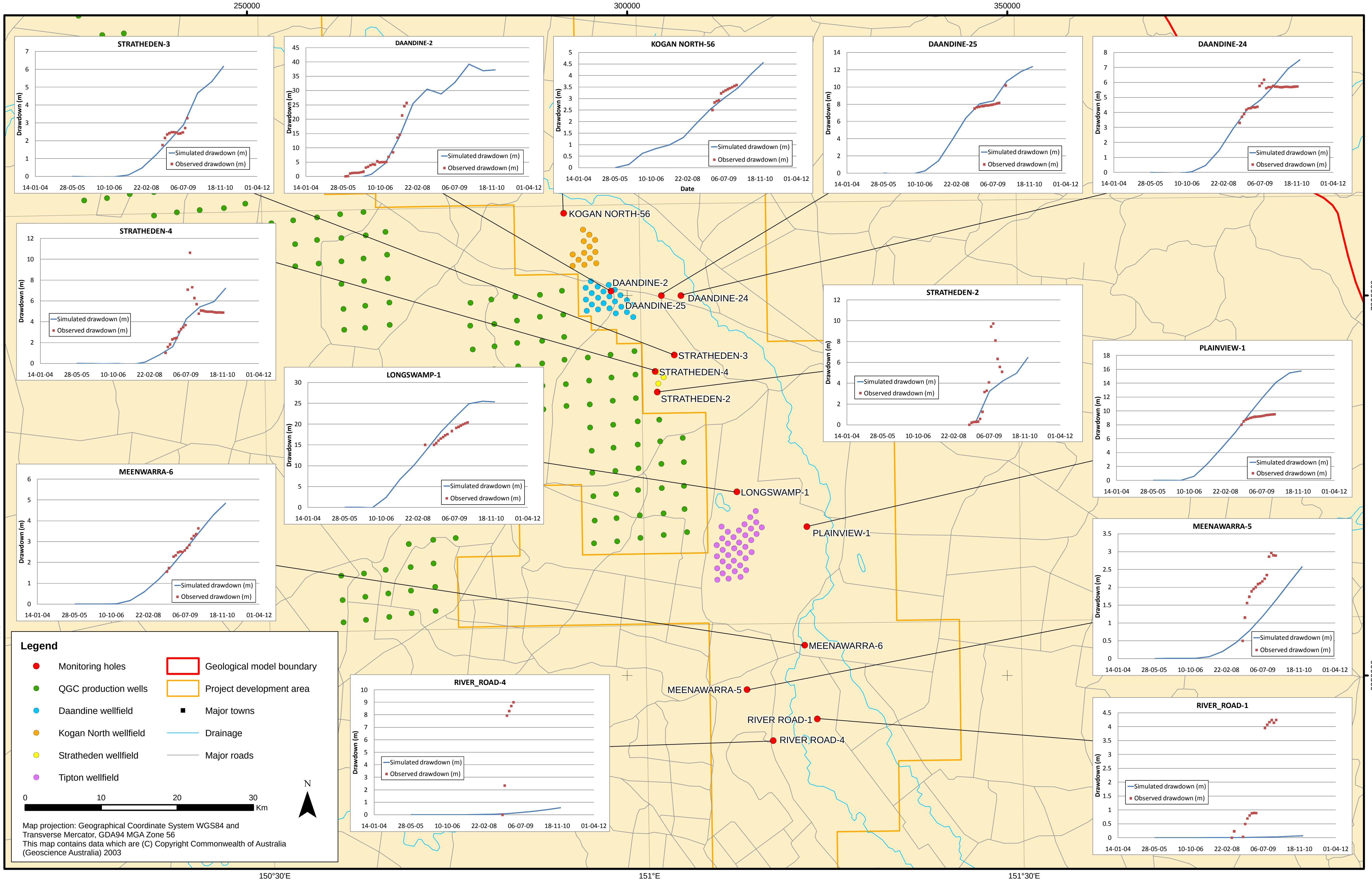
Figure 3.20 Observed and simulated drawdown at Arrow monitoring bores



4 PREDICTIVE MODELLING

4.1 Predictive scenarios

Three scenarios have been developed that investigate the effects of groundwater abstraction from Arrow, QGC, Origin and Santos CSG developments on the regional groundwater system. The total abstractions for each scenario are displayed in Figure 4.1. All abstractions have been based on those described in Section 2.6.3. They are:

- Scenario 1 – Arrow Only Reference Case (Figure 4.2). This scenario seeks to determine the impacts on the groundwater system resulting from Arrow CSG operations alone.
  - Abstraction from Arrow CSG wells based on the "reference case"
  - No (future) abstraction from QGC, Santos or Origin
  - No abstraction from any non-CSG source (private or public)
- Scenario 2 – Combined Base Case (Figure 4.3). This scenario seeks to determine the impacts on the groundwater system resulting from a combination of Arrow CSG operations and other CSG projects that have taken Final Investment Decision (FID) prior to the 31st January 2011.
  - Abstraction from Arrow CSG wells based on the "reference case"
  - Abstraction from QGC and Santos CSG wells
  - No (future) abstraction from Origin
  - No abstraction from any non-CSG source (private or public)
- Scenario 3 – Cumulative case (Figure 4.4). This scenario seeks to determine the impacts on the groundwater system resulting from all CSG operations in the Surat Basin, whether they have taken FID or not.
  - Abstraction from Arrow CSG wells based on the "reference case"
  - Abstraction from QGC and Santos CSG wells
  - Abstraction from Origin CSG wells
  - No abstraction from any non-CSG source (private or public)

4.2 Model set up

All boundary conditions and hydraulic parameters used in the predictive models are the same as those used in the calibrated time variant model. The only exceptions to this are the abstractions which are modified to represent the scenarios described above.

The projected CSG operations will require the drilling of several thousand wells over a number of years, the final locations of which are not known. It is impractical and unnecessary to simulate each well in the model. Therefore, as with the Santos, Origin and QGC historical abstractions, projected Arrow abstractions have also been simplified for use in the model. Santos, QGC and Origin abstraction locations are used directly from the historical model. Arrow abstraction ceases from the historical fields and is allocated to the five development areas (LNG facilities) and 3 domestic supply fields. A single well is assigned to each model cell within these areas. The representation of the abstractions in each scenario is illustrated in Figures 4.2 to 4.4. Where LNG facilities and domestic supply overlap, a single well is still used, but it is assigned the combined abstraction rate.

As with the historical CSG abstraction, the projected CSG abstractions are assigned to the Juandah and Taroom Coal Measures and the Tangalooma Sandstone using the MNW well package.

The Scenario 1 predictive model simulates 30 years of Arrow CSG associated water production followed by 20 years of recovery. This model therefore simulates the period from the 1st January 2011 to the 1st January 2061. The abstraction portion has been split into 30 stress periods, each of 12 month duration, and the recovery period into 10 stress periods, each of 24 month duration. All stress periods in the Scenario 1 predictive model are split into 30 time steps of equal length (time step multiplier of 1).

The Scenario 2 and 3 predictive models simulate 40 years of CSG associated water production followed by 20 years of recovery. These models, therefore, simulate the period from the 1st January 2011 to the 1st January 2071. The abstraction portion has been split into 40 stress periods, each of 12 month duration, and the recovery period into 10 stress periods, each of 24 month duration. All stress periods in the Scenario 2 and 3 predictive models are split into 30 time steps of equal length (time step multiplier of 1).

The initial groundwater levels assigned to the predictive models are those from the final time step in the time variant historical model.

4.3 Model mass balance

The time variant mass balance from each predictive run is displayed in Figure 4.5. These graphs show that the recharge remains constant throughout time and is identical in all the simulations. Abstraction, however, (MNW out) varies through time and increases significantly from Scenarios 1 to 3. This has the effect of perturbing (reducing) the flow of water out of the model via the drain boundary conditions. This reaches a maximum reduction of 7%, 13% and 16% (in Scenarios 1, 2 and 3 respectively) of the flow at the start of the predictive model run. For a number of years in Scenarios 2 and 3, abstraction of associated water from the CSG fields exceeds modelled inflow to the system (i.e. recharge and constant head inflow).

4.4 Model prediction analysis

The results are considered in terms of:

- The time variant drawdown at a set of "hypothetical" monitoring locations. Hydrographs of drawdown are provided at the following locations (also see Figures 4.2 to 4.4):
    - Proposed monitoring locations "Longswamp 7", "Tipton 155" and "Carn Brea 4". These are located in the Millmerran / Kogan Development Areas and within the Condamine Alluvium. Predicted drawdown is presented at these locations for the Condamine Alluvium only
    - A point roughly central to the Wandoan Development Area. At this location the Orallo Formation, Springbok Sandstone, Juandah Coal Measures and Hutton and Precipice Sandstones are present and predicted drawdown is provided from each of these layers of the model

- A point roughly central to the Chinchilla Development Area. At this location predicted drawdown is provided for the Springbok Sandstone, Juandah Coal Measures and Hutton and Precipice Sandstones

- A point roughly central to the Dalby and Millmerran / Kogan Development Areas (coincident with proposed location "Tipton 155"). At this location predicted drawdown is provided for the Springbok Sandstone, Juandah Coal Measures and Hutton and Precipice Sandstones, and

- A point roughly central to the Goondiwindi Development Area. At this location predicted drawdown is provided for the Kumbarilla Beds, Juandah Coal Measures and Hutton and Precipice Sandstones

- The drawdown in groundwater levels relative to the predicted levels at the start of 2011 (end of historical time variant model). The results from Scenario 1 are provided for all "aquifer" units and all Walloon Subgroup units. The results from Scenarios 2 and 3 are provided only for the main aquifers (the Condamine Alluvium and Springbok, Hutton and Precipice Sandstones). Results are provided for 2 model time steps:

    - The time of maximum predicted drawdown for the layer in question (therefore variable), and

    - The 31st December 2061 (20 years after Arrow abstraction ceases). However, as abstraction continues until 2051 in Scenarios 2 and 3, in these cases this output time is 20 years after Arrow abstraction ceases but only 10 years after the cessation of all CSG abstraction.

4.5 Results

4.5.1 Scenario 1

Hydrographs of predicted drawdown at the "hypothetical" monitoring locations are displayed in Figures 4.6 to 4.8 and contours of drawdown are provided in Figures 4.9 – 4.18. The results are described in detail below.

Condamine Alluvium

Predicted drawdown in the Condamine Alluvium (Figures 4.6 and 4.9) ranges from just over 1 m to less than 0.1 m. Over the vast majority of the area the predicted drawdown is less than 1 m. The greatest drawdown is predicted to occur in the vicinity of the Dalby Development Area, along the western extent of the alluvium. In this area the peak in predicted drawdown occurs in 2059, just 2 years before the cessation of abstraction from Arrow CSG operations. This is some 30 years after the peak in Arrow CSG abstraction, but the predicted time lag is a factor of the time varying and spatially varying abstraction, the distance between the abstraction and the alluvium and the hydraulic connection between the Walloons and the alluvium.

The hydrographs show that at these locations the greatest predicted drawdown is in the order of 0.5 m (at Carn Brea 4). At the other locations the maximums are 0.25 m (Longswamp 7) and 0.3 m (Tipton 155). At all locations recovery is predicted to occur at a slower rate than drawdown. By 2071 the predicted recovery of water levels is between 25 and 50% (of the initial condition) at the three locations.

Kumbarilla Beds

The Kumbarilla Beds subcrop or outcrop (*'outcrop' is used to represent both terms in text below*) within and to the west of the Arrow Development Areas and it is in this area that the maximum drawdown is predicted (Figure 4.10). The greatest predicted drawdown occurs in 2029, with between 20 and 30 m predicted to the northeast and 15 to 20 m to the southeast. However, this level of drawdown is limited to relatively small areas and the average drawdown in the vicinity of the Arrow Development Areas is about 2.5 to 5.0 m at this time. By 2061 the maximum value of predicted drawdown is between 5 and 10 m. However, the extent of impacts (as defined by the 0.1 m drawdown contour) has increased further to the south.

The monitoring location defined within the Goondiwindi Development Area intercepts a thickness of Kumbarilla Beds. The hydrograph (Figure 4.8) shows that the model predicts a maximum of 6 m drawdown at this location (in roughly 2039). By 2071, the water levels have recovered to about 60% of the 2011 values.

Mooga Sandstone

The Mooga Sandstone is present mostly to the west of the Arrow abstractions. For this reason virtually no drawdown is predicted in this unit at any time during the simulation (Figure 4.11). Predicted drawdown reaches a maximum of 5 m directly above the Goondiwindi Development Area in 2047 and then declines.

Gubberamunda Sandstone

The Gubberamunda Sandstone outcrops within the western extents of the Arrow Development Areas and this is where the greatest drawdown is predicted (Figure 4.12). The maximum occurs in the southern portion of the Millmerran / Kogan Development Area, where it peaks at between 10 and 15 m in 2031. By 2071 this has reduced to between 5 and 7.5 m.

Springbok Sandstone

The Springbok Sandstone outcrops within and along the eastern margin of the Arrow Development Areas. Predicted drawdown peaks in 2024 at about 30 m in a small area within the northeast of the Wandoan Development Area (Figure 4.13). Over the majority of the remaining outcrop area the predicted drawdown in 2024 is between about 0.5 and 5 m. By 2061 this area of maximum drawdown has dissipated and the maximum is now not greater than 10 m. At this time, however, the limit of predicted drawdown between 0.1 and 5 m has increased to cover the entire Springbok eastern extent (from north to south). The area to the south of Miles labelled in Figure 4.13 as "predicted recovery" is caused by the recovery of groundwater levels following the cessation of QGC historical abstraction at the end of the historical predictive scenario (i.e. it is not continued into Scenario 1). This, therefore, allows levels to recover in this area.

The "hypothetical" monitoring locations in the Wandoan, Chinchilla and Dalby and Millmerran / Kogan Development Areas intercept a thickness of Springbok Sandstone. The maximum drawdown predicted at these locations varies from about 1.4 m to 1.7 m (Figures 4.7 and 4.8). The minimum value is predicted in the centre of the Wandoan Development Area, however this hydrograph suggests that whilst the rate of drawdown increase has reduced and is beginning to level off, the maximum at this location has not been reached by 2071. In the Chinchilla and Dalby and Millmerran / Kogan Development Areas, however, almost 100% recovery of water levels is predicted by 2071.

Juandah Coal Measures, Tangalooma Sandstone and Taroom Coal Measures

Drawdown in these units is predicted to be greatest in the Juandah Coal Measures where it peaks in 2024 at a value in excess of 75 m (Figure 4.14). The actual drawdown at the location of the wells, and within specific coal seams, will be much greater than this as the model averages or spreads the abstraction over a cell area of 1 km^2. At this time predicted drawdown is constrained roughly within the Arrow Development Areas, and decreases to less than 5 m at a distance of about 10 km from the wellfields. The region of recovery to the south of Miles and west of Chinchilla is associated with the cessation of QGC historical abstractions and water levels are increasing here.

The maximum predicted drawdown (which also occurs in 2024) in the Taroom Coal Measures and the Tangalooma Sandstone is 50 to 75 m (Figures 4.15 and 4.16).

Significant recovery is predicted by 2061. The residual drawdown at this time is predicted to be less than 10 m throughout the Juandah and Taroom Coal Measures and the Tangalooma Sandstone.

All "hypothetical" monitoring locations intercept a thickness of the Juandah Coal Measures. These hydrographs show that the maximum predicted drawdown is in the Goondiwindi Development Area where it reaches about 130 m (Figures 4.7 and 4.8). This is in part due to the greater peak in abstraction in this area, but also due to the thinning of the (modelled) Walloon Subgroup to the south of the Surat Basin. However, both the abstraction and the thickness in this area are subject to greater uncertainty than their equivalents to the north. In the other areas the maximums range between 60 and 90 m. In all areas the drawdown hydrographs roughly match the abstraction schedule of the Development Area in which they are situated and recovery of water levels is rapid, with over 90% recovery predicted by 2050.

Hutton (and Marburg) Sandstone

The maximum predicted drawdown in the Hutton Sandstone occurs in the Goondiwindi Development Area in about 2035. The maximum in all other areas occurs in 2027 and is between 20 – 30 m (Figure 4.17), with the largest impact in the Wandoan Development Area. Other areas with predicted drawdown in excess of 15 m are the southern portions of the Chinchilla and Dalby Development Areas. The 0.5 m drawdown contour extends about 25 km to the west, but less than 5 km to the east of the wellfields.

By 2061 drawdown in all areas has reduced to less than 15 m. The 0.5 m drawdown contour in 2061 extends about 60 km to the west and 20 km to the east of the abstraction area.

The hydrographs of predicted drawdown at "hypothetical" locations (Figures 4.7 and 4.8) confirm that the Goondiwindi Development Area experiences the greatest drawdown (about 60 m). However, this area also experiences the most rapid recovery, about 90% of the 2011 groundwater levels by 2061. At the other locations recovery to about 80% of the 2011 groundwater levels is predicted by 2071.

Precipice (and Helidon) Sandstone

The maximum predicted drawdown in the Precipice Sandstone is between 10 and 15 m in 2042 (Figure 4.18). This occurs in the region of the Dalby Development Area. At this time drawdown in excess of 2.5 m is predicted within all Arrow Development Areas to the north of Goondiwindi. By 2061 the maximum predicted drawdown has reduced to between 5 and 10 m in the same area. The 2.5 m drawdown contour has extended in all directions.

All "hypothetical" monitoring locations intercept a thickness of the Precipice Sandstone. Hydrographs at these positions (Figures 4.7 and 4.8) confirm the above statements and show that maximum drawdown occurs at quite different times depending on location, and that recovery of groundwater levels is relatively slow (although, as drawdown peaks late in the simulation, time for recovery is limited).

4.5.2 Scenario 2

This scenario includes abstraction from QGC and Santos CSG fields in addition to the abstraction defined for Scenario 1. The total abstraction in Scenario 2 is just over 3 times greater than the abstraction in Scenario 1. Simulated abstraction in this scenario peaks at just under 300 ML/d in 2018. The discussion of results (below) is focused on the most relevant "aquifer" units.

Condamine Alluvium

The pattern of predicted drawdown in the Condamine Alluvium (Figure 4.19) in Scenario 2 is much the same as in Scenario 1. The magnitude of drawdown is, however, greater, peaking in 2060 at between 0.5 and 2 m along the western extent of the alluvium. In the majority of the rest of the alluvium predicted drawdown at this time is between 0.1 and 0.5 m.

The hydrographs show that maximum drawdown at these monitoring locations is still just under 0.45 m, but this is now predicted at Longswamp 7 as well as Carn Brea 4 (Figure 4.6). The hydrographs also show that with this greater abstraction, recovery of water levels in the Condamine Alluvium is predicted to be slower than predicted in Scenario 1.

Springbok Sandstone

The maximum predicted drawdown in the Springbok Sandstone is between 40 and 50 m and occurs between Miles and Chinchilla in 2036 (Figure 4.20). At the same time, between 30 and 40 m is predicted to the west of the Dalby Development Area and 15 to 20 m in the Goondiwindi Development Area. As QGC abstraction continues post 2011 in this scenario, no isolated zones of recovery are predicted in these areas. By 2061 water levels have recovered in most areas to within 10 m of the 2011 levels. In an area to the west of the Dalby Development Area, (in the vicinity of the QGC Southern Development Area) drawdown is predicted to remain at between 20 and 30 m by 2061.

At the "hypothetical" monitoring locations (apart from in the centre of the Wandoan Development Area) the predicted maximum drawdown is similar to the Scenario 1 case (Figures 4.7 and 4.8). The recovery of water levels at all locations is however more gradual, with a 60% recovery by 2071. The hydrograph in the centre of the Wandoan Development Area shows that predicted drawdown is about 0.5 m greater at this location in the Scenario 2 case, as compared to Scenario 1, and that drawdown is still increasing beyond 2071.

Hutton (and Marburg) Sandstone

Predicted drawdown in the Hutton in Scenario 2 is greatest in an area coincident with the QGC Central and Southern Development Areas (Figure 4.21). Predicted drawdown peaks here at between 40 and 60 m in 2029. Drawdown in the region of all Arrow and QGC wellfields is greater than 20 m at this time. By 2061 the impacts to the north have subsided somewhat, but the predicted drawdown extent has extended significantly to the west and south. At this time the maximum drawdown is between 30 and 40 m immediately above the QGC Central and Southern Development Areas.

At the "hypothetical" monitoring locations (apart from within the Goondiwindi Development Area) drawdown from Scenario 2 is predicted to be up to about 40% higher than the Scenario 1 case (Figures 4.7 and 4.8). Recovery of groundwater levels is also predicted to be slower. The predictions in the Goondiwindi Development Area vary little between Scenarios 1 and 2 because there are no QGC or Santos abstractions in the vicinity.

Precipice (and Helidon) Sandstone

Predicted drawdown in the Precipice Sandstone in Scenario 2 is greatest to the southwest of Dalby, in the vicinity of the QGC Southern Development Area and the Arrow Dalby Development Area (Figure 4.22). Predicted drawdown peaks here at between 30 and 40 m in 2039. Therefore, although the location of greatest drawdown is the same as predicted in the Hutton Sandstone, the maximum impact occurs 10 years later in the Precipice Sandstone. By 2061 the maximum is in the same area, but has reduced to between 20 and 30 m. By this time drawdown of at least 1 m is predicted over about 75% of the modelled Precipice extent.

The hydrographs at "hypothetical" monitoring locations show that in most cases the predicted drawdown in the Precipice has more than doubled as compared to Scenario 1 (Figures 4.7 and 4.8). The result in the Goondiwindi Development Area is, however, unchanged.

4.5.3 Scenario 3

This scenario includes abstraction from Origin CSG fields in addition to the abstraction defined for Scenario 2. The total abstraction in Scenario 3 is just over 4.5 times greater than the abstraction in Scenario 1 and 1.5 times greater than in Scenario 2. Simulated abstraction in this scenario peaks at just under 450 ML/d in 2021. The discussion of results (below) is focused on the most relevant "aquifer" units.

Condamine Alluvium

Maximum drawdown of about 2.5 m is predicted in the west of the Condamine Alluvium extent in 2065 (Figure 4.23). In most areas the predicted drawdown in this scenario is very similar to the Scenario 2 predictions. The only significant difference is found to the southwest where the 0.5 and 1.0 m drawdown contours extend further to the east in Scenario 3.

For the most part the simulated hydrographs at locations within the Condamine Alluvium are very similar to those from Scenarios 2 (Figure 4.6). Only Carn Brea-4 displays significantly different behaviour, and drawdown is predicted to continue to increase to the end of the simulation time (2071) at this location.

Springbok Sandstone

Predicted drawdown in the Springbok Sandstone in this scenario peaks at between 50 and 60 m between Miles and Chinchilla (associated with the combined Origin Group 2 and Chinchilla Development Area abstractions) in 2039 (Figure 4.24). This reduces to between 20 and 30 m by 2061. Other high drawdown locations include the area of abstractions associated with Origin Group 1 (20 to 30 m), QGC Southern Development Area (30 to 40 m) and combined Origin Group 3 and southern Millmerran / Kogan Development Areas (40 to 50 m). By 2071 levels at these locations have recovered and the maximum predicted drawdown is between 20 to 30 m.

The hydrographs display two different groundwater level responses in the Springbok Sandstone (Figures 4.7 and 4.8):

- In the Wandoan Development Area drawdown continues to increase up to the end of the simulation time (2071). At this time the drawdown is about 1 m greater than the Scenario 1 case.
- In the Chinchilla and Dalby and Millmeran / Kogan Development Area locations, maximum drawdown is roughly the same as the Scenario 1 case. In Chinchilla the drawdown plateaux's from this point on until the middle of the 2050's. After this time the water levels quickly recover to a level greater than predicted in 2011. In Millmeran / Kogan it recovers gradually from the peak onwards.

This unusual behaviour predicted at the Chinchilla monitoring location is most likely due to the drying out of a number of model cells (which then become inactive) in Layer 1 which also occupy drain boundary conditions. This occurs as the water levels fall in response to abstraction. As the water levels recover, the dry model cells do not reactivate, and as such, flow out of the model at these locations does not occur. As inflow from the boundary conditions (constant heads and recharge) does not reduce, the water levels in this situation can recover to a level higher than the original. As the stress to the system increases (i.e. abstraction) this phenomenon will become more obvious. However, it clearly does not represent an accurate prediction of water level recovery.

Hutton (and Marburg) Sandstone

The maximum predicted drawdown in the Hutton Sandstone (Figure 4.25) occurs in 2039 in an elongate zone just to the west of the Chinchilla, Millmerran / Kogan and Dalby Development Areas. Drawdown in this area is between 50 and 75 m. By 2071 this has reduced to between 30 and 50 m in most areas, apart from an area to the west of Chinchilla where it remains at above 50 m.

The hydrographs produced in the centre of the Wandoan and Chinchilla Development Areas show that this scenario produces significantly more drawdown in these areas than Scenario 2 (Figures 4.7 and 4.8). In the other areas the results from both scenarios are comparable, although recovery is slower in Scenario 3.

Precipice (and Helidon) Sandstone

Predicted drawdown in the Precipice Sandstone in Scenario 3 is greatest to the southwest of Dalby, in the vicinity of the QGC Southern Development Area and the Arrow Dalby Development Area (Figure 4.26). Predicted drawdown peaks here at between 30 and 40 m in 2042. By 2061 drawdown at this location has reduced to between 20 and 30 m.

As with the Hutton Sandstone, the hydrographs produced in the centre of the Wandoan and Chinchilla Development Areas show that this scenario produces significantly more drawdown in these areas than Scenario 2 (Figures 4.7). In the other areas the results from both scenarios are comparable, although recovery is slower in Scenario 3 (Figures 4.8).

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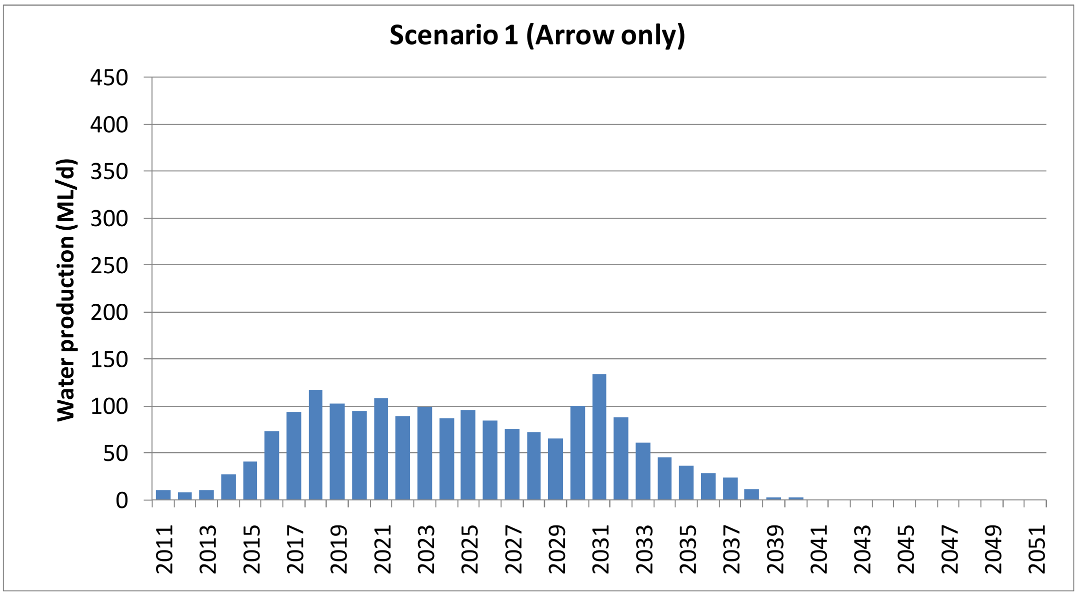
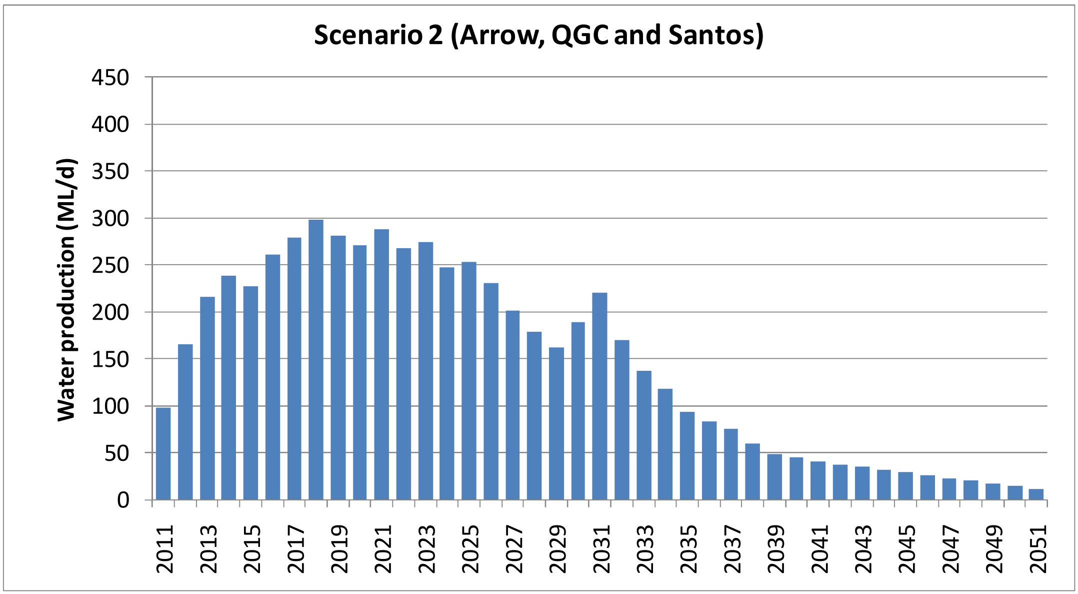
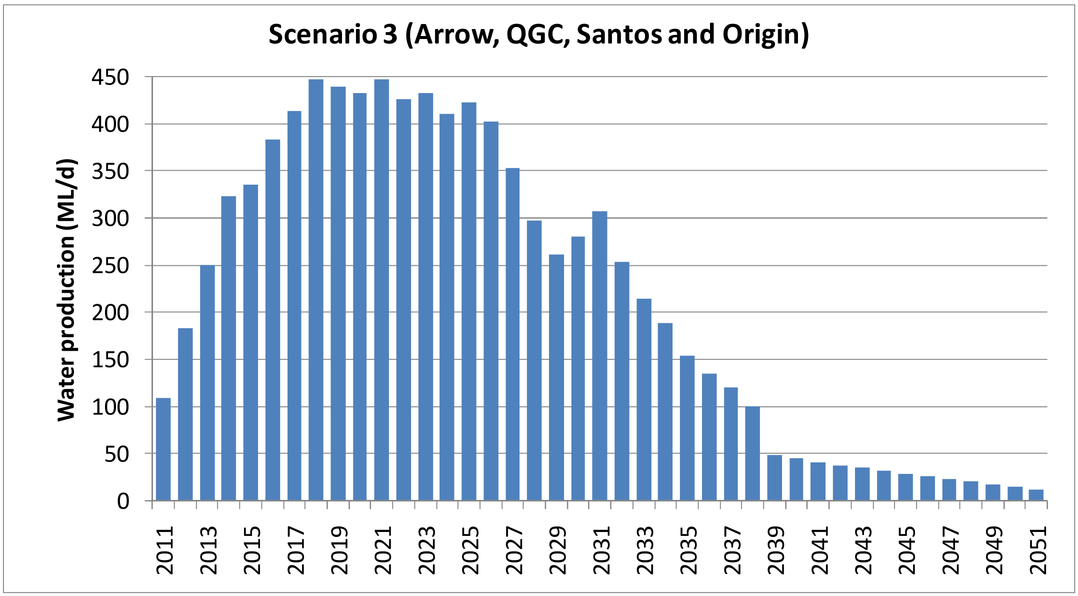
Figure 4.1 Total abstraction, predictive Scenarios 1, 2 and 3







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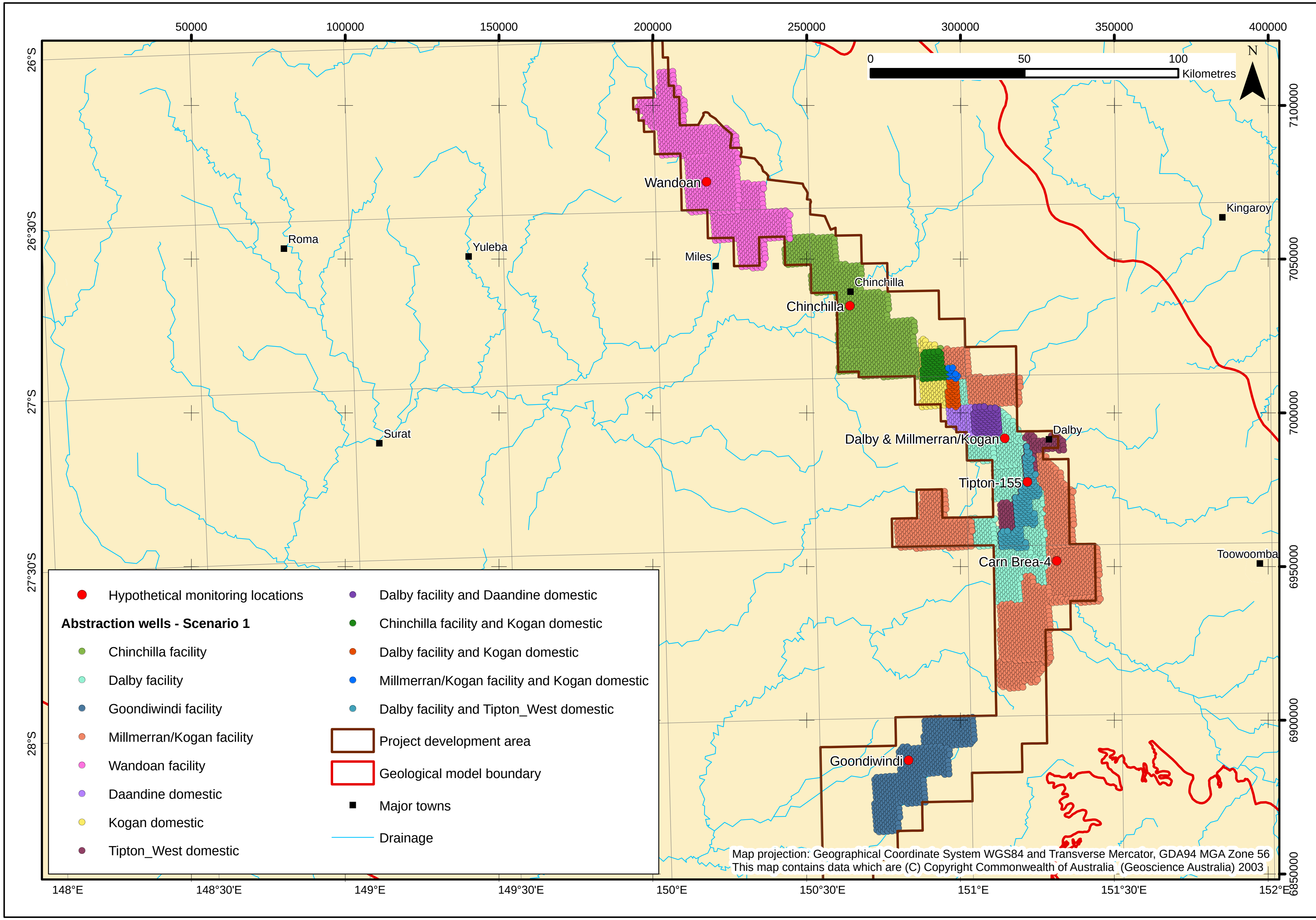

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Figure 4.2 Simulated abstraction sites (Scenario 1 - Arrow only)

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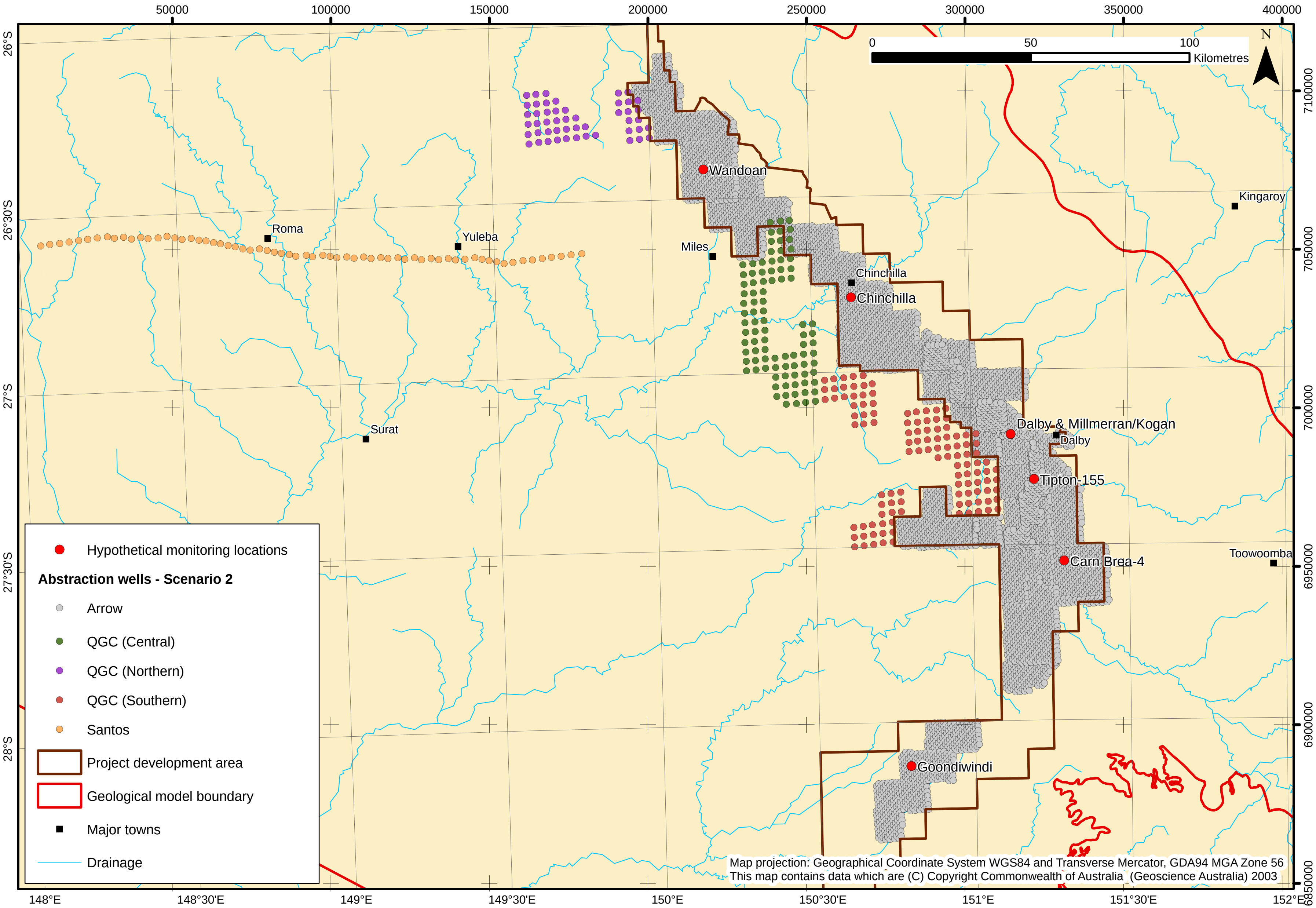

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Figure 4.3 Simulated abstraction sites (Scenario 2 - Arrow, QGC and Santos)

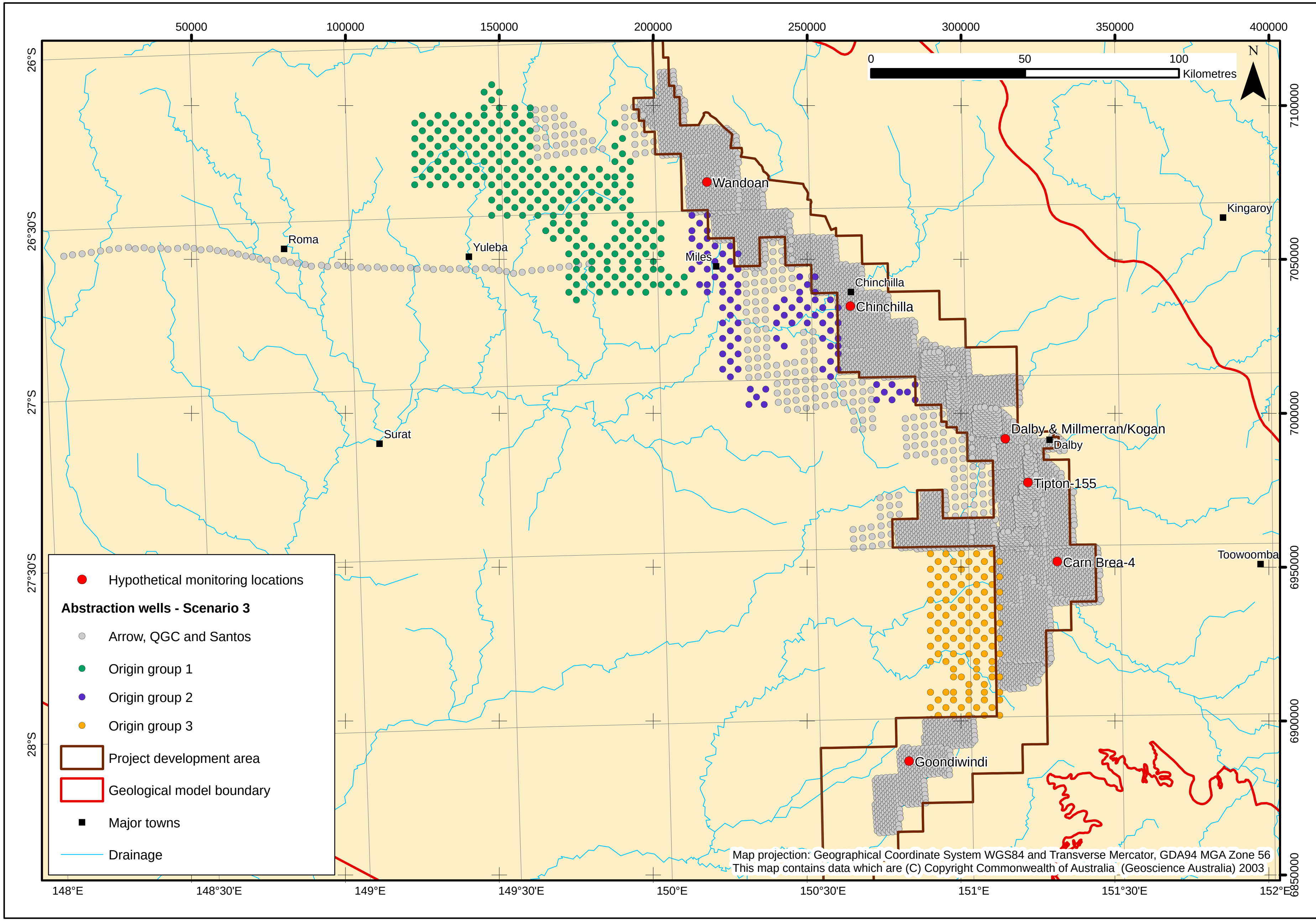

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Figure 4.4 Simulated abstraction sites (Scenario 3 - Arrow, QGC, Santos and Origin)

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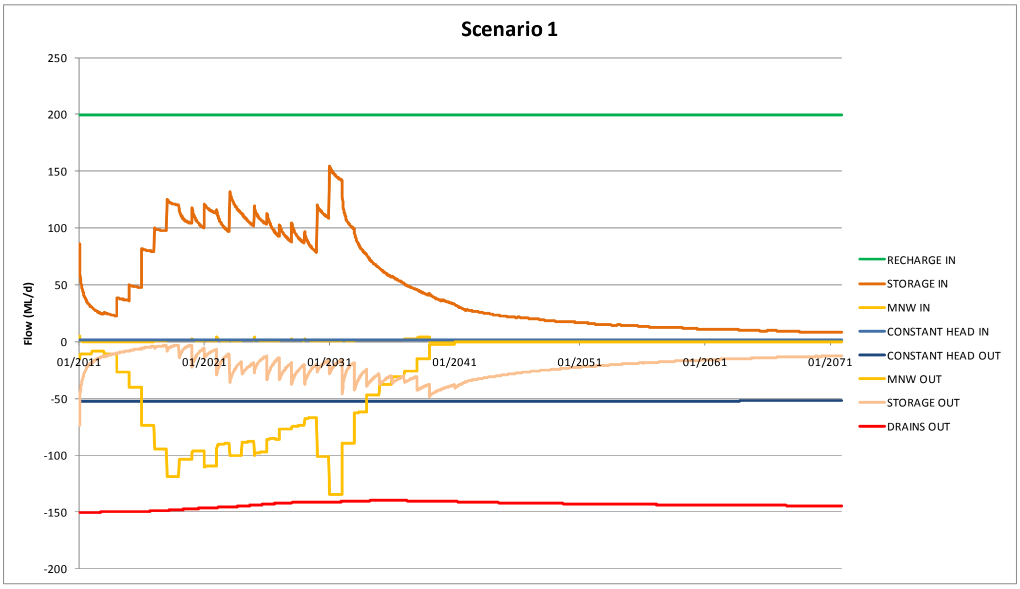
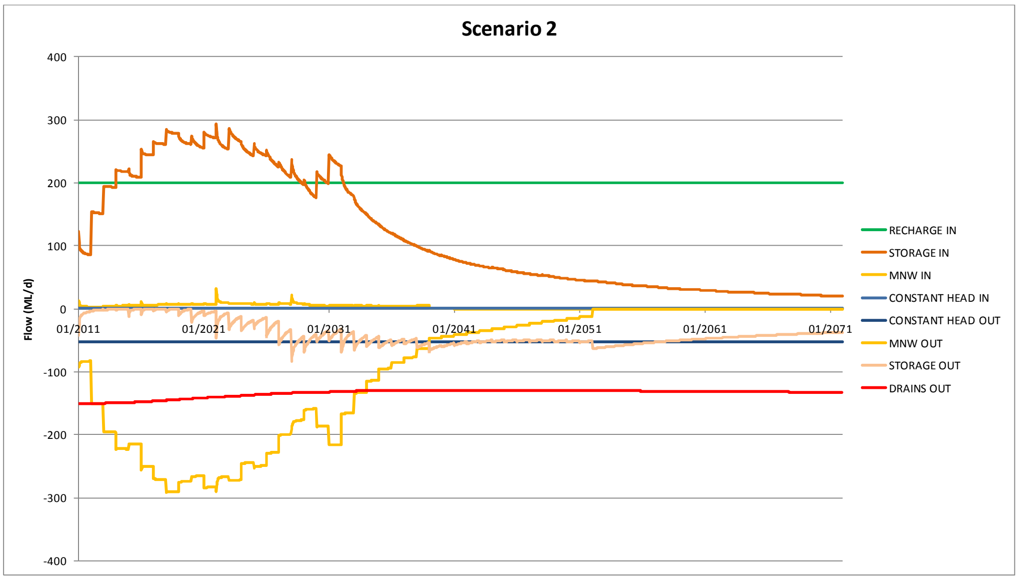
Figure 4.5 Time variant predictive models mass balance (Scenarios 12 and 3)





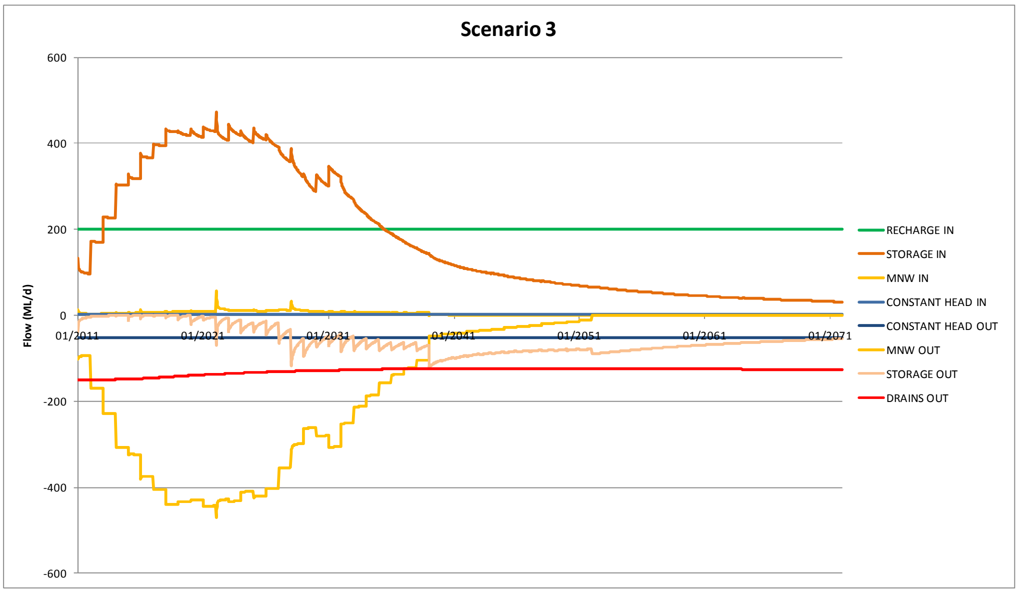


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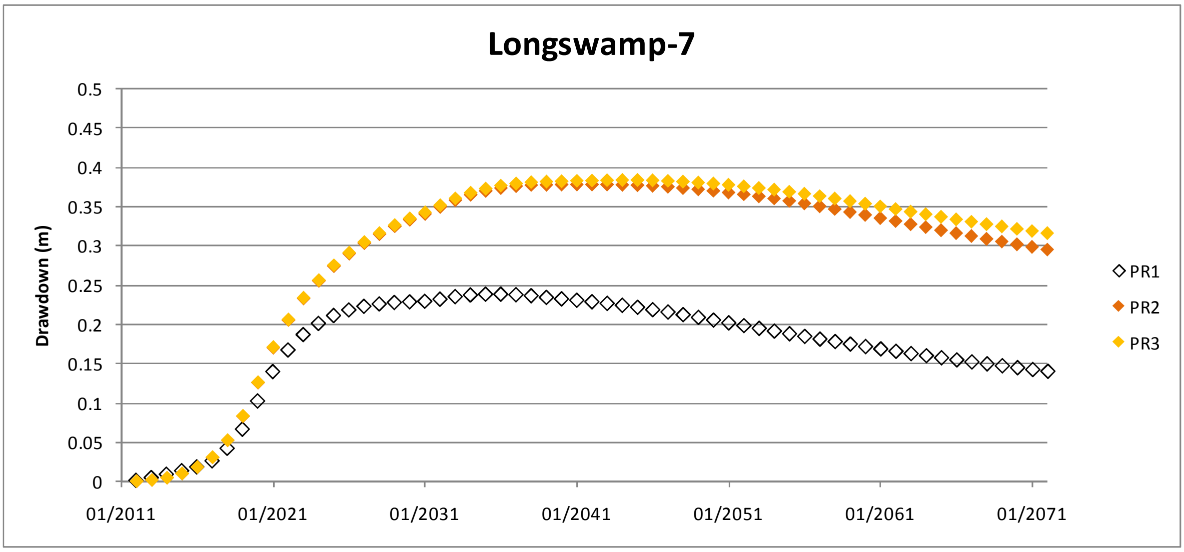
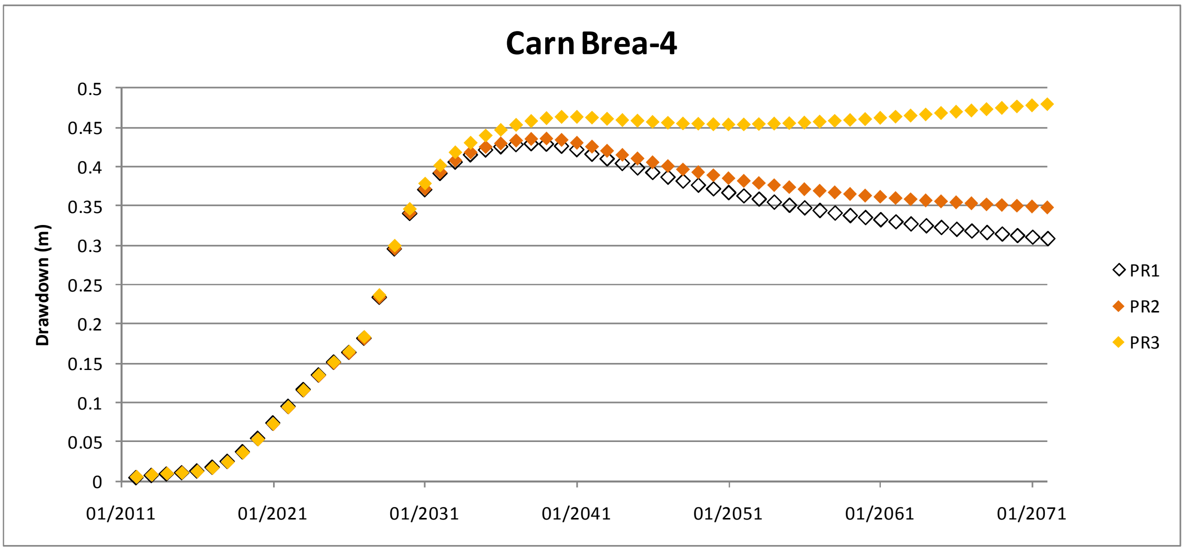
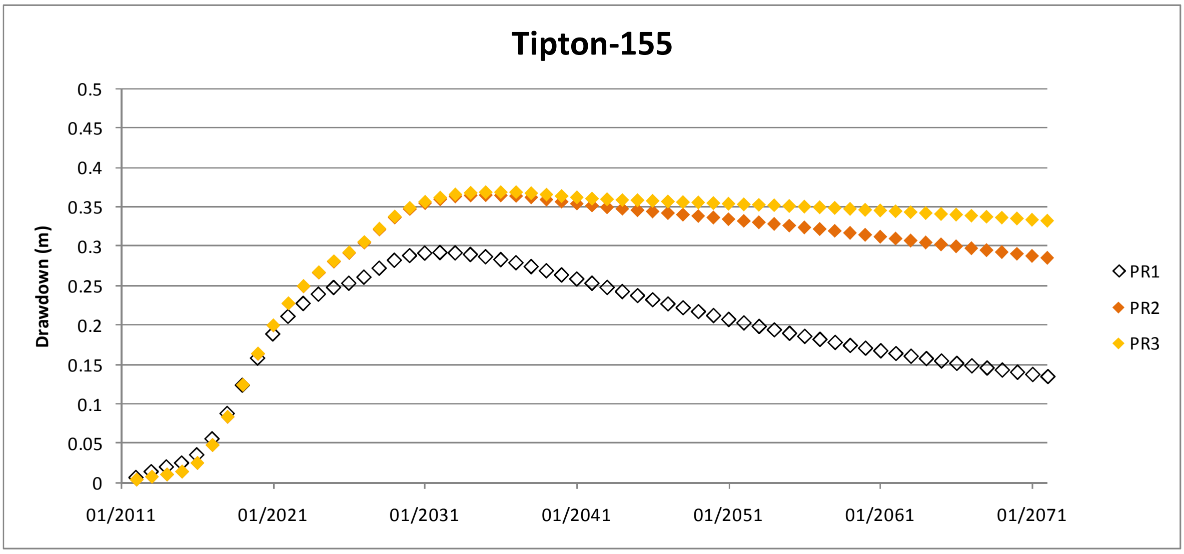
Figure 4.6 Scenarios 1, 2 and 3 predicted drawdown (Condamine Alluvium locations)







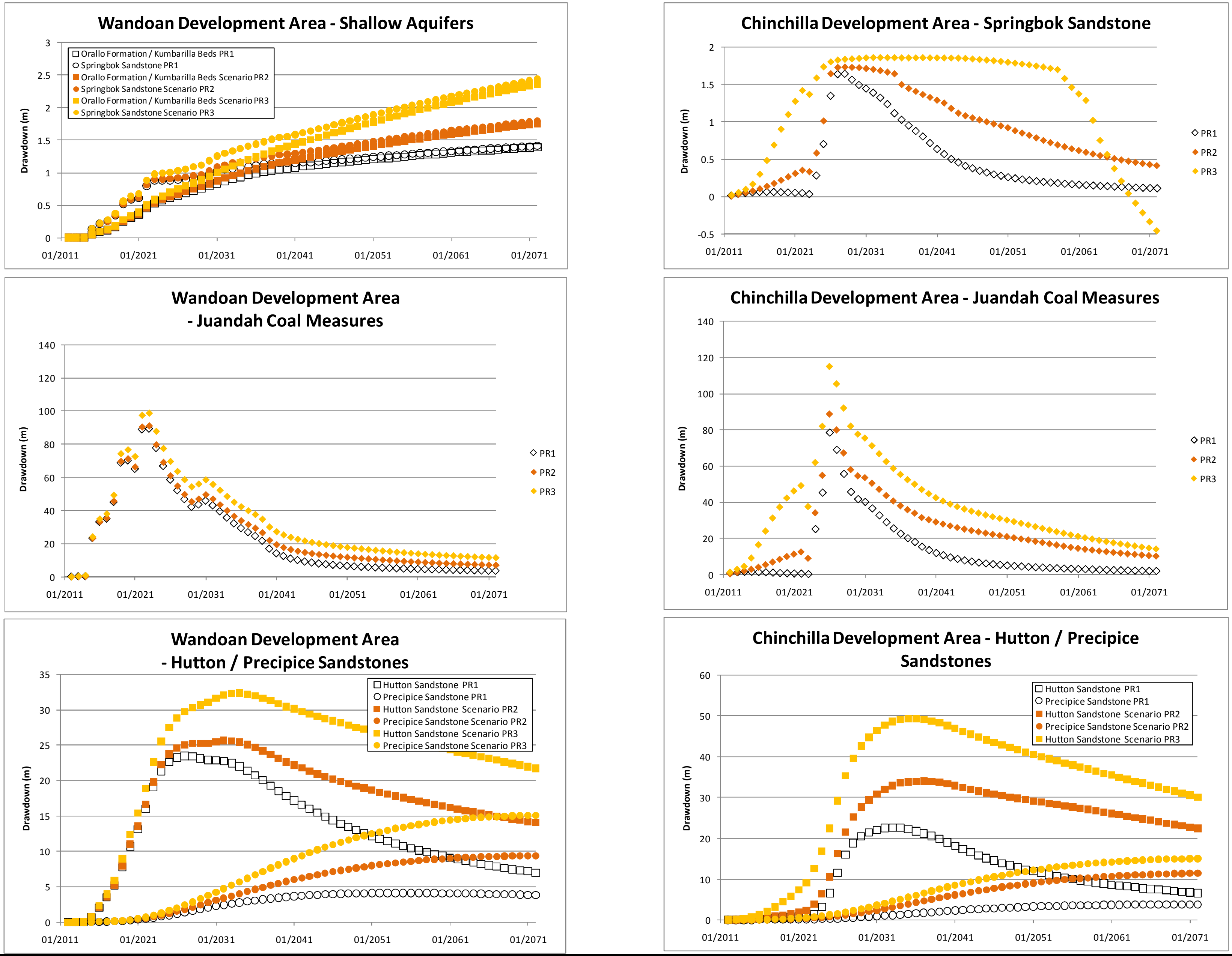


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Figure 4.7 Scenarios 1, 2 and 3 predicted drawdown (Wandoan and Chinchilla locations)

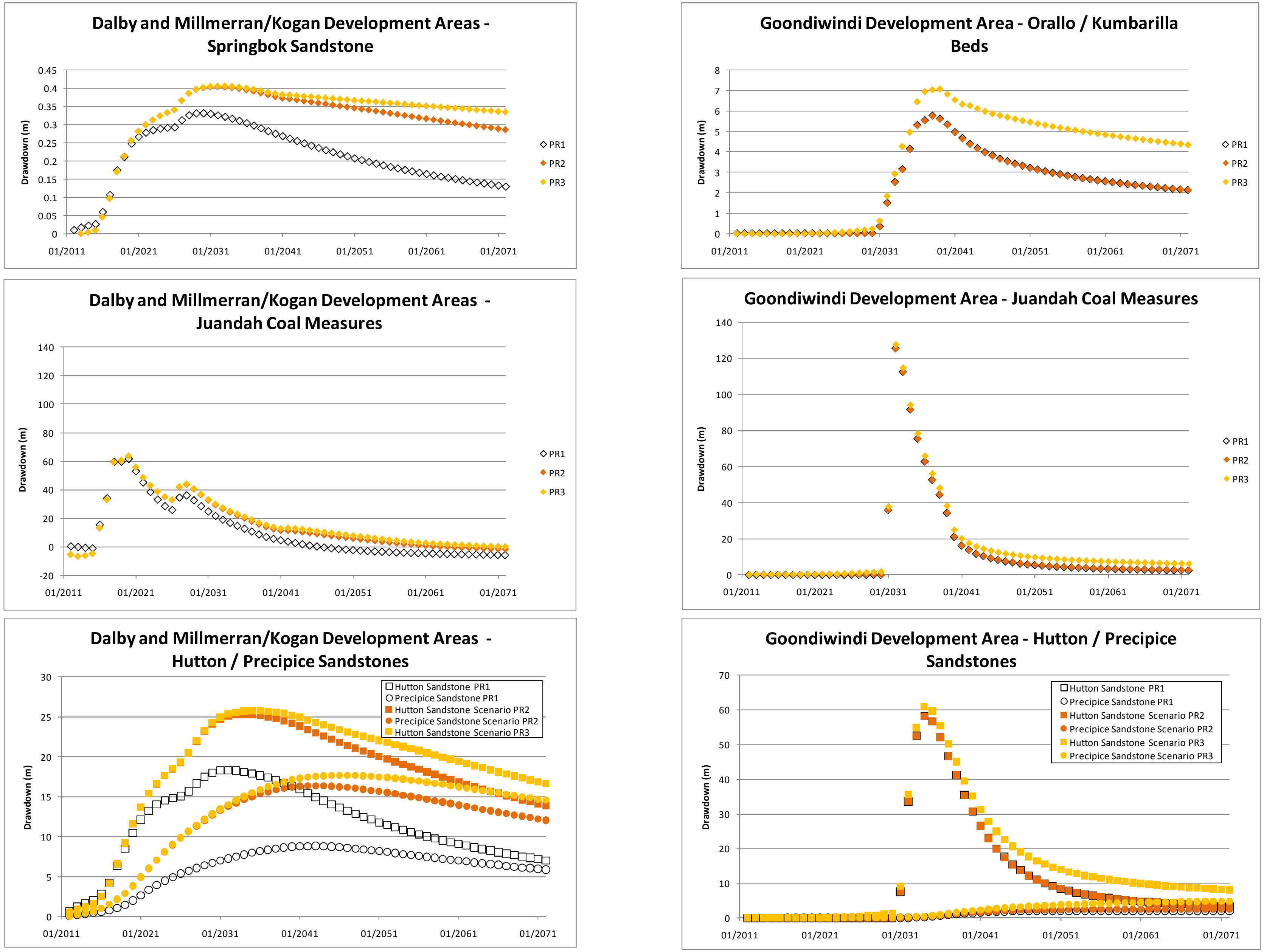

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Figure 4.8 Scenarios 1, 2 and 3 predicted drawdown (Dalby and Millmerran / Kogan locations)

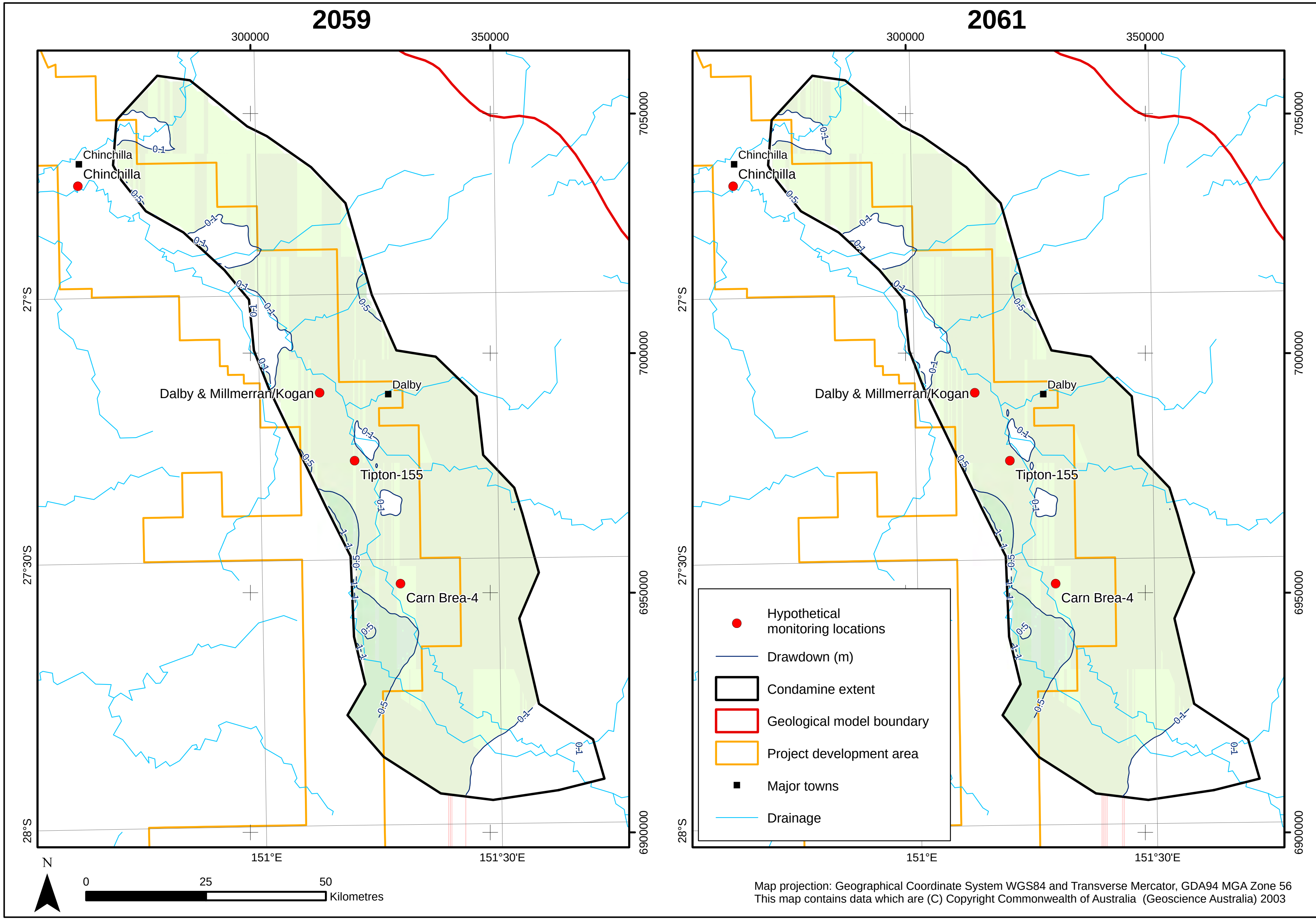

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Figure 4.9 Scenario 1 predicted drawdown contours, Condamine Alluvium (2059 & 2061)

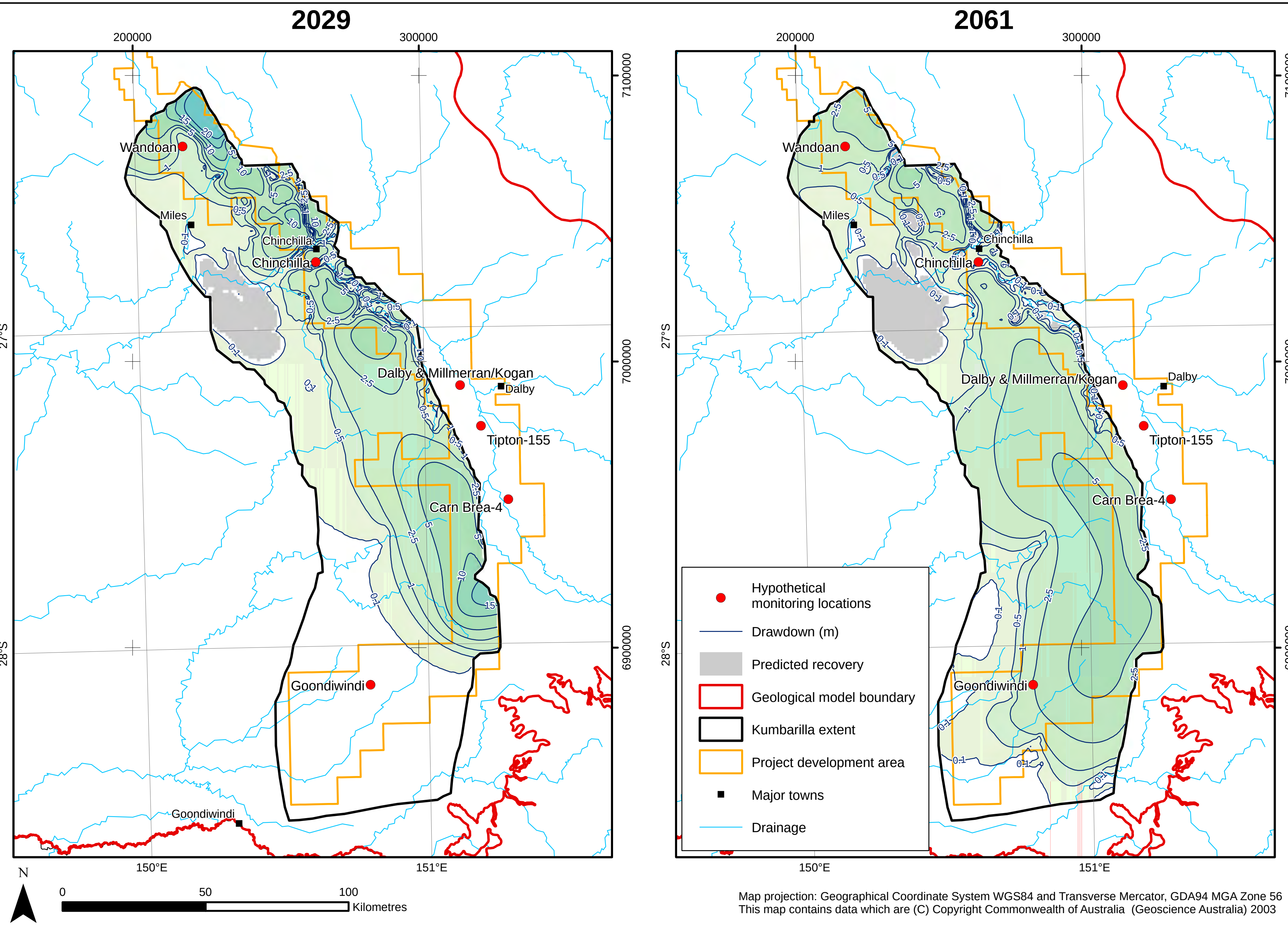

Figure 4.10 Scenario 1 predicted drawdown contours, Kumbarilla Beds (2029 & 2061)

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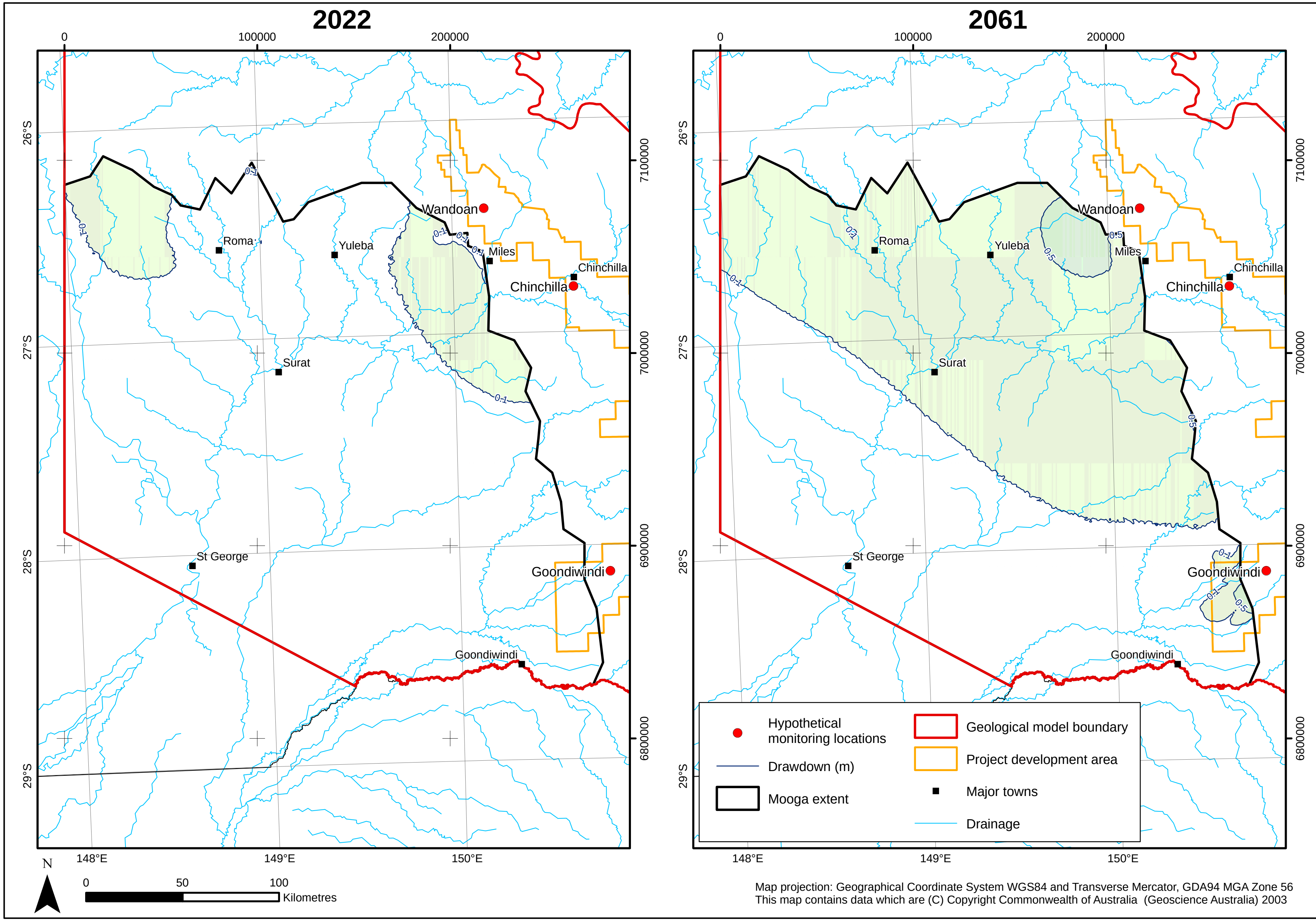

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Figure 4.11 Scenario 1 predicted drawdown contours, Mooga Sandstone (2022 & 2061)

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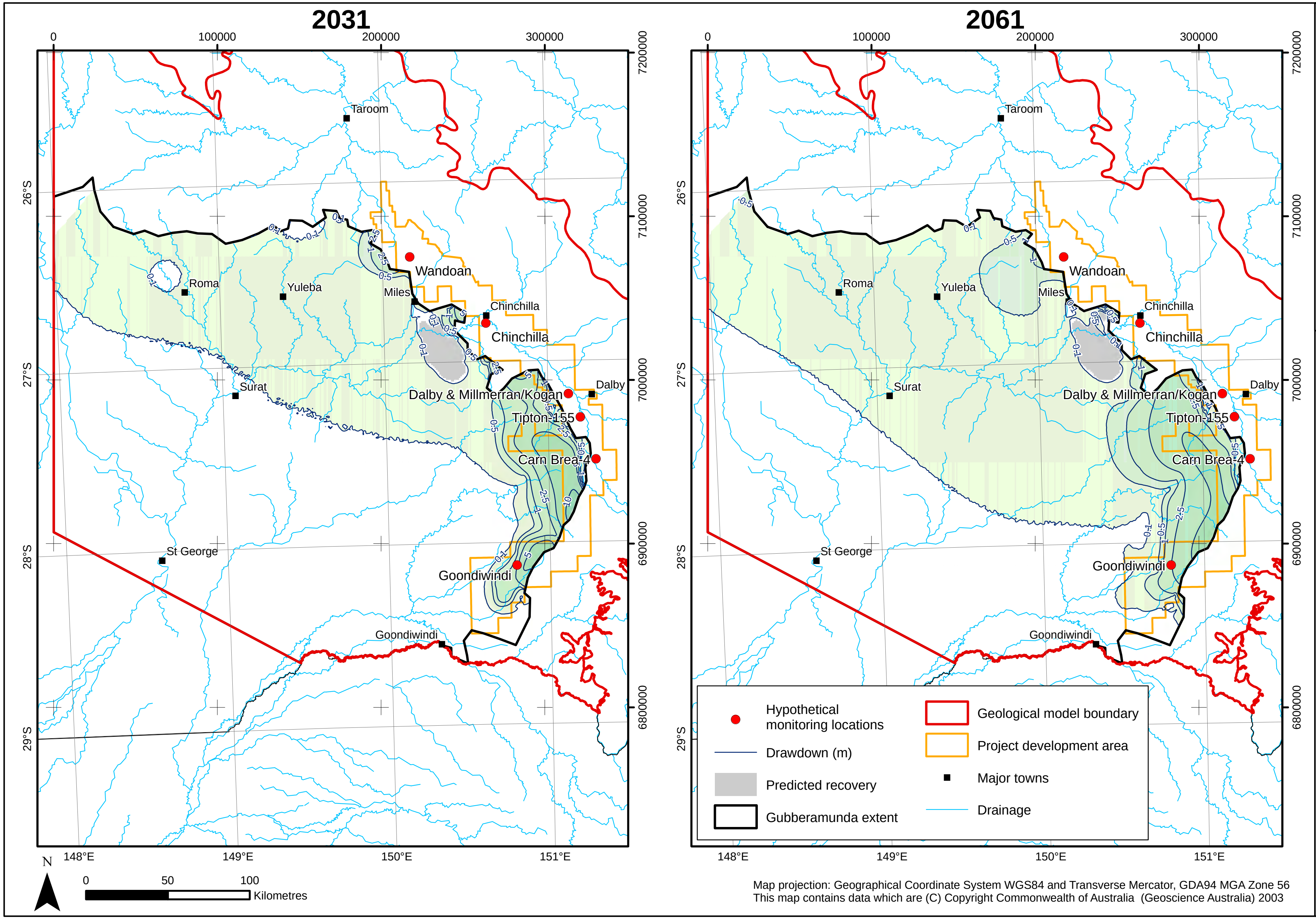

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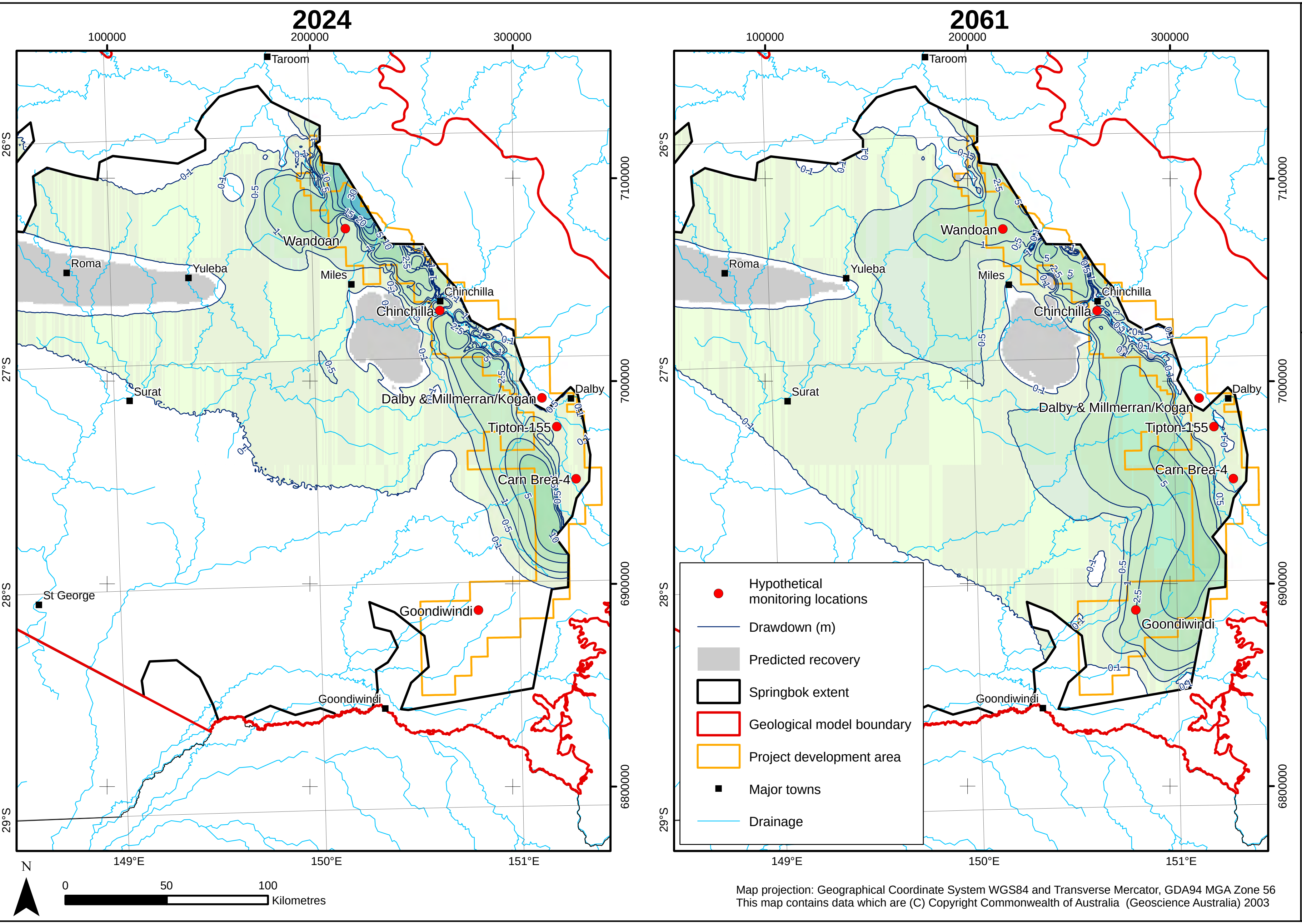
Figure 4.12 Scenario 1 predicted drawdown contours, Gubberamunda Sandstone (2031 & 2061)



Map projection: Geographical Coordinate System WGS84 and Transverse Mercator, GDA94 MGA Zone 56

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Figure 4.13 Scenario 1 predicted drawdown contours, Springbok Sandstone (2024 & 2061)

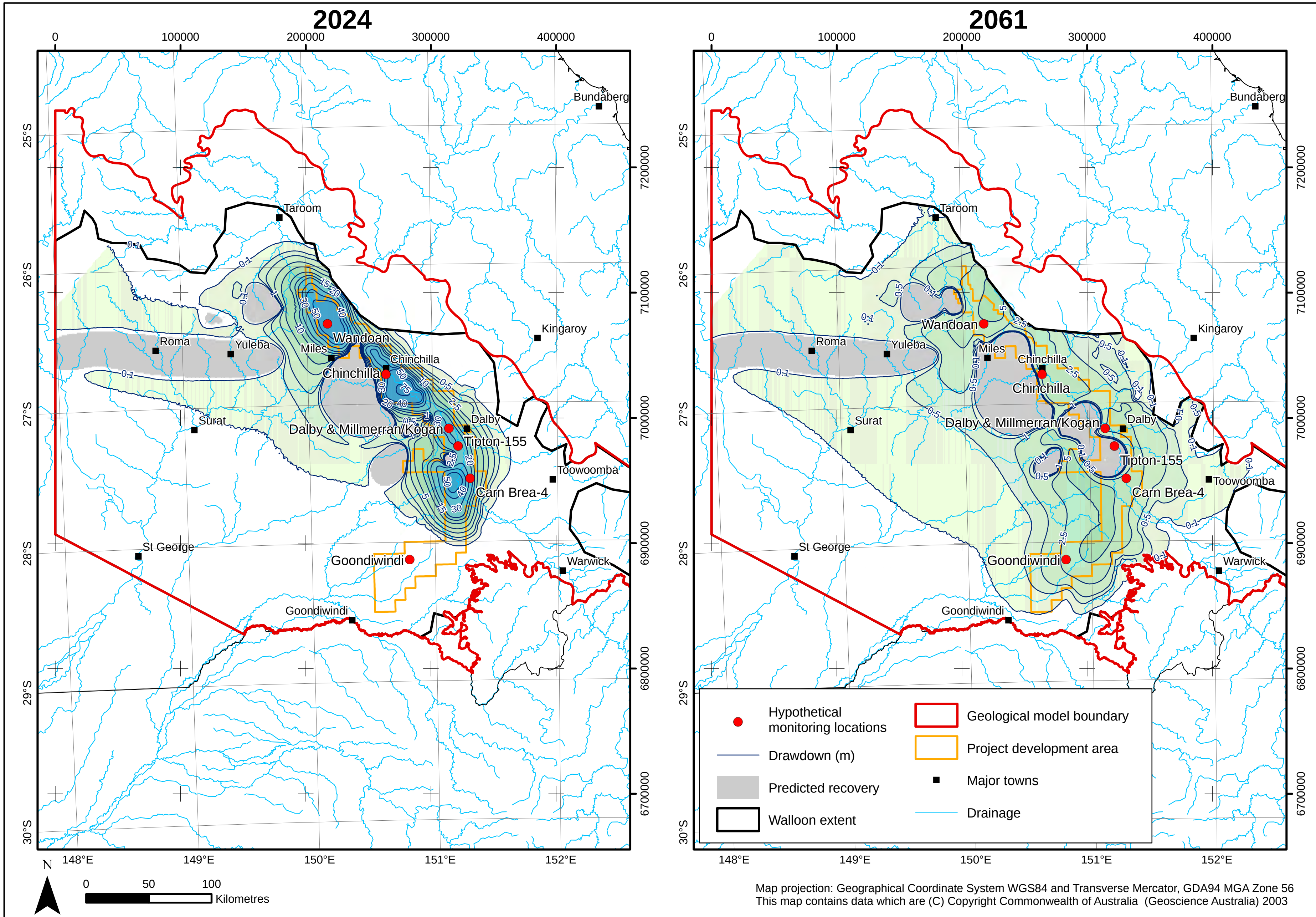

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Figure 4.14 Scenario 1 predicted drawdown contours, Juandah Coal Measures (2024 & 2061)

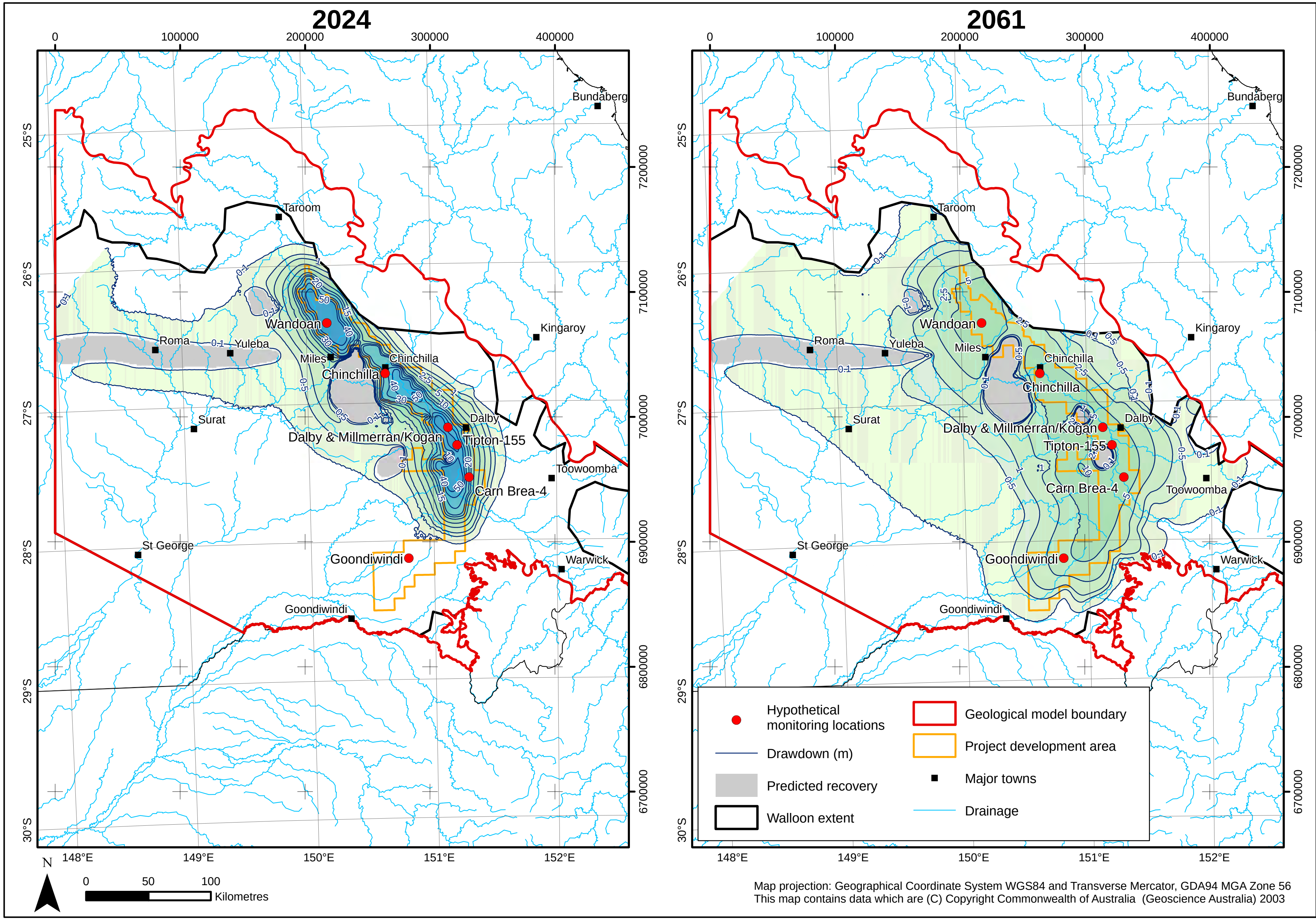

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Figure 4.15 Scenario 1 predicted drawdown contours, Tangalooma Sandstone (2024 & 2061)

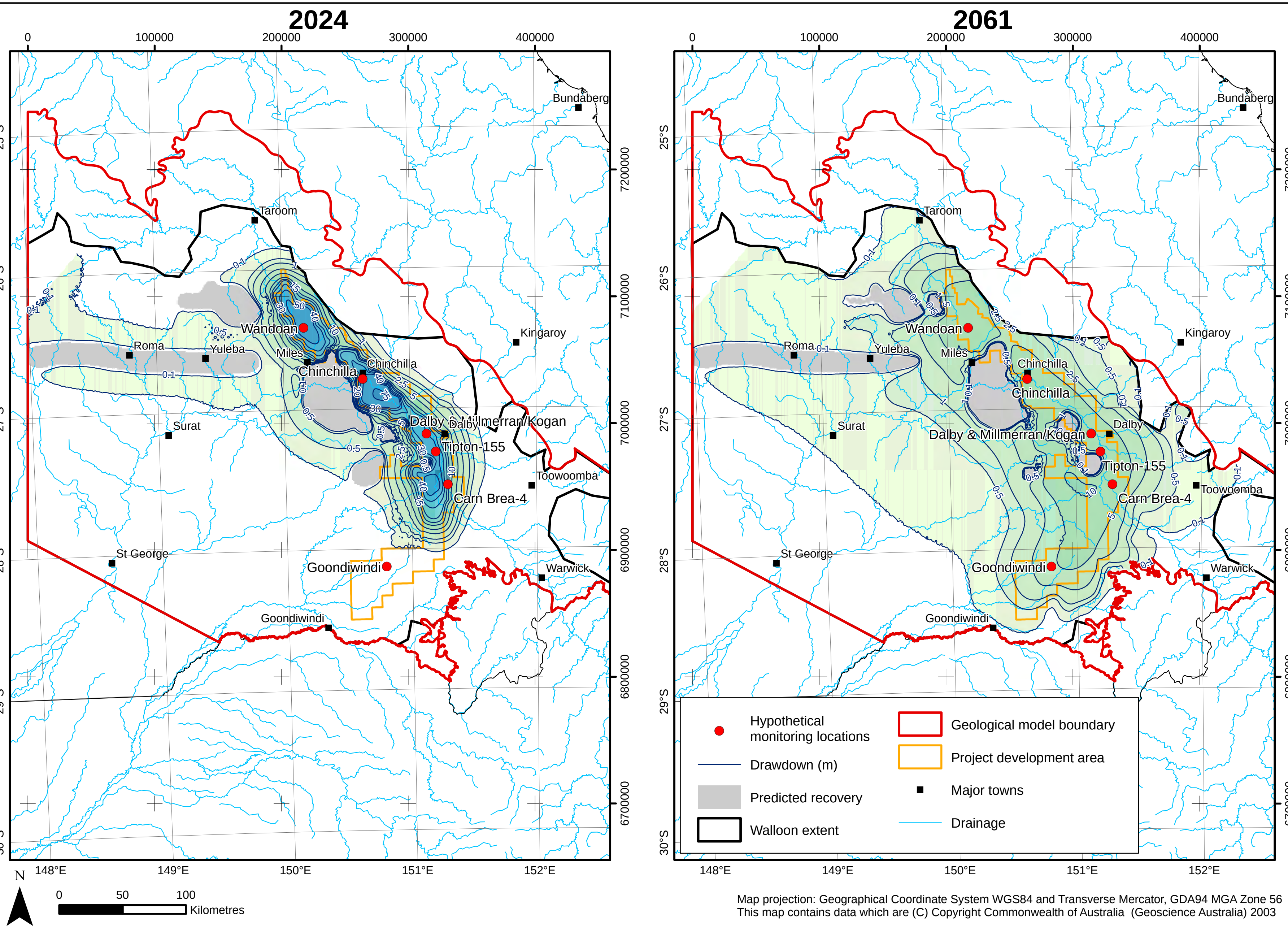

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Figure 4.16 Scenario 1 predicted drawdown contours, Taroom Coal Measures (2024 & 2061)

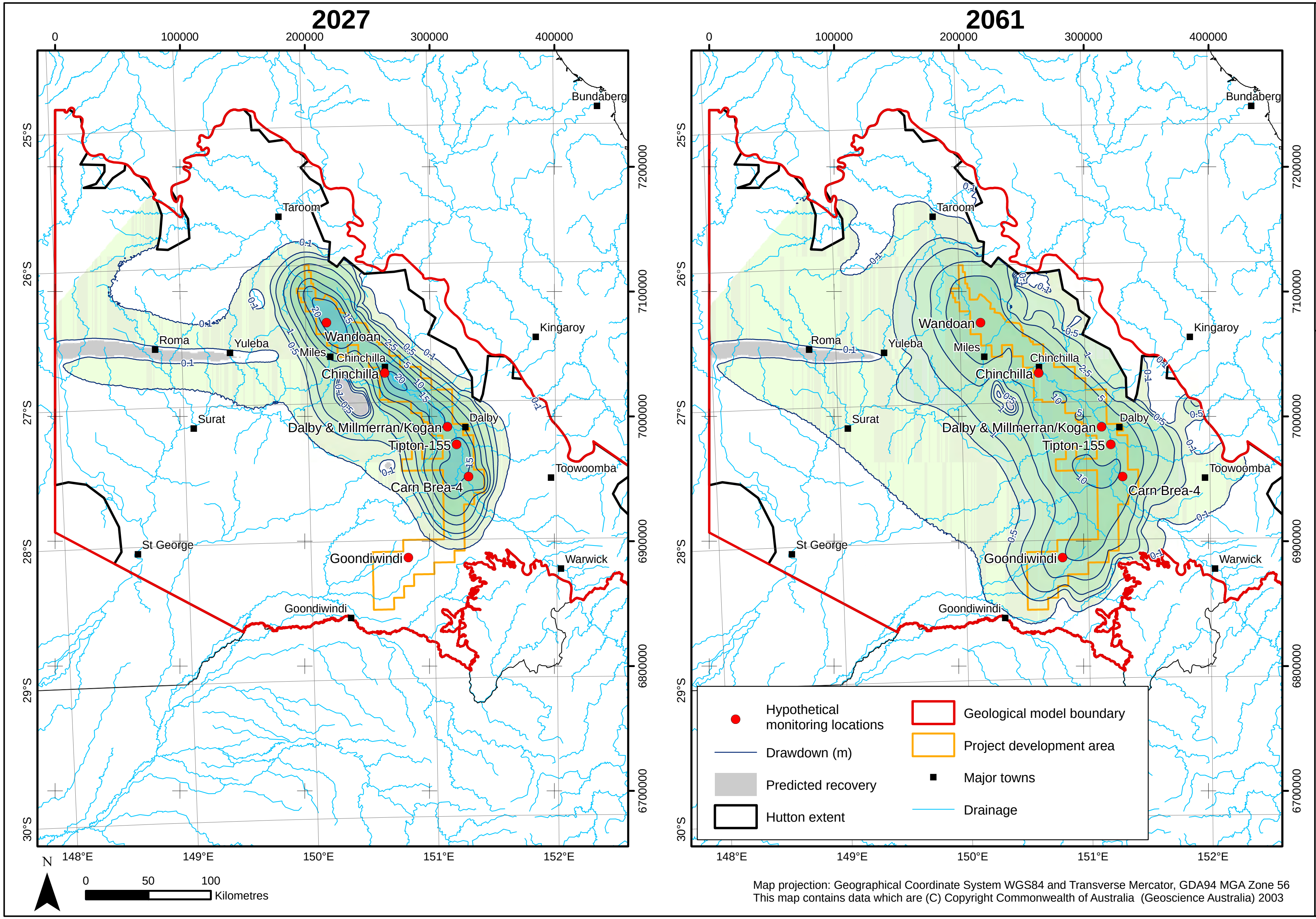
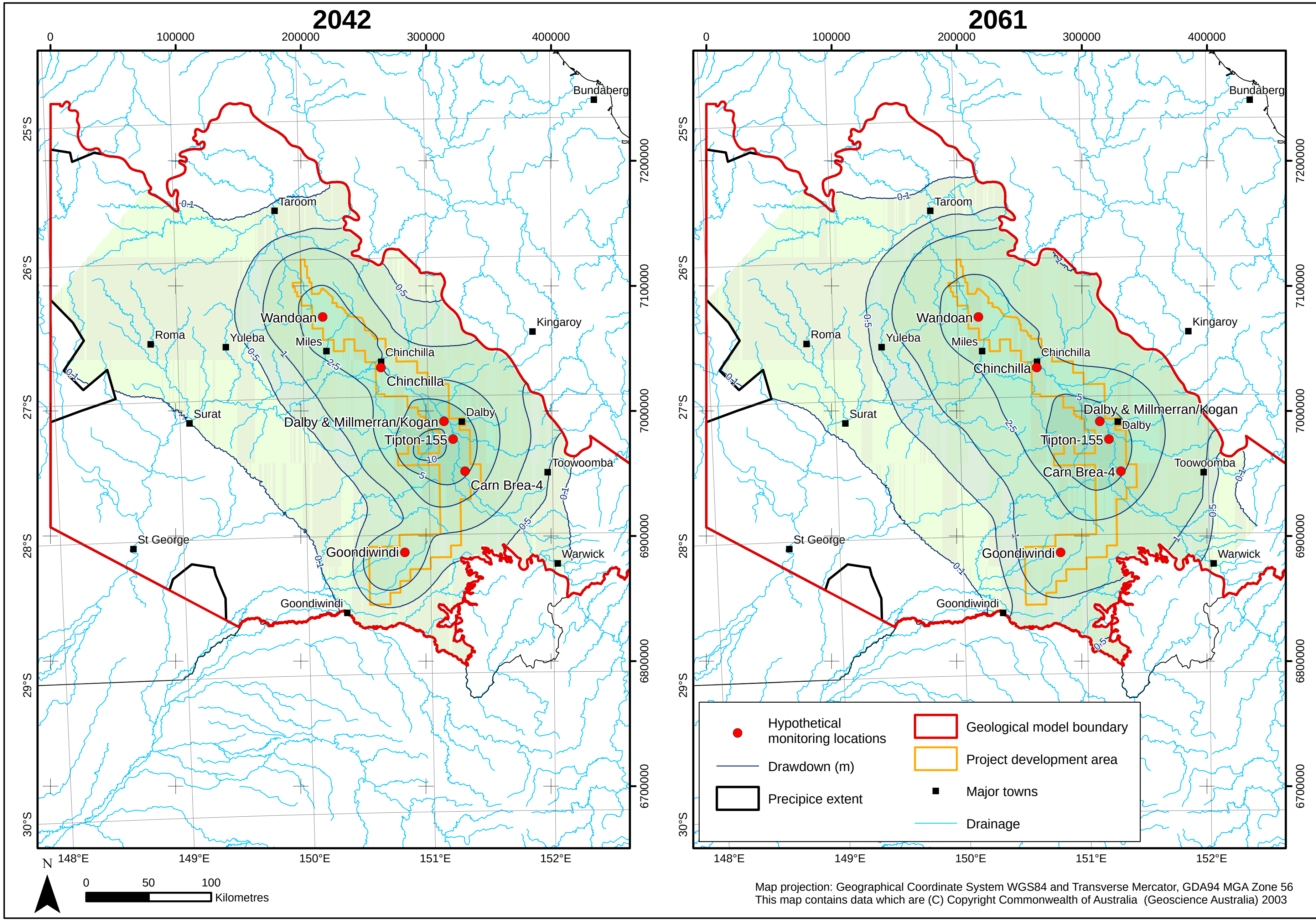


Figure 4.17 Scenario 1 predicted drawdown contours, Hutton Sandstone (2027 & 2061)



Map projection: Geographical Coordinate System WGS84 and Transverse Mercator, GDA94 MGA Zone 56

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Figure 4.18 Scenario 1 predicted drawdown contours, Precipice Sandstone (2042 & 2061)

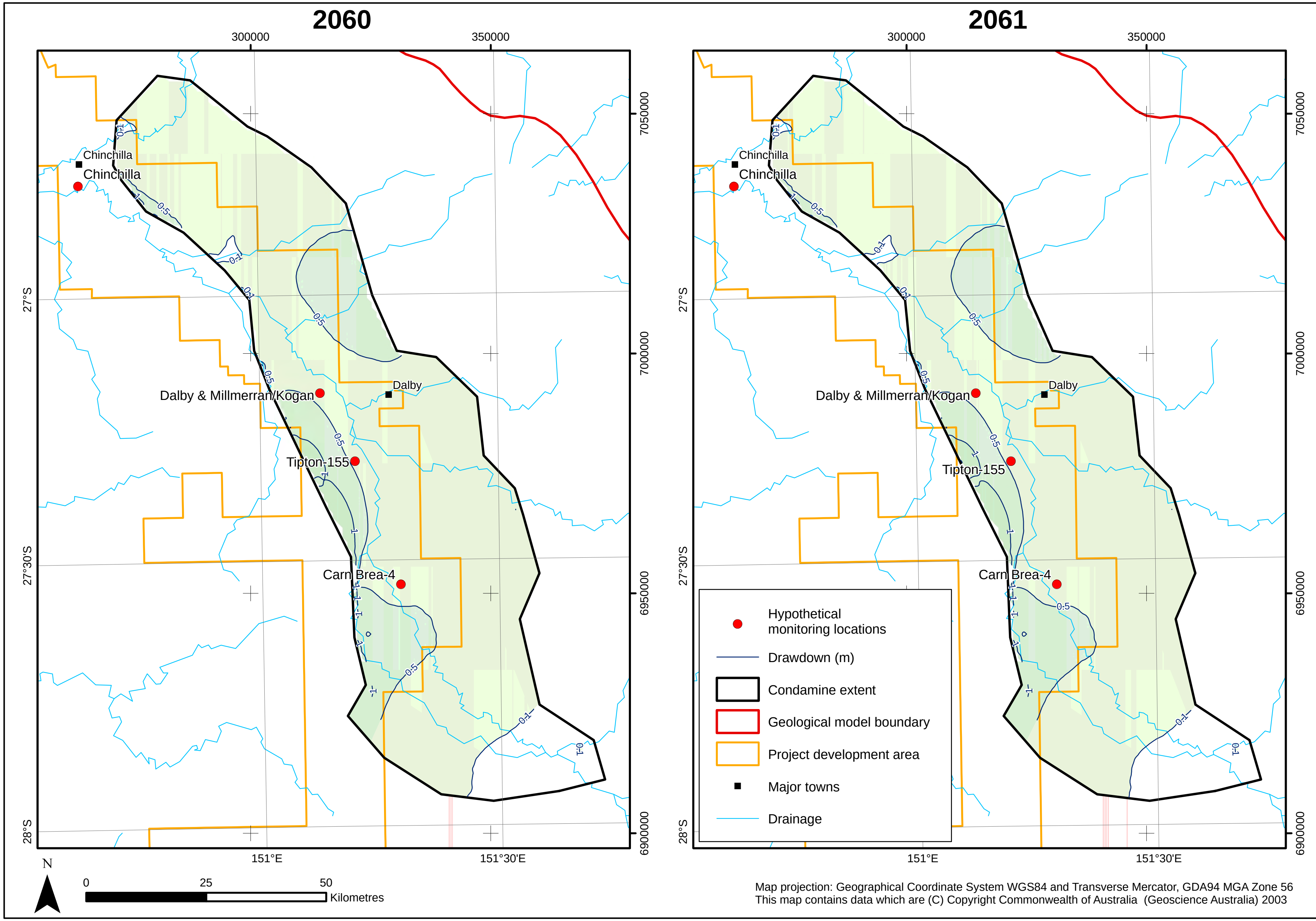

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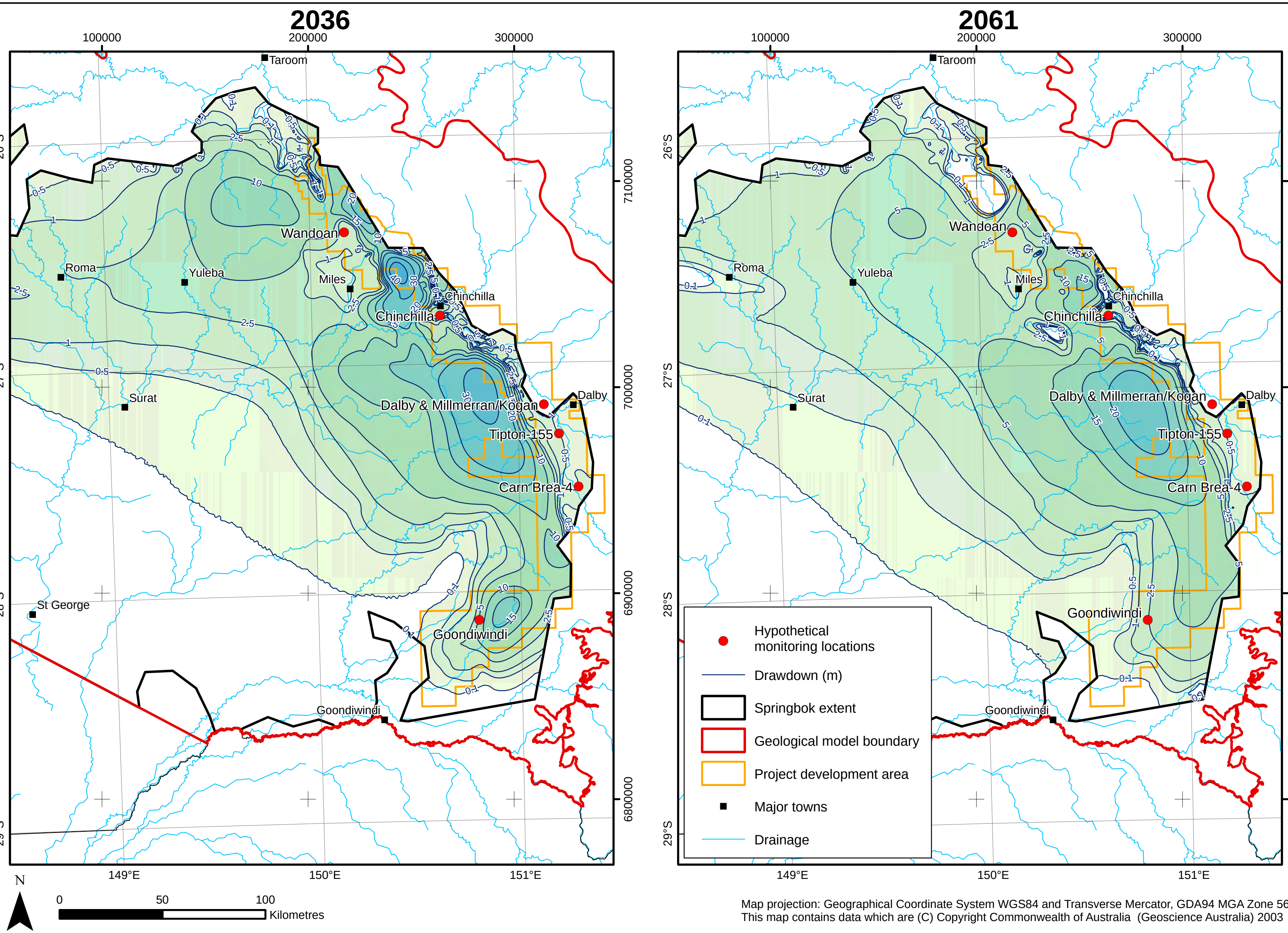
Figure 4.19 Scenario 2 predicted drawdown contours, Condamine Alluvium (2060 & 2061)



Map projection: Geographical Coordinate System WGS84 and Transverse Mercator, GDA94 MGA Zone 56
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Figure 4.20 Scenario 2 predicted drawdown contours, Springbok Sandstone (2036 & 2061)

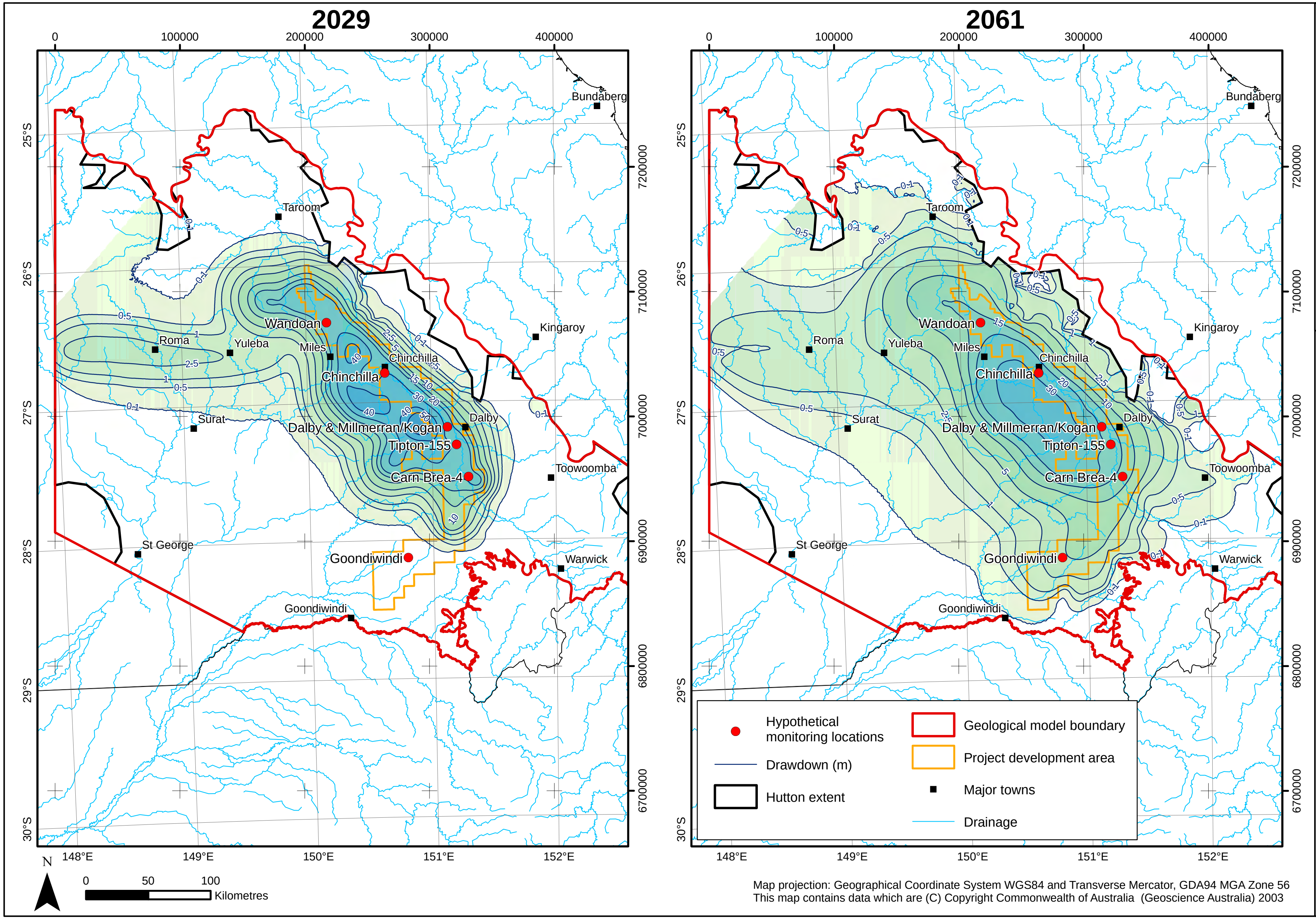

Figure 4.21 Scenario 2 predicted drawdown contours, Hutton Sandstone (2029 & 2061)

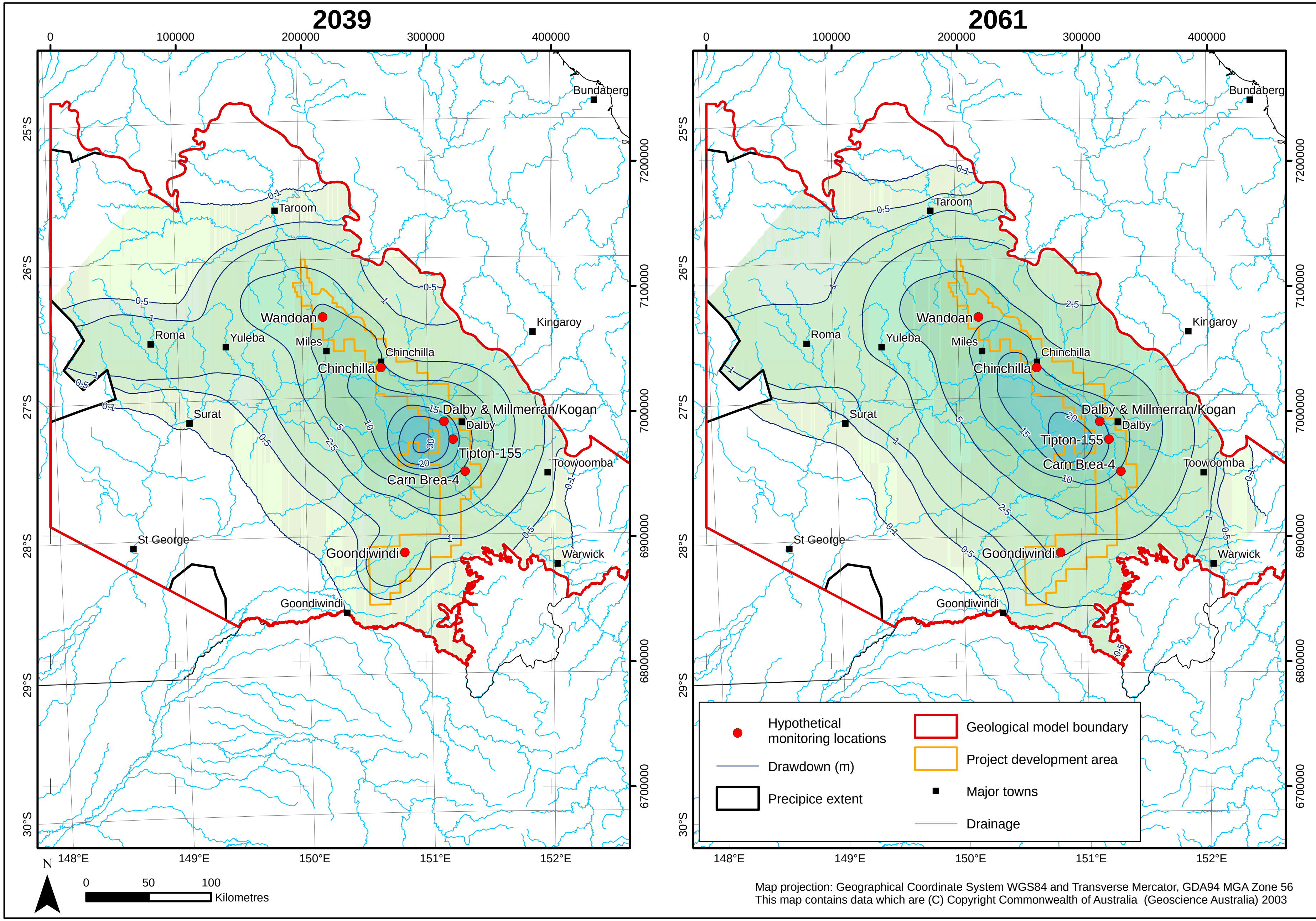

Figure 4.22 Scenario 2 predicted drawdown contours, Precipice Sandstone (2039 & 2061)

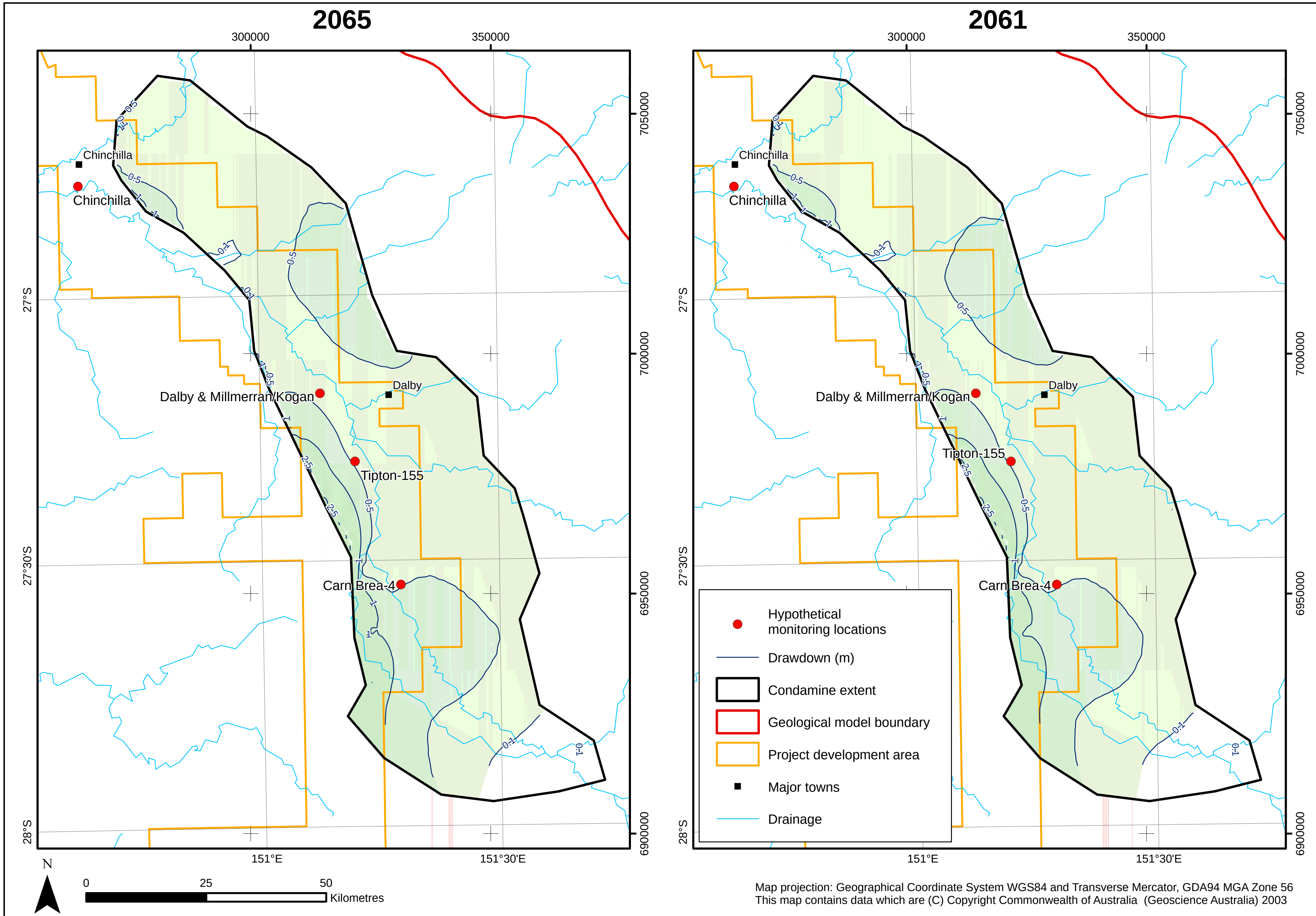

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Figure 4.23 Scenario 3 predicted drawdown contours, Condamine Alluvium (2065 & 2061)

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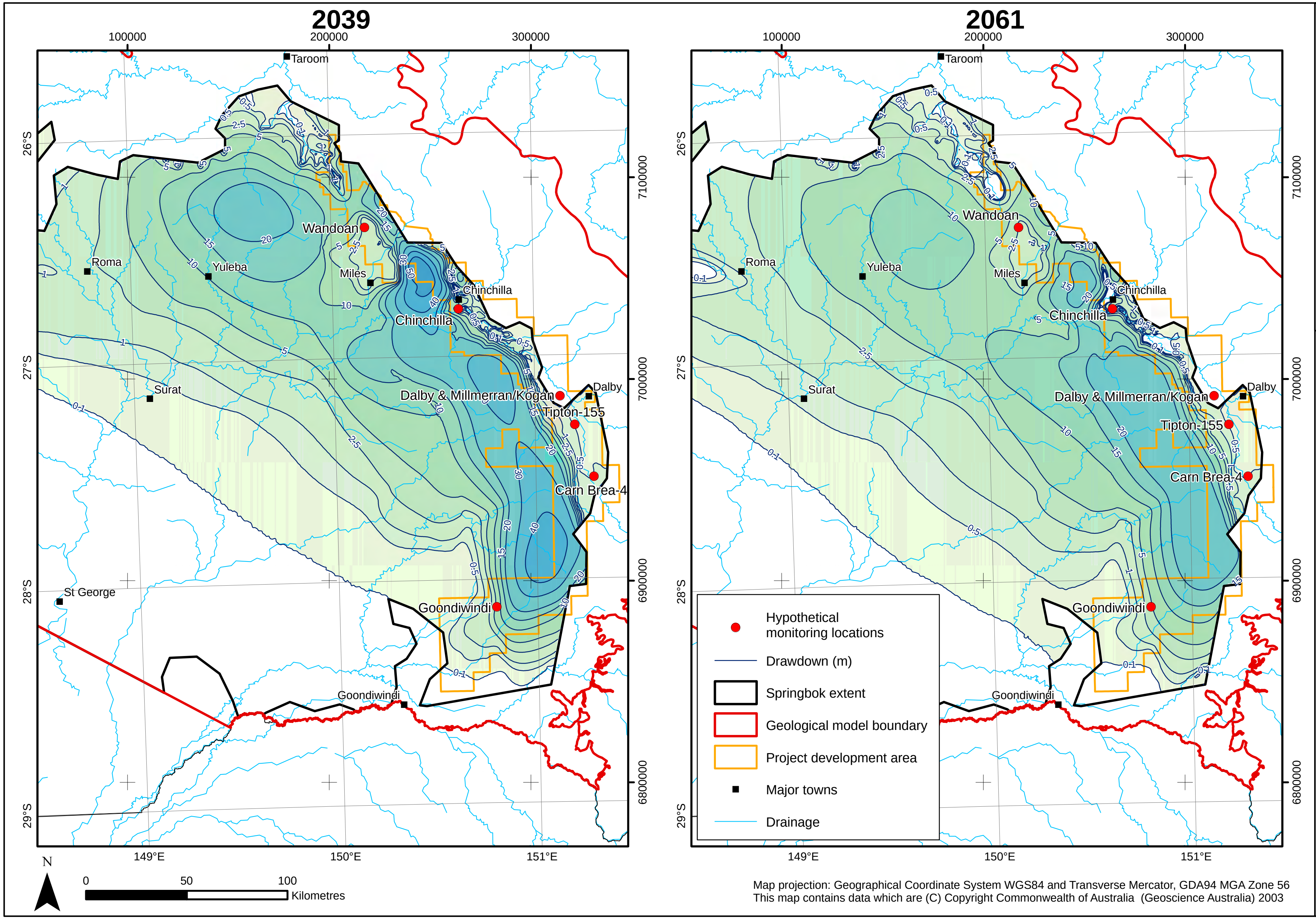

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Figure 4.24 Scenario 3 predicted drawdown contours, Springbok Sandstone (2039 & 2061)

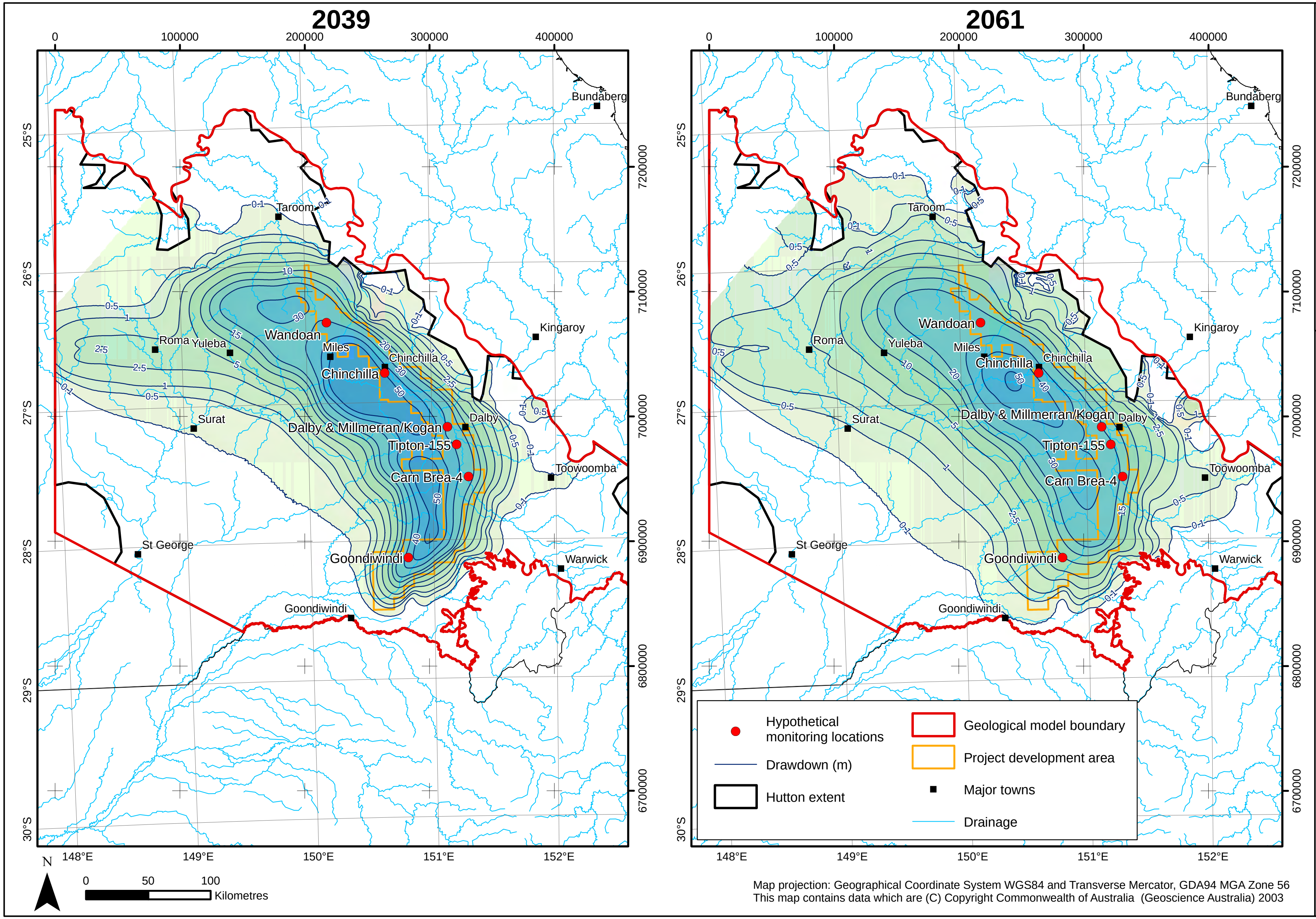

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Figure 4.25 Scenario 3 predicted drawdown contours, Hutton Sandstone (2039 & 2061)

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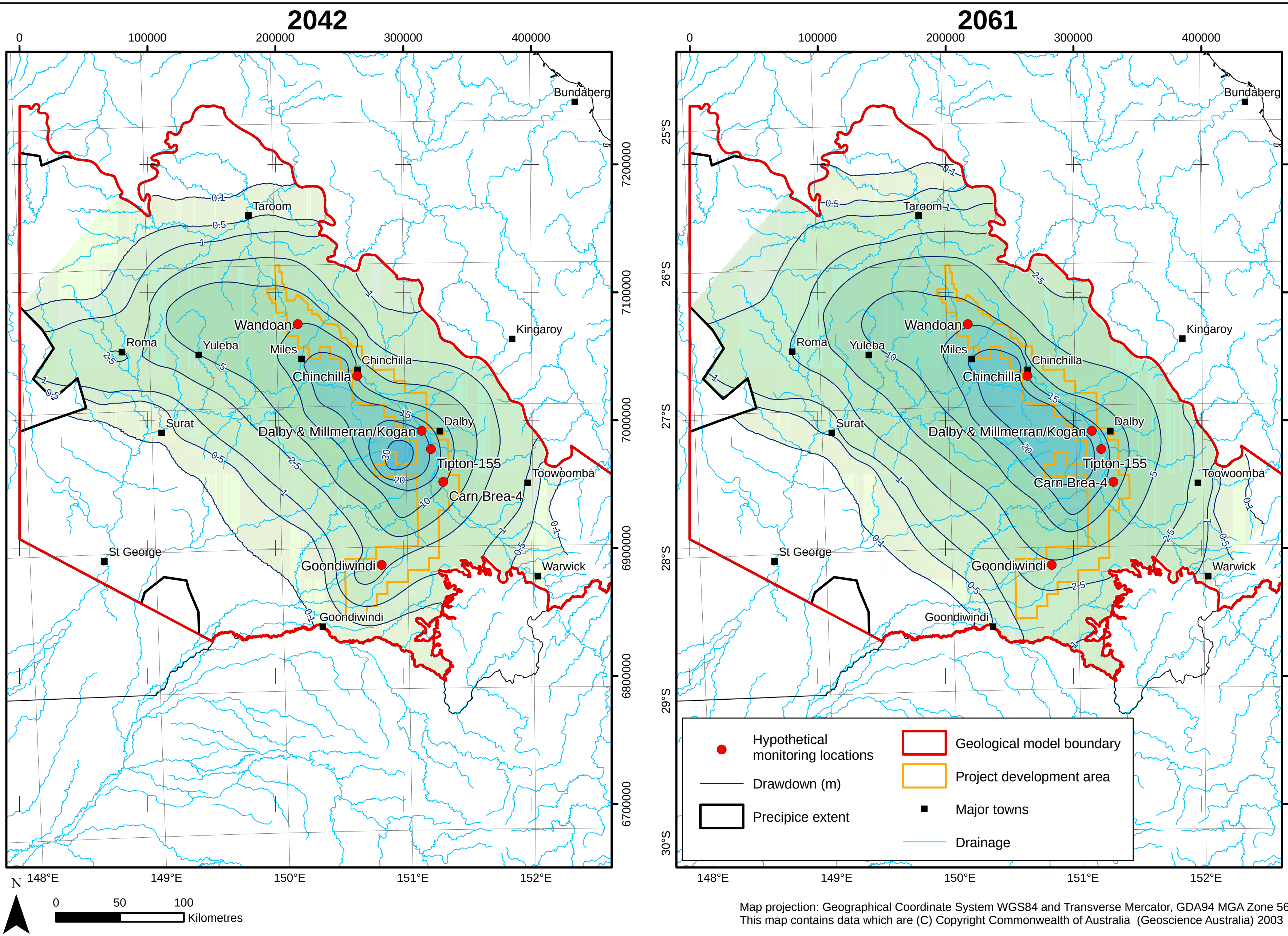

Map projection: Geographical Coordinate System WGS84 and Transverse Mercator, GDA94 MGA Zone 56
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Figure 4.26 Scenario 3 predicted drawdown contours, Precipice Sandstone (2042 & 2061)

5 SENSITIVITY ANALYSIS

5.1 Introduction

Sensitivity analyses have been undertaken with the Scenario 1 predictive model. The analysis assesses the influence that hydraulic parameters of key stratigraphic units have on model predictions of drawdown. The analysis is focussed on the specific storage (Ss) value used in all layers and the Kv of some key lithological units, specifically the "aquitards". The connection between the Walloon Coal Measures and the Condamine Alluvium is also considered, as are all hydraulic properties of the Juandah and Taroom Coal Measures. Each sensitivity run requires changes to the relevant parameters in the steady state (changes to K only), time variant historical and time variant predictive models and then running these in sequence. This is necessary to ensure that the initial conditions for the predictive model correspond to the correct hydraulic parameters. The projected CSG abstractions used in Scenario 1 (i.e. Arrow only) are applied to all of the sensitivity runs.

5.2 Sensitivity scenarios

The configuration of the 15 sensitivity runs is described in Table 5.1.

Sensitivities A and B consider the effect of a general reduction / increase in the Ss value assigned to all units (apart from the Juandah and Taroom Coal Measures) on predicted drawdown. Changing all the model Ss values in this way reflects the paucity of data (hydraulic testing and time variant calibration opportunity) corresponding to this parameter in the Surat Basin outside of the Walloon Coal Measures.

Sensitivities C and D consider the variation of drawdown in the absence of a low permeability unit above the Juandah Coal Seams (Sensitivity C) and when this unit has an order of magnitude lower vertical K than in the calibrated basecase model (Sensitivity D).

Sensitivity E considers the effect of applying the same calibrated basecase K values used in the Westbourne Formation in the portion of that model layer assigned to the Kumbarilla Beds, thus reducing the vertical hydraulic connection between the CSG abstraction and the Upper Jurassic and Alluvium above.

Sensitivities F and G investigate the effect on predicted drawdown of lower Kv values in the unit directly below the Taroom Coal Measures and the unit that separates the Hutton and Precipice Sandstones.

Sensitivities H to L investigate the effect of varying the Ss, Kh and Kv values assigned to the Juandah and Taroom Coal Measures. In all but the case of Kv, both a higher and lower value of each parameter is trialled. Sensitivity J considers a higher Kv of these units, but there is no equivalent low value sensitivity as the calibrated value is considered towards the low end of realistic values (Section 2.5.3).

Sensitivities M and N consider firstly an increased Kh of the Tangalooma Sandstone and then, combined with this, a higher Kv. As the CSG production bores are designed to be open throughout the Juandah Coal Measures, the Tangalooma Sandstone and the Taroom Coal Measures, the hydraulic properties of this unit may provide a significant control on the predicted impacts.

Sensitivity O investigates the effect of a reduced Kv in the Condamine Alluvium and thus a reduced connection between these sediments and the coal measures. Considered in parallel with Sensitivity J and the calibrated model these two runs provide a range of "connection scenarios".

Table 5.1 Configuration of sensitivity runs

Run	Layer / lithology	Change
A	All (except Layers 1 (CA), 9 (J) and 11 (T))	Ss divided by 10 ($5x10^{-7}$ m^{-1})
B	All (except Layers 1 (CA), 9 (J) and 11 (T))	Ss multiplied by 10 ($5x10^{-5}$ m^{-1})
C	Layer 8 – 10 m thick shale	K set to equal Springbok Sandstone: Kh = 0.5 m/d and Kv = 0.05 m/d
D	Layer 8 – 10 m thick shale	K divided by 10: Kh = 0.005 m/d and Kv = $1x10^{-4}$ m/d
E	Layer 6 – Kumbarilla Beds in Westbourne Formation	K set to equal Westbourne Formation: Kh = 0.001 m/d and Kv = $1x10^{-5}$ m/d
F	Layer 12 – Eurombah / Durabilla	Kv divided by 10 ($1x10^{-4}$ m/d)
G	Layer 14 – Evergreen Formation	Kv divided by 10 ($1x10^{-6}$ m/d)
H	Layers 9 and 11 (Juandah and Taroom)	Kh set at (0.1 m/d)
I	Layers 9 and 11 (Juandah and Taroom)	Kh set at (0.005 m/d)
J	Layers 9 and 11 (Juandah and Taroom)	Kv set at (0.0005 m/d) – Kv:Kh = 100
K	Layers 9 and 11 (Juandah and Taroom)	Ss set at ($1x10^{-5}$ m^{-1})
L	Layers 9 and 11 (Juandah and Taroom)	Ss set at ($1x10^{-7}$ m^{-1})
M	Layer 10 (Tangalooma)	Kh increased to 0.05 m/d
N	Layer 10 (Tangalooma)	As above + Kv increased to 0.005 m/d
O	Layer 1 – Condamine Alluvium	Reduced Kv (divided by 10)

* CA (Condamine Alluvium), J (Juandah) and T (Taroom)

5.3 Affect of sensitivities on model calibration

The sensitivity analyses have been undertaken by varying the hydraulic parameters of the calibrated model. In most cases this will perturb the calibration (the match between observed and simulated groundwater levels). The results of these runs must therefore be reviewed with this in mind. However, as each analysis involved the re-running of the time variant historical model, and in most cases the steady state model, this provides an opportunity to compare the calibration of each one with the calibrated basecase. Table 5.2 provides the steady state SRMS for each run and Figures 5.1 to 5.15 present the time variant observed and simulated groundwater levels at Arrow monitoring bores (all within the Walloon Coal Measures).

Table 5.2 Sensitivity run steady state model SRMS

Sensitivity Run	Steady state SRMS (%)	Difference to the calibrated basecase
A	N/A	N/A
B	N/A	N/A
C	6.8	0.0
D	6.8	0.0
E	8.5	+1.7
F	6.8	0.0
G	6.9	+0.1
H	6.8	0.0
I	6.8	0.0
J	6.6	-0.2
K	N/A	N/A
L	N/A	N/A
M	6.8	0.0
N	6.8	0.0
O	6.8	0.0

The Table shows that there is little difference between any of the sensitivity run steady state SRMS values and the calibrated case. Sensitivity E produces a different result, but it is still relatively low (8.5% compared to 6.8% for the calibrated case). This analysis shows that the calibration to the steady state regional dataset is relatively insensitive to these changes. This does not mean however that at a local scale some more significant variations in simulated groundwater level will not be found.

The hydrographs (Figures 5.16 to 5.39) show that for the following sensitivity runs the simulated time variant response in the Walloon Coal Measures is similar to the calibrated basecase:

- Sensitivity A. This sensitivity produces slightly more drawdown in the coal measures due to the lower Ss of the surrounding layers
- Sensitivity B. This sensitivity produces slightly less drawdown in the coal measures due to the higher Ss of the surrounding layers
- Sensitivity C. This sensitivity produces an identical response to the calibrated case
- Sensitivity E. This sensitivity produces slightly more drawdown in the coal measures due to the lower Kh and Kv of the Kumbarilla Beds above them (therefore reduced vertical flow of water into them)
- Sensitivity F. This Sensitivity produces an identical response to the calibrated case
- Sensitivity G. This sensitivity produces slightly more drawdown in the coal measures due to the lower Kv of the Evergreen Formation below them (therefore reduced vertical flow of water into them)
- Sensitivity H. This sensitivity produces slightly less drawdown due to the higher Kh assigned to the Juandah and Taroom Coal Measures. At Daandine 25 the simulated groundwater levels compare better to the observed than the calibrated case

- Sensitivity M. This Sensitivity produces a very similar response to the calibrated case
- Sensitivity N. This Sensitivity produces a very similar response to the calibrated case
- Sensitivity O. This Sensitivity produces an identical response to the calibrated case

At a number of locations, the calibration to Walloon Coal Measure observed groundwater levels has been, on the whole, negatively affected. However, due to the heterogeneity of the system, whilst at the majority of locations the comparison between observed and simulated is worse, there are locations where it has become better. These results therefore suggest that caution should be taken when considering the predictions from these sensitivity runs, but they also provide information as to the potential hydraulic characteristics in local areas. The following sensitivity runs fall into this category:

- Sensitivity D. Reduction of the Kh and Kv assigned to the layer representing a 10 m thick "shale" immediately above the Juandah Coal Measures has a significant effect at all monitoring locations. Simulated drawdown increases significantly and is far more than observed in most cases. At River Road 1 however the increased drawdown results in a very good match to observed data in the first half of 2009. In this location 1 m of drawdown is simulated in this sensitivity compared to 0 m in the calibrated case.
- Sensitivity I. Decreasing the Kh in the Juandah and Taroom Coal Measures has the effect of increasing drawdown in the vicinity of abstractions and decreasing drawdown away from them. This means that the predicted drawdown response at the observation locations can be either greater or smaller than the calibrated basecase. At the majority of locations this produces a poor or relatively unchanged drawdown response compared to the calibrated case. At Plainview 1 however the simulated drawdown is similar to observed in this sensitivity, where in the calibrated case the simulated drawdown is too great. In the region of Plainview 1 then, this parameter combination may be more appropriate.
- Sensitivity K. Increasing the Ss of the Juandah and Taroom Coal Measures has the effect of decreasing drawdown in the same units. The results suggest in fact that this value ($1x10^{-5}$ m^{-1}) is not representative, as at most locations predicted drawdown has reduced to almost zero. At Daandine 25 however the change improves the match between observed and simulated drawdown, and may better reflect the system at this locality.
- Sensitivity L. Decreasing the Ss of the Juandah and Taroom Coal Measures has the effect of increasing drawdown in the same units, and producing more rapid recovery when abstraction rates decrease. The effect is less pronounced than the equivalent increase in Ss (Sensitivity K) but at most locations it reduces the goodness of fit between observed and simulated groundwater levels. Only in the Meenawarra area (evidenced by both Meenawarra 5 and 6) is the match improved.

5.4 Results

Predicted drawdown from the sensitivity runs is displayed at the position of the 3 "hypothetical" monitoring locations in the Condamine Alluvium and the 4 locations at the centres of the Arrow Development Areas. The latter set provides predictions of drawdown in the Springbok Sandstone, Kumbarilla Beds, Juandah Coal Measures and Hutton and Precipice Sandstones. The hydrographs are displayed in Figures 5.16 to 5.39.

The results are described for each sensitivity scenario and comparisons made to the original predictive Scenario 1 results below.

Sensitivities A and B (Figures 5.16 to 5.18)

These sensitivities investigate both a significant reduction and a significant increase in Ss (in all layers apart from the Juandah and Taroom Coal Measures and Condamine Alluvium). The reduction in Ss results in greater predictions of drawdown in every model layer. The increase results in lower drawdown. The model predictions are therefore sensitive to the "regional" Ss value.

In the reduced Ss run (Sensitivity A) the Condamine Alluvium experiences almost 60% greater drawdown compared to the calibrated basecase. However, at the "hypothetical" monitoring locations this still equates to a peak of less than 1 m. A similar response (in terms of magnitude) is observed in the Springbok Sandstone, although in the Goondiwindi Development Area it is far more pronounced than in the areas to the north. The effect is also greater in the Hutton and Precipice Sandstones, where predicted drawdown is more than three times greater than the calibrated basecase in some areas.

In the increased Ss run (Sensitivity B) all model layers are predicted to observe reduced drawdown compared to the calibrated basecase. The greatest effect is seen in the Hutton and Precipice Sandstones, where drawdown is reduced by around 80% in many locations.

In most cases the timing of the peak in drawdown is also affected by this parameter change, and it occurs a few years earlier in Sensitivity A compared to the calibrated basecase, and a few years later in Sensitivity B.

Recovery of water levels in Sensitivity A is also more rapid than the calibrated basecase. In Sensitivity B it is slower. This leads to a situation in some units (e.g. the Hutton Sandstone) where the water levels have recovered further in Sensitivity A than the calibrated basecase by the end of the model (2071).

Sensitivity C and D (Figures 5.19 to 5.21)

At the regional scale of the modelling there are no significant differences between the predictions of the Sensitivity C run and the calibrated basecase model in any of the main hydrogeological units.

The changes made to the "10 metre thick shale" in Sensitivity D however do have an effect on the predictions. However, these effects are generally quite limited, both in scale and spatially. For example no change in drawdown compared to the calibrated basecase is predicted in the Dalby, Millmerran / Kogan or Goondiwindi Development Areas, and no difference is predicted in any part of the Condamine Alluvium.

The model predictions are therefore not particularly sensitive to this parameter (although the calibration was very sensitive to it in Sensitivity D).

Sensitivity E (Figures 5.22 to 5.24)

Reducing the Kh and Kv of the Kumbarilla Beds within the Westbourne Formation has a significant effect on predicted drawdown in the upper model layers (Condamine Alluvium to Springbok Sandstone) but virtually none in the lower layers (Juandah Coal Measures to Precipice Sandstone).

This parameter change reduces the hydraulic connection between the Condamine Alluvium and the Walloon Subgroup and therefore results in lower drawdown predictions in this unit compared to the calibrated basecase. Beneath the Kumbarilla Beds within the Westbourne Formation however, the availability of water is limited by this change compared to the calibrated basecase. This results in significantly more predicted drawdown in the Springbok Sandstone, especially in the Wandoan Development Area.

Sensitivity F and G (Figures 5.25 to 5.27)

Reducing the Kv of the Eurombah / Durabilla Formations (Sensitivity F) has almost no effect on predicted drawdown throughout the model.

Predicted drawdown is only marginally more sensitive to reducing the Kv of the Evergreen Formation (Sensitivity G). This change has the effect of increasing predicted drawdown in the Hutton Sandstone (as less water flows in from the Precipice Sandstone) and reducing the predicted drawdown in the Precipice Sandstone (as the hydraulic connection between it and the Walloon Subgroup is reduced).

Sensitivity H and I (Figures 5.28 to 5.30)

The hydrographs reveal that model predictions show a limited sensitivity to variations in Juandah and Taroom Coal Measure Kh, and the response is spatially variable. A reduction in Kh produces an increase in predicted drawdown compared to the calibrated basecase, and an increase in Kh has the opposite effect. The response to the former is greater than the latter, but this is primarily due to the greater magnitude of reduction of Kh in Sensitivity I (divided by 10) compared to the increase in Sensitivity H (multiplied by 2).

Apart from in the coal measures themselves, the most obvious effects are limited to the Condamine Alluvium and Springbok Sandstone. The reduction in Kh (Sensitivity I) has a significant effect on predicted drawdown in the Condamine Alluvium, but in the 3 “hypothetical” monitoring positions it remains below 0.5 m. In the Dalby and Millmerran / Kogan Development Area almost 50% more drawdown is predicted in the Springbok Sandstone compared to the calibrated basecase. However, Sensitivity I also showed a significantly compromised calibration so the results should be considered with caution.

Sensitivity J and O (Figures 5.37 to 5.39)

Both of these sensitivity runs consider the connection between the Condamine Alluvium and the Walloon Subgroup. Sensitivity J considers an increase (by increasing the Kv of the coal measures) and Sensitivity O considers a decrease (by reducing the Kv of the alluvium). The runs produce significantly different results in terms of the change from calibrated basecase predictions.

Sensitivity O has only a very limited effect, and predictions are roughly the same as those from the calibrated basecase.

Sensitivity J results in a very significant change, and in all model layers. Predicted drawdown increases significantly in the upper units but reduces in the lower units (particularly the coal measures). In the Condamine Alluvium predicted drawdown increases to over 1 m at Carn Brea 4 (about 1.5 m) and Tipton 155 (about 1.1 m). This is the only sensitivity run where this magnitude of increase is predicted in the alluvium. The increase is also significant in the Springbok Sandstone. In the Chinchilla Development Area the recovery of water levels to a value greater than the initial values points to a major change in the dynamics of the model. The significant reduction in levels has caused a reduction in discharge from the model via the drain cells (including model cells that have dewatered and become inactive). Inflow to the model via constant heads has not varied significantly, and inflow via recharge has not changed at all. This means that the model recovers much more strongly in certain areas, and these results in particular may be inaccurate. This effect can also be seen in the Hutton Sandstone in the Chinchilla Development Area. It is not however experienced in other areas of the model. This phenomenon was also noted in the results of Predictive Scenario 3.

Sensitivity K and L (Figures 5.31 to 5.33)

The hydrographs reveal that model predictions show a limited sensitivity to the reduction in Juandah and Taroom Coal Measure Ss. The timing of the drawdown is affected slightly, but the magnitude is virtually the same.

Model predictions show a much greater sensitivity to the increase in Juandah and Taroom Coal Measure Ss. At all “hypothetical” monitoring locations significantly less drawdown is predicted in Sensitivity K than the calibrated basecase. However, in almost all locations recovery is also slower, meaning that at the end of the simulation (2071) this sensitivity predicts greater drawdown than the calibrated basecase.

Sensitivity M and N (Figures 5.34 to 5.36)

Both of these sensitivities consider the hydraulic parameters of the Tangalooma Sandstone. The results show that the model predictions are insensitive to the value of Kh assigned to them (Sensitivity M). They also show however that the predictions are more sensitive to their Kv value (Sensitivity N). The increased Kv value results in slightly less predicted drawdown in most model layers (including the Condamine Alluvium).

5.5 Conclusions

The sensitivity analysis described above has provided the following:

- An understanding of which model hydraulic parameters have the greatest control on simulated drawdown from the production of associated water from CSG activities, and
- Given the uncertainties in the "calibrated" hydraulic parameters, an understanding of the potential magnitude range of drawdown that can be expected from the production of associated water from CSG activities.

The model parameters which have the greatest affect on predicted drawdown are the groundwater storage of the confined system, the horizontal and vertical hydraulic conductivity of the Kumbarilla Beds, and the horizontal and vertical hydraulic conductivity of the Juandah and Taroom Coal Measures. Changes to these parameters result in significant changes in the timing, extent and magnitude of drawdown in the regional system.

Predicted drawdown at each of the hypothetical monitoring bores is provided for the sensitivity runs. This illustrates the range of drawdown that can be expected based on these parameter combinations. For example, the maximum predicted drawdown in the Condamine Alluvium has been shown to vary between about 0.2 m and 1.6 m (at Carn Brea 4).

The results from these sensitivities, especially in terms of the predicted magnitude of drawdown, should be considered with some caution as the changes in parameters may also have an effect on the ability of the model to simulate the (historic) observed groundwater system. When this is the case, the ability of the models to accurately simulate the groundwater system into the future is also in doubt.

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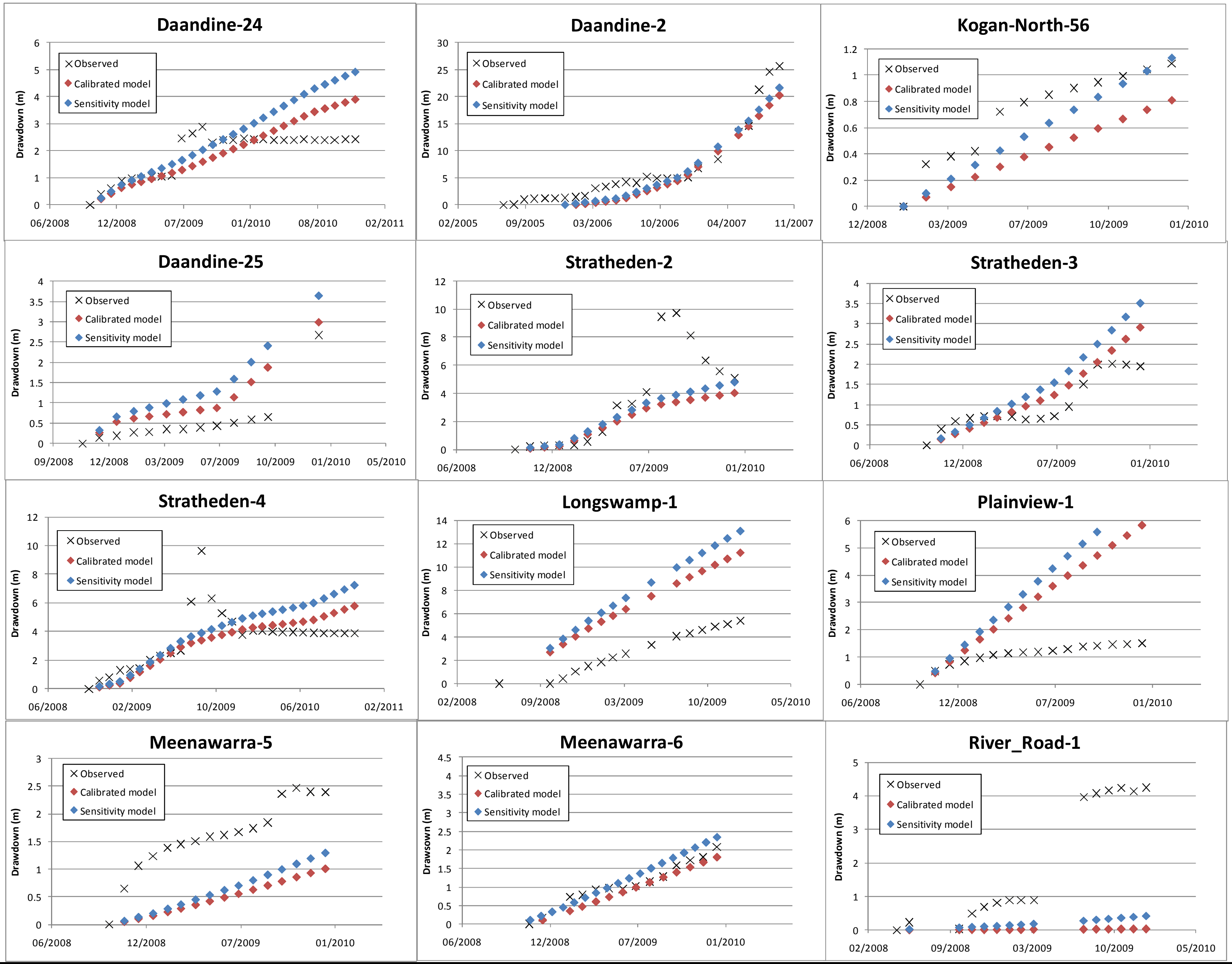

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Figure 5.1 Sensitivity A time variant calibration to Arrow monitoring data

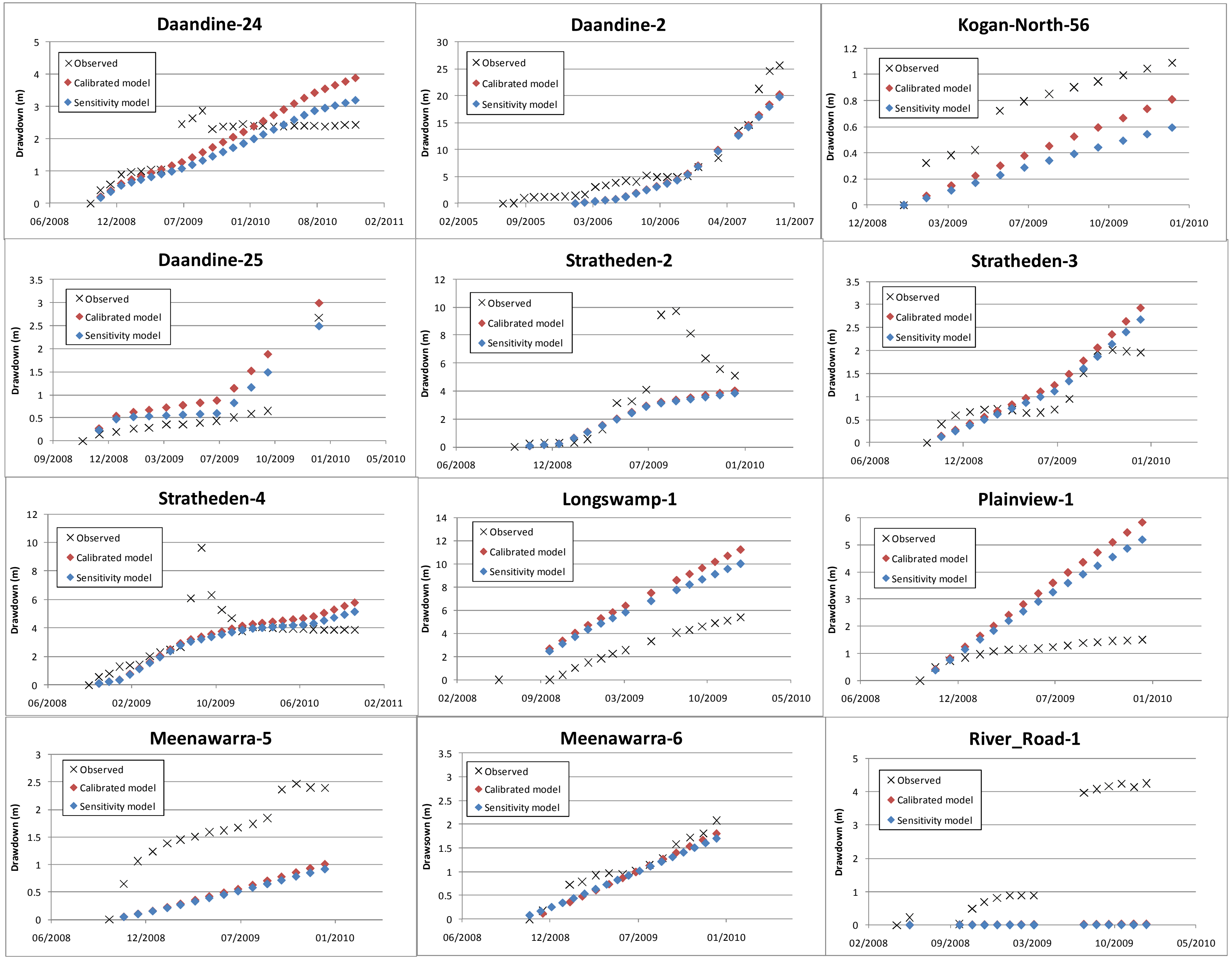

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Figure 5.2 Sensitivity B time variant calibration to Arrow monitoring data

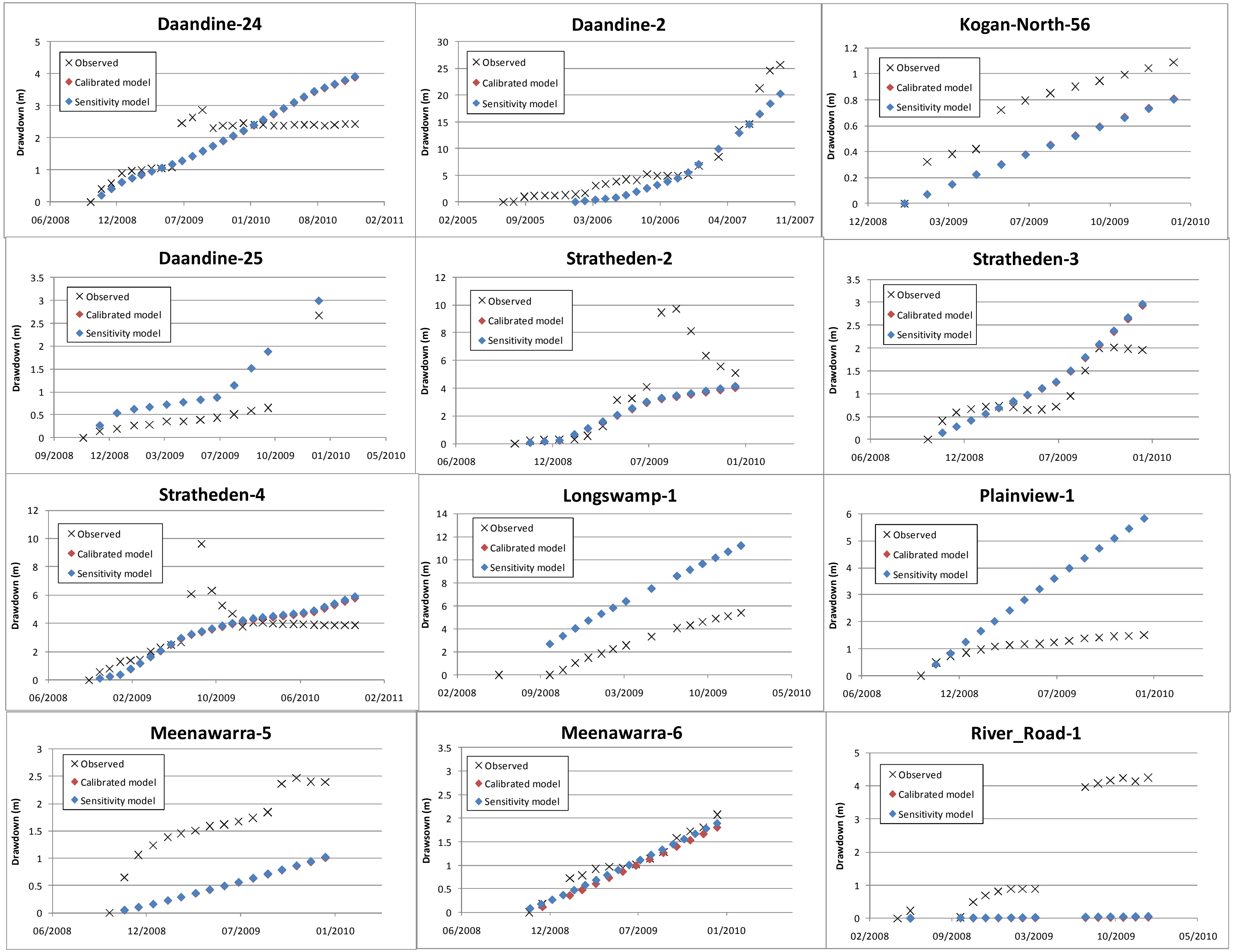

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Figure 5.3 Sensitivity C time variant calibration to Arrow monitoring data

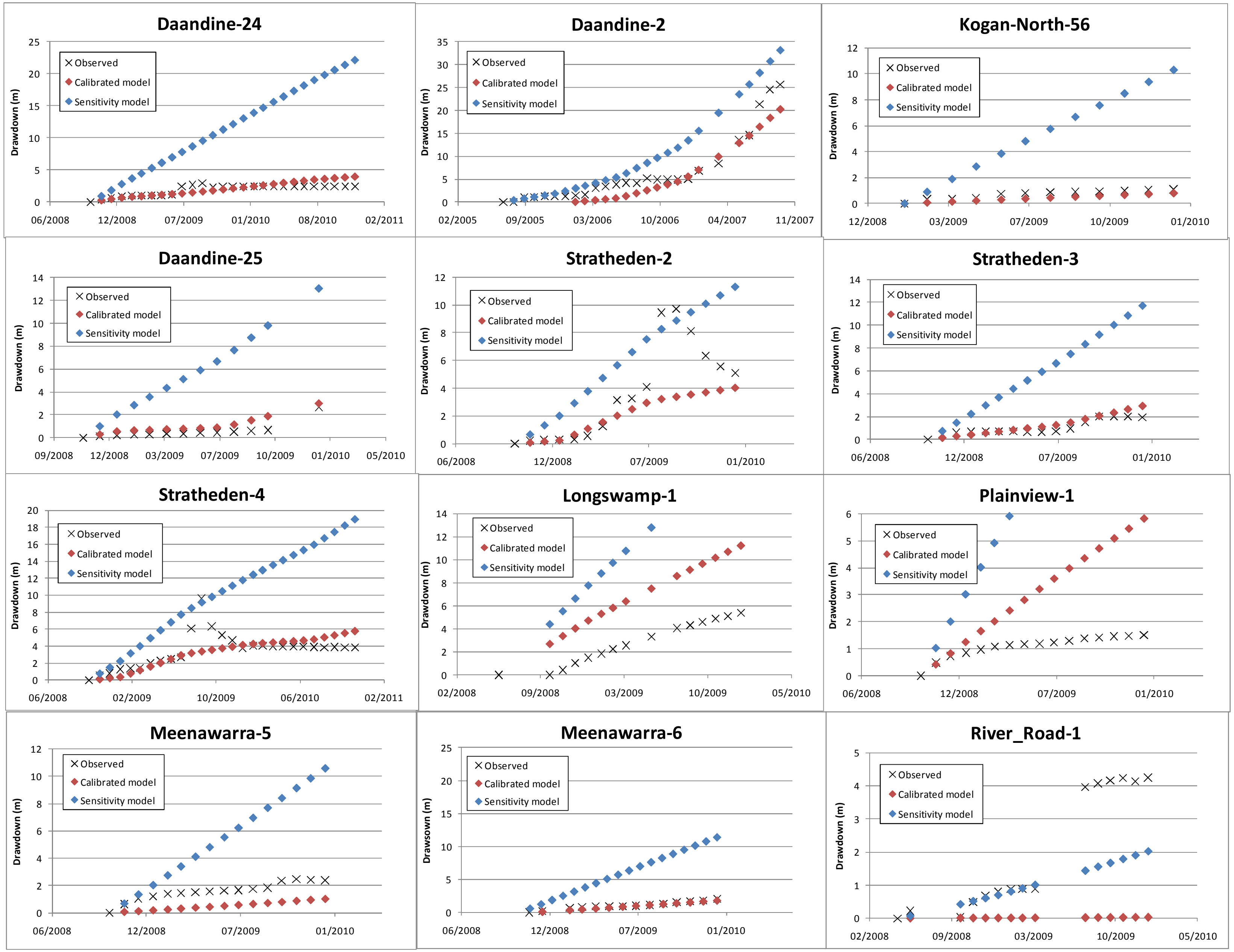

Figure 5.4 Sensitivity D time variant calibration to Arrow monitoring data

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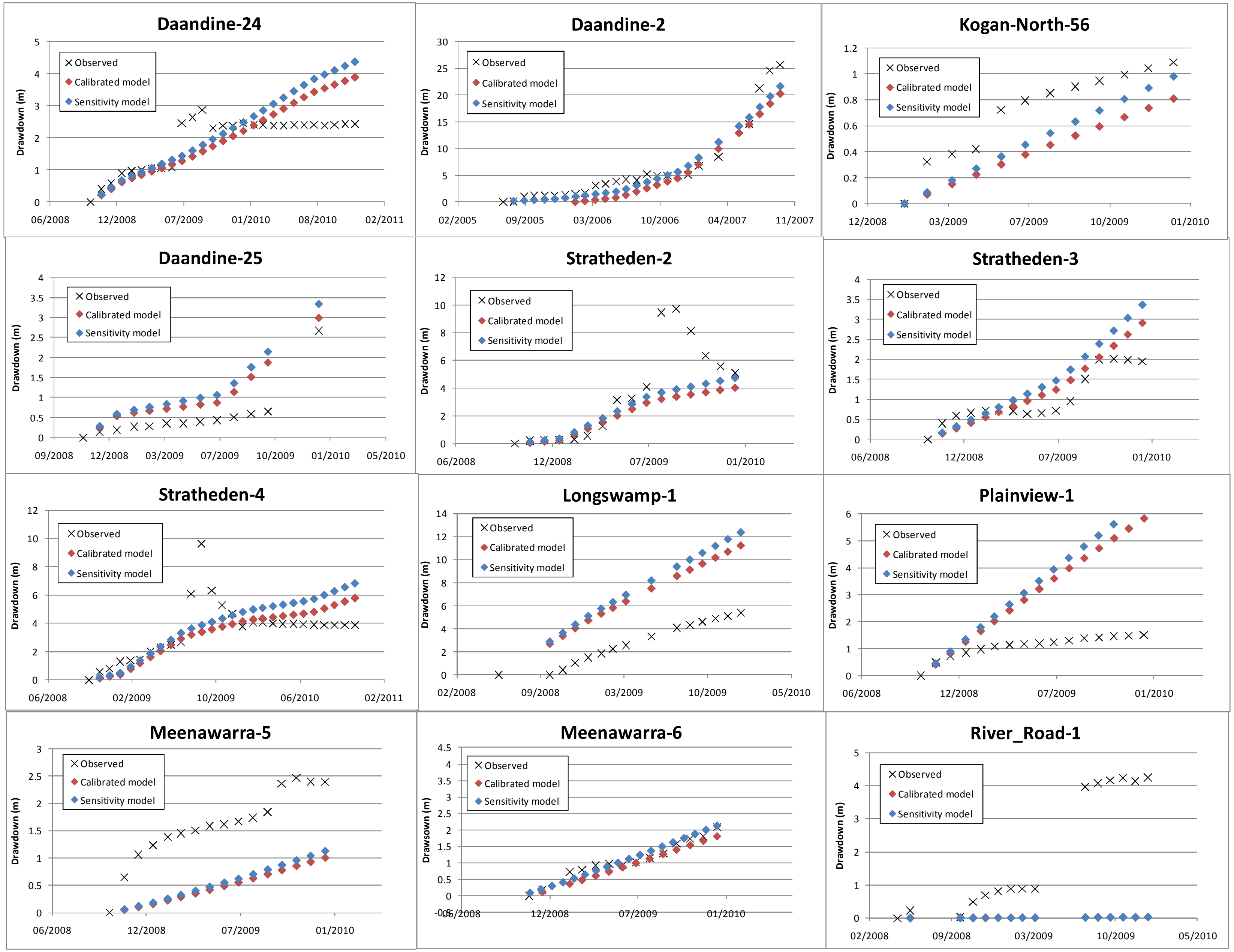

Figure 5.5 Sensitivity E time variant calibration to Arrow monitoring data

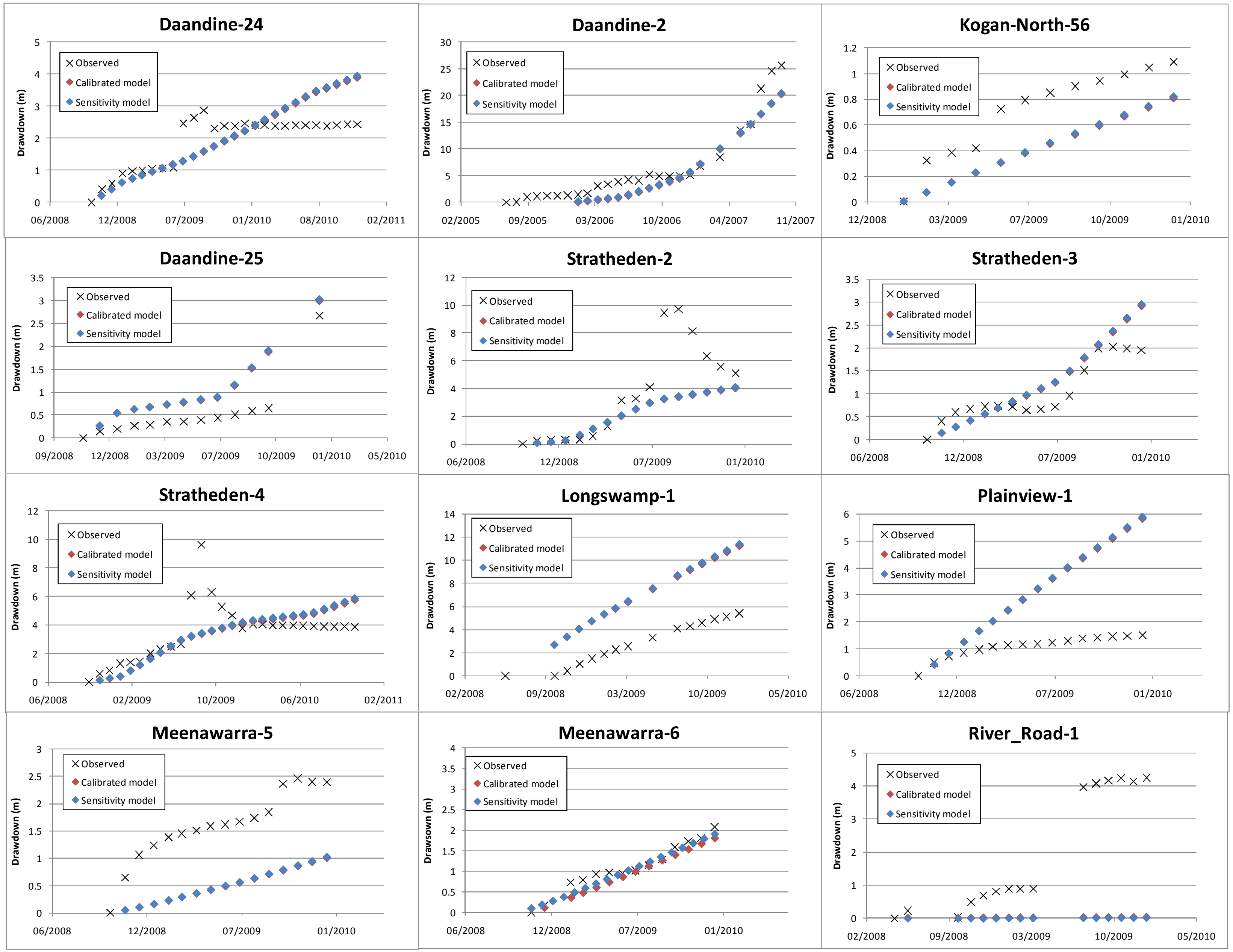

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Figure 5.6 Sensitivity F time variant calibration to Arrow monitoring data

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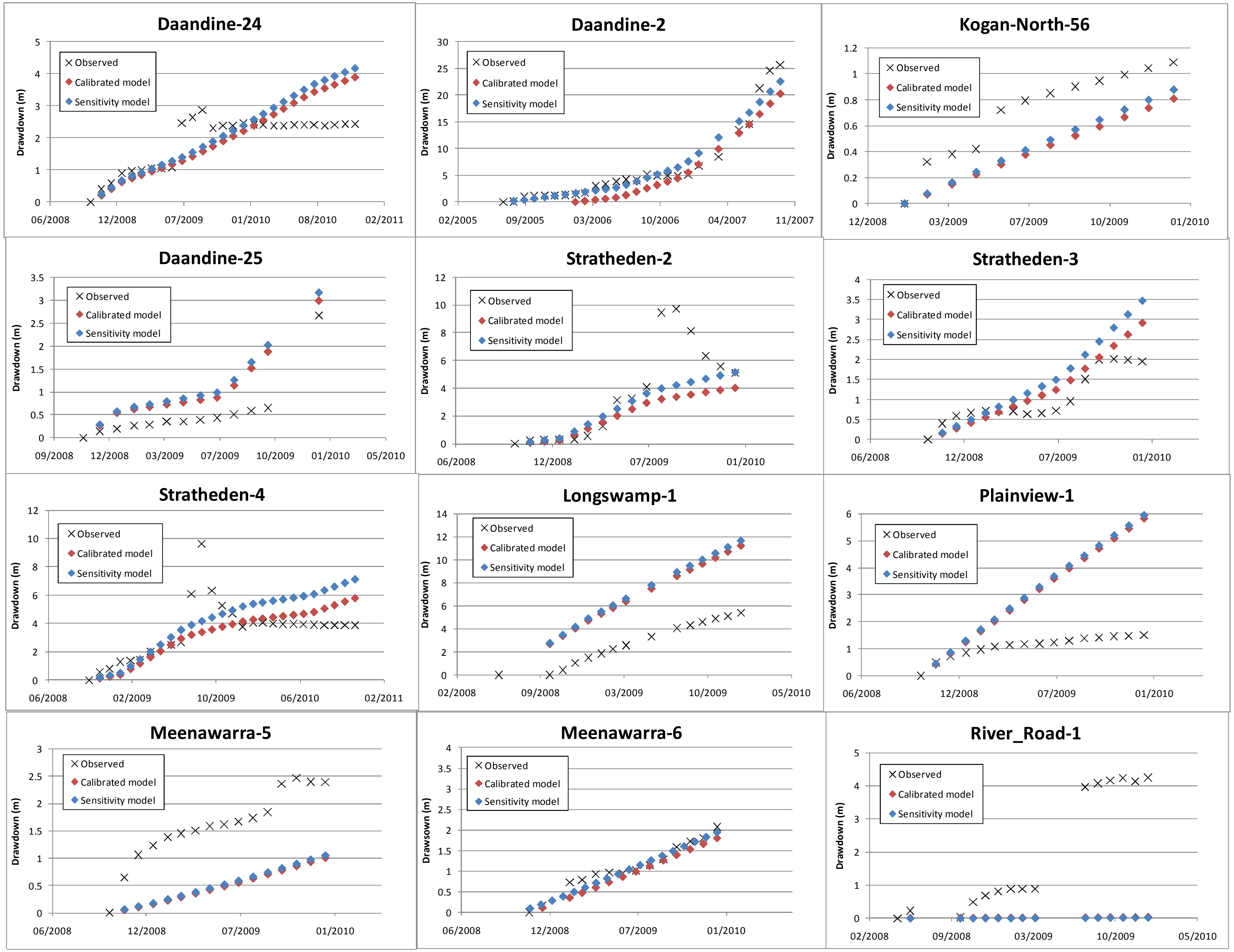

Figure 5.7 Sensitivity G time variant calibration to Arrow monitoring data

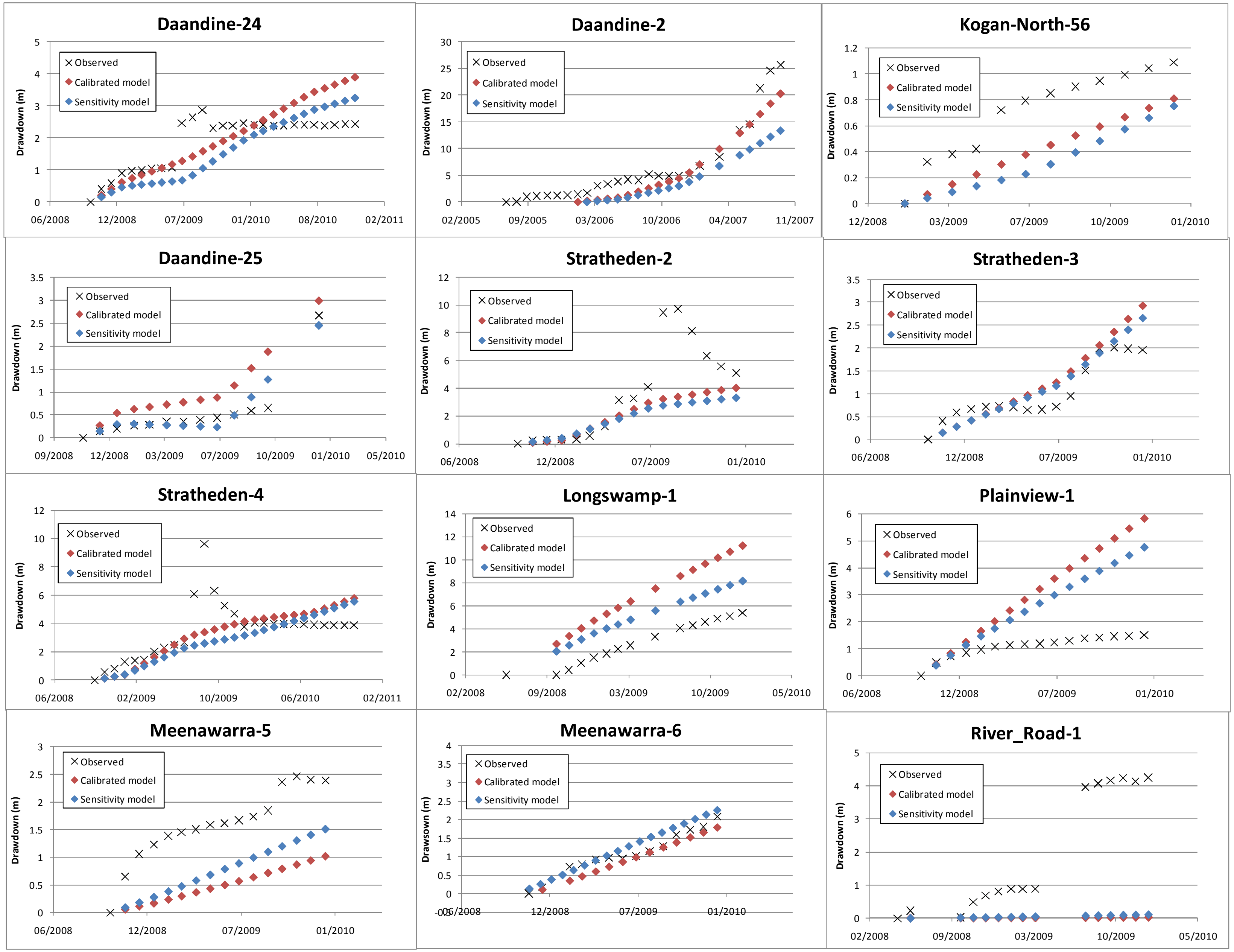

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Figure 5.8 Sensitivity H time variant calibration to Arrow monitoring data

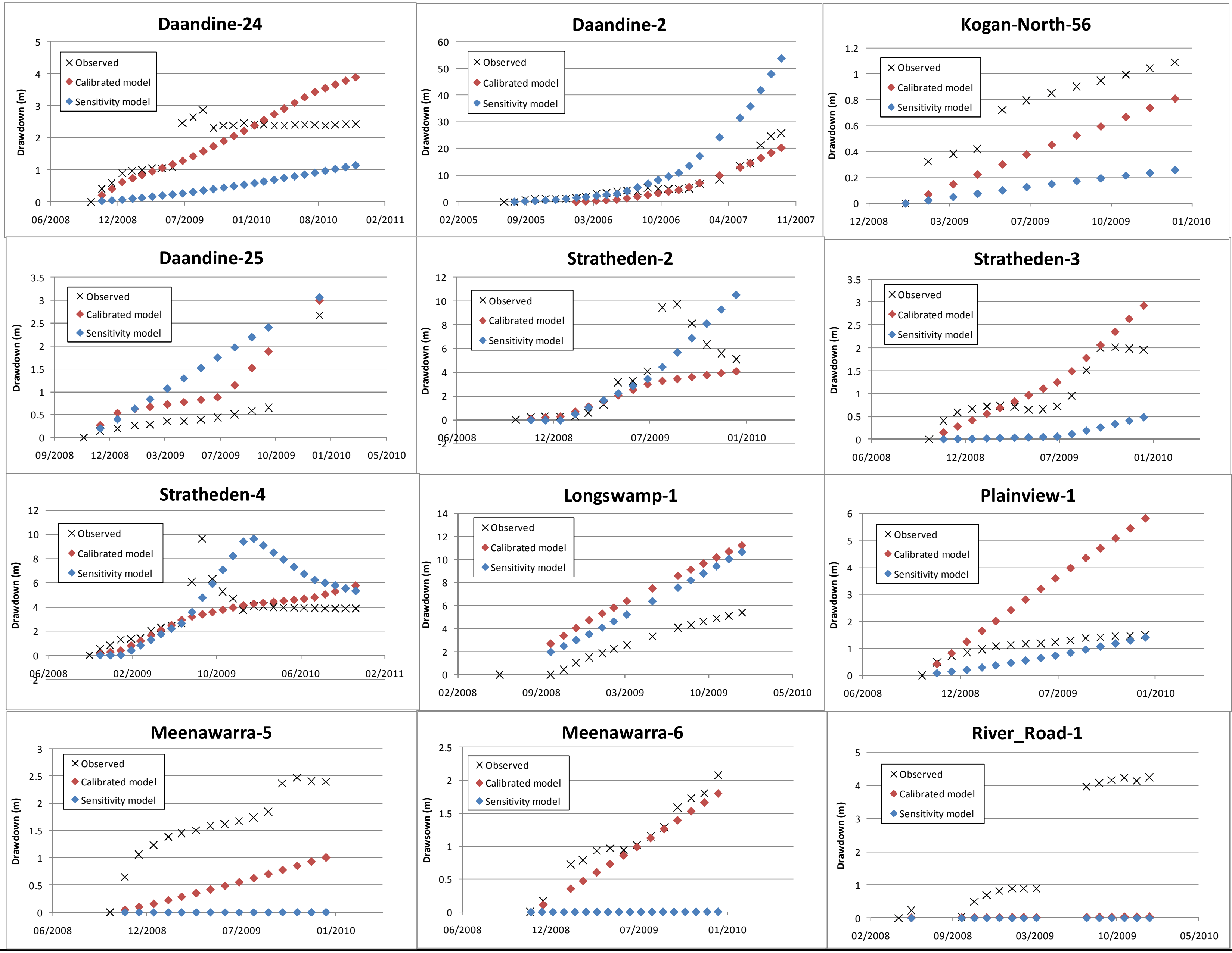

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Figure 5.9 Sensitivity I time variant calibration to Arrow monitoring data

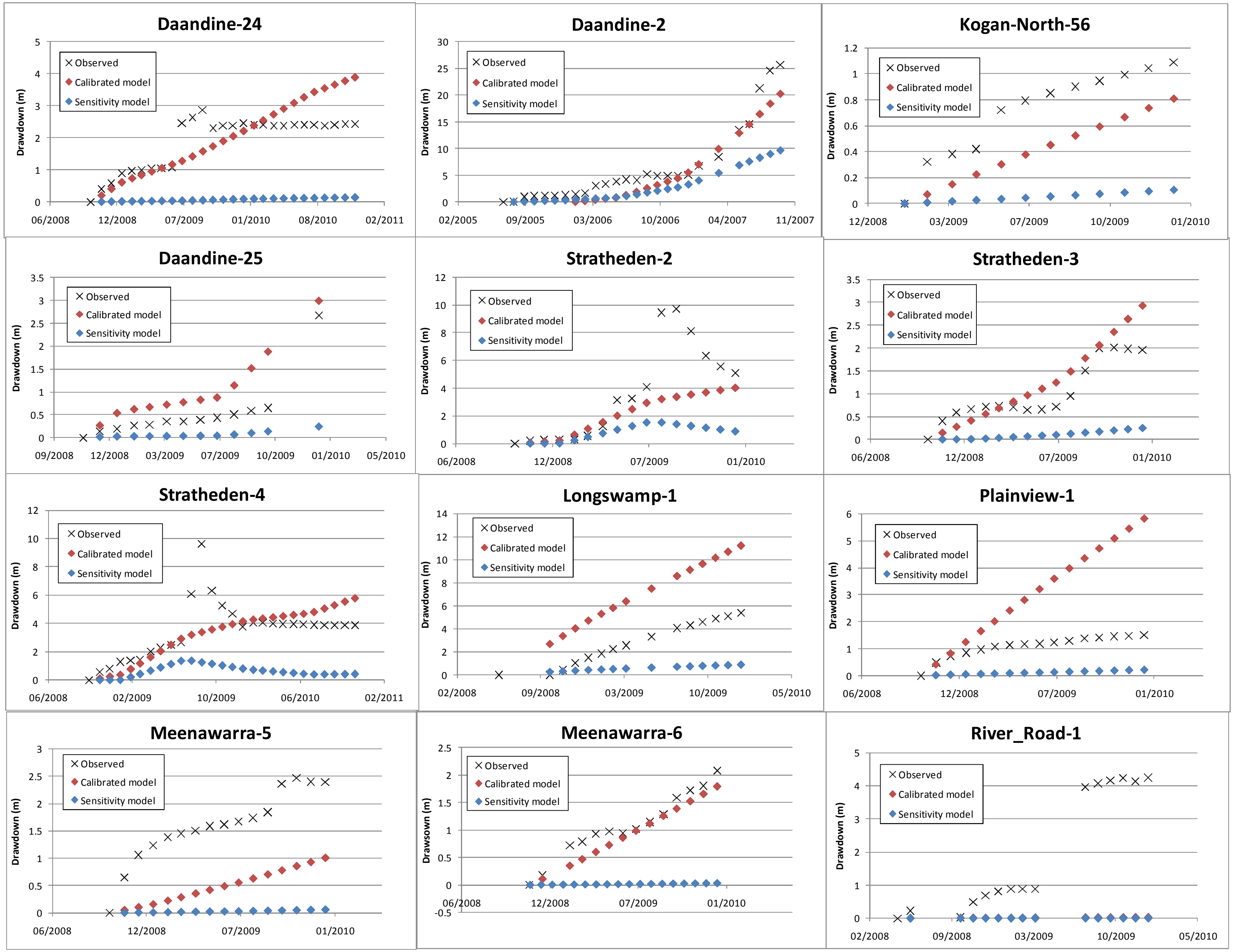

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Figure 5.10 Sensitivity J time variant calibration to Arrow monitoring data

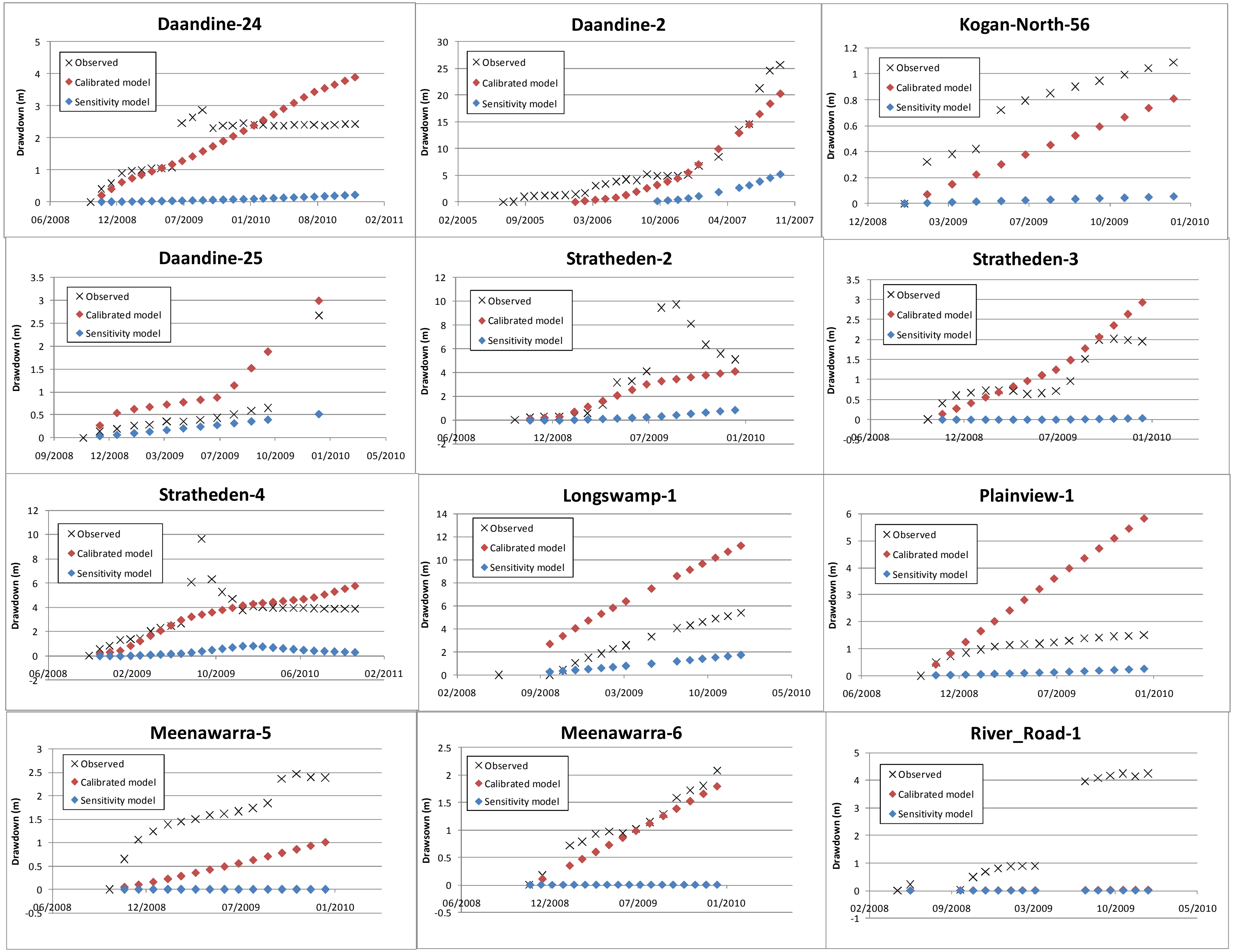

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Figure 5.11 Sensitivity K time variant calibration to Arrow monitoring data

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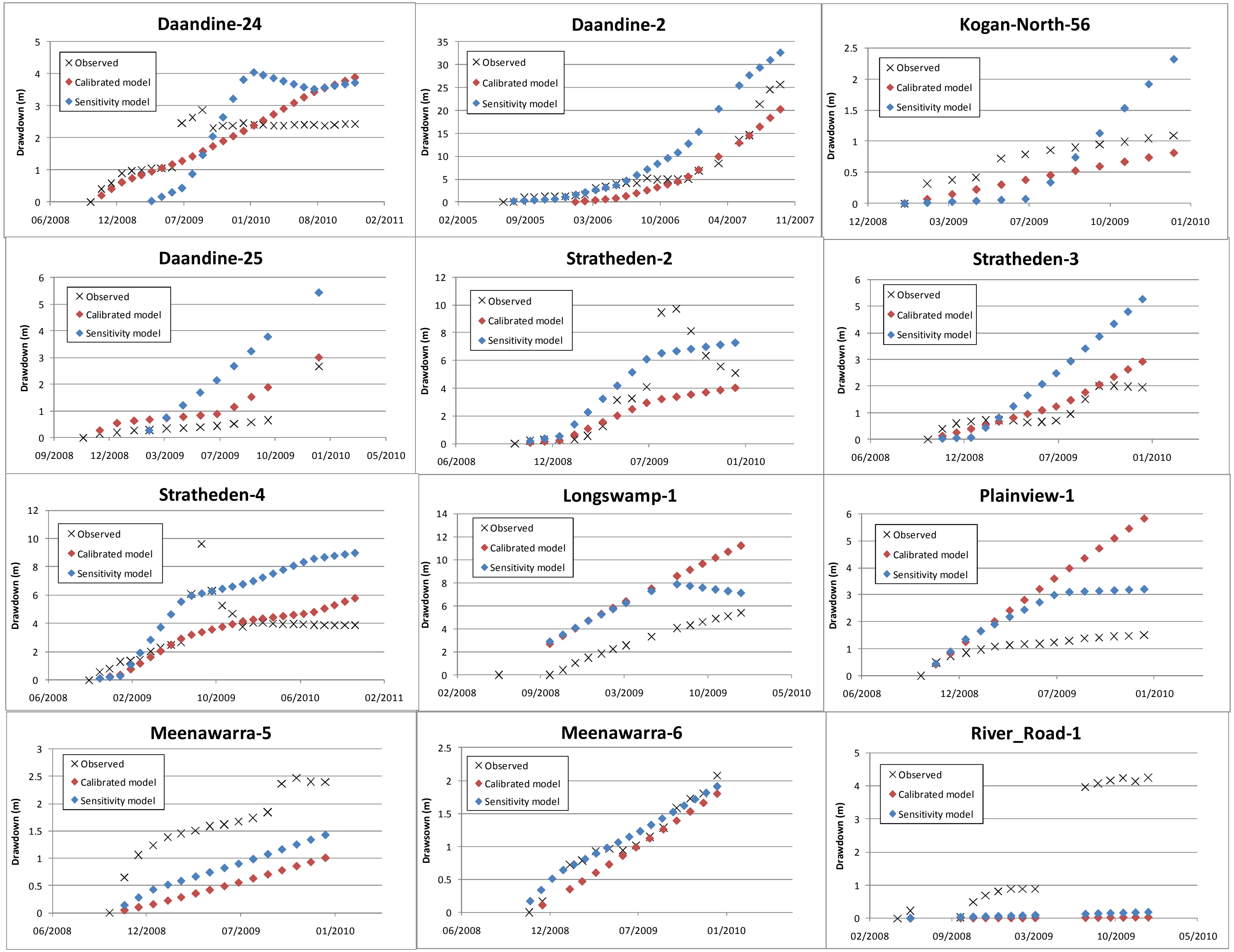

Figure 5.12 Sensitivity L time variant calibration to Arrow monitoring data

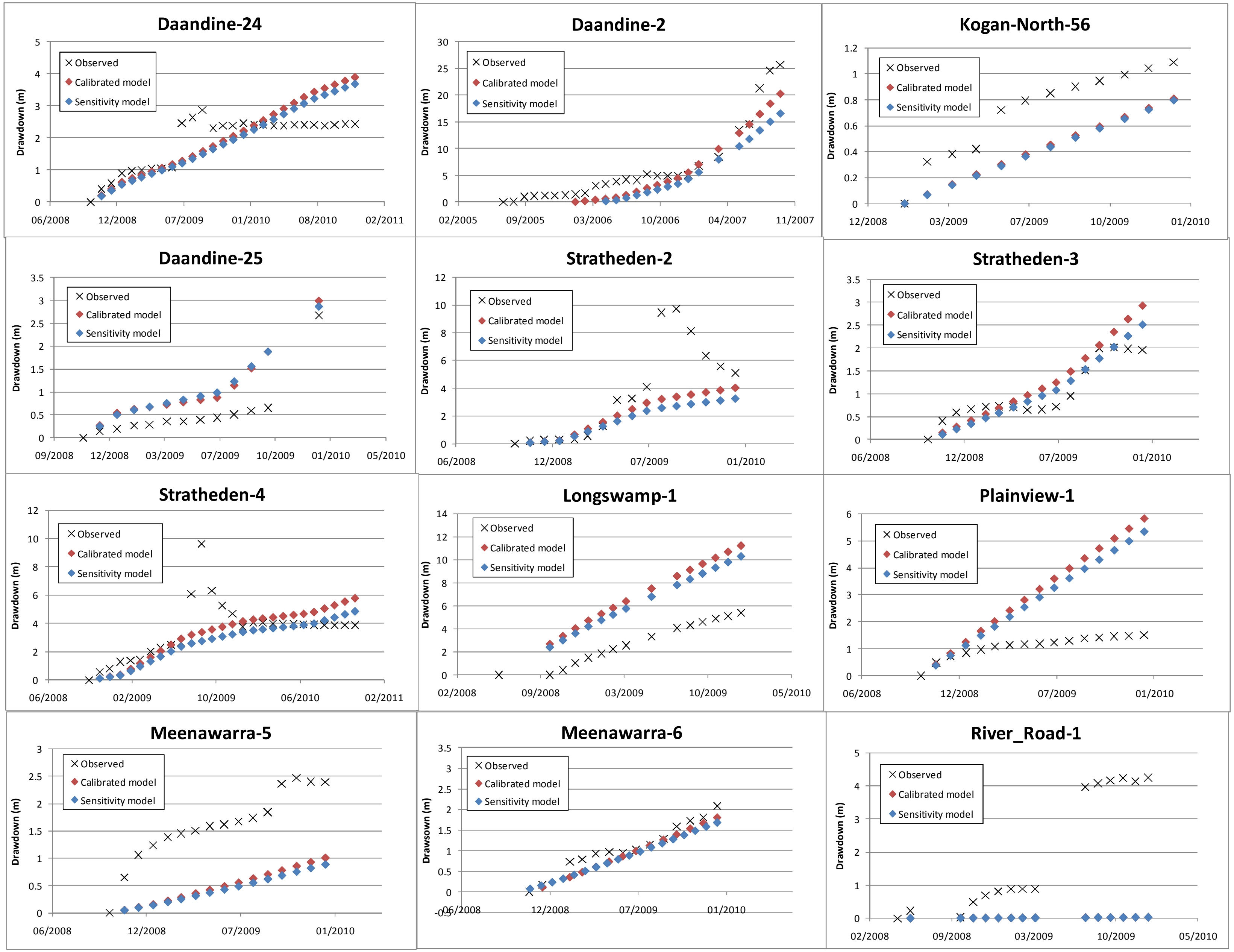

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Figure 5.13 Sensitivity M time variant calibration to Arrow monitoring data

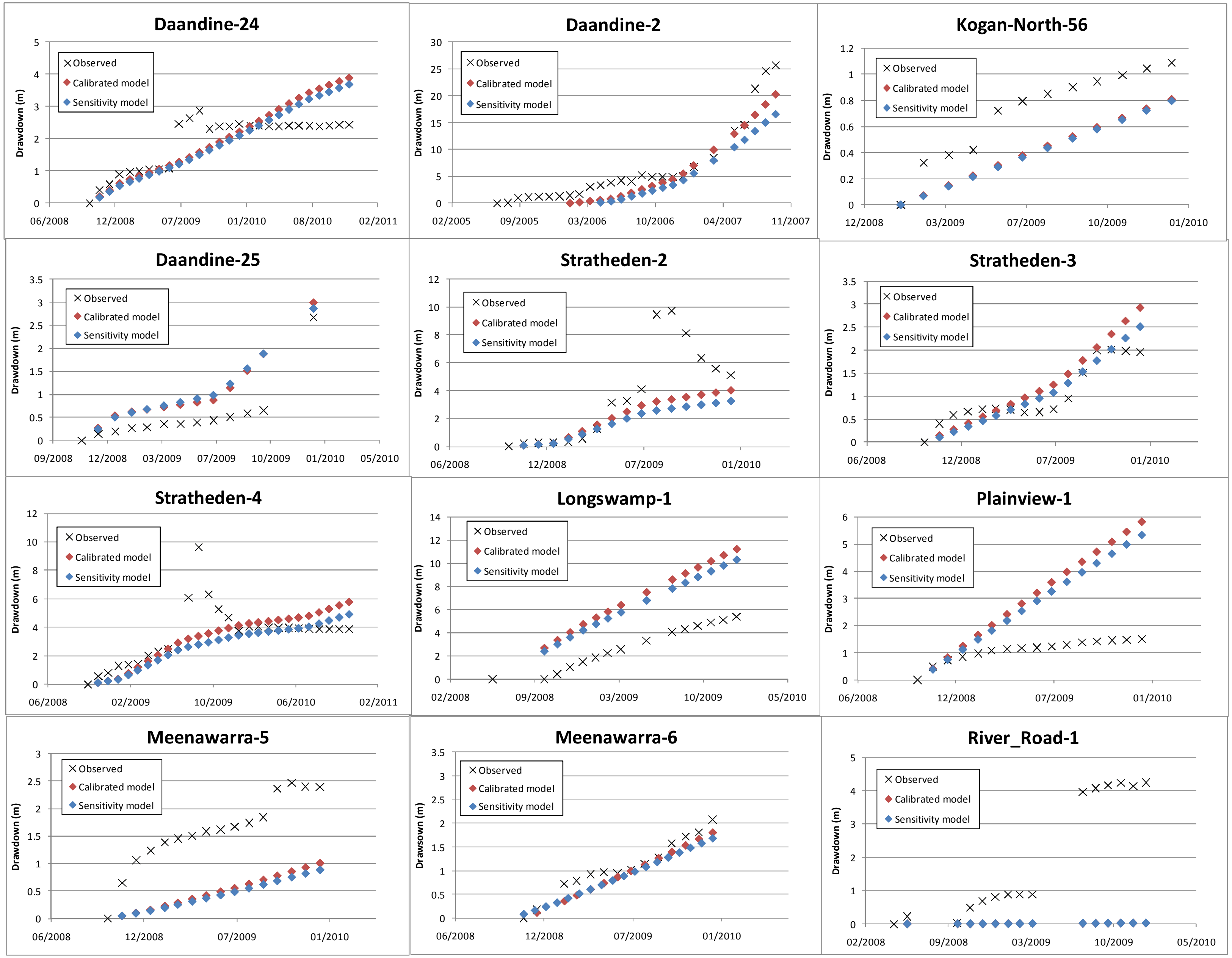

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Figure 5.14 Sensitivity N time variant calibration to Arrow monitoring data

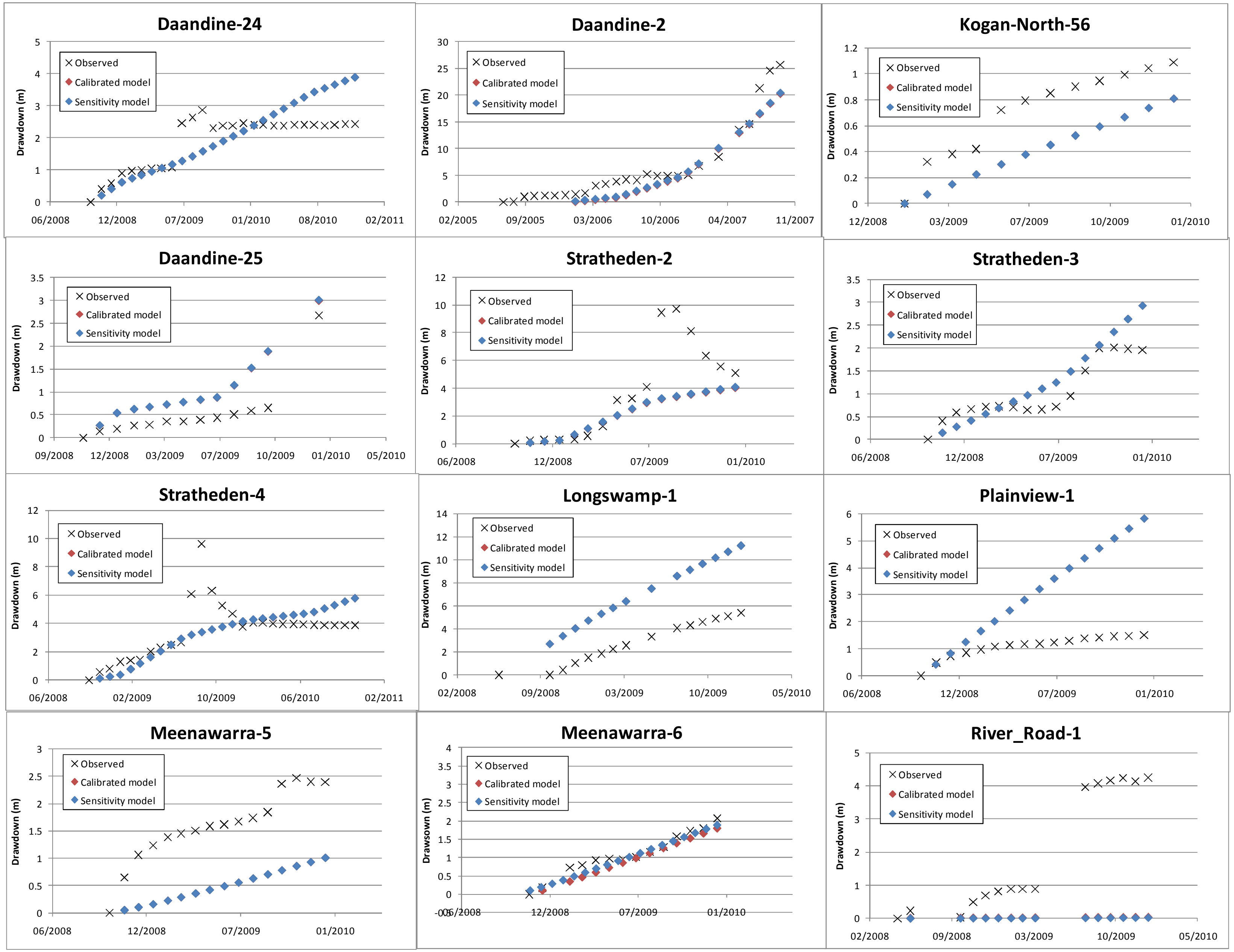

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Figure 5.15 Sensitivity 0 time variant calibration to Arrow monitoring data

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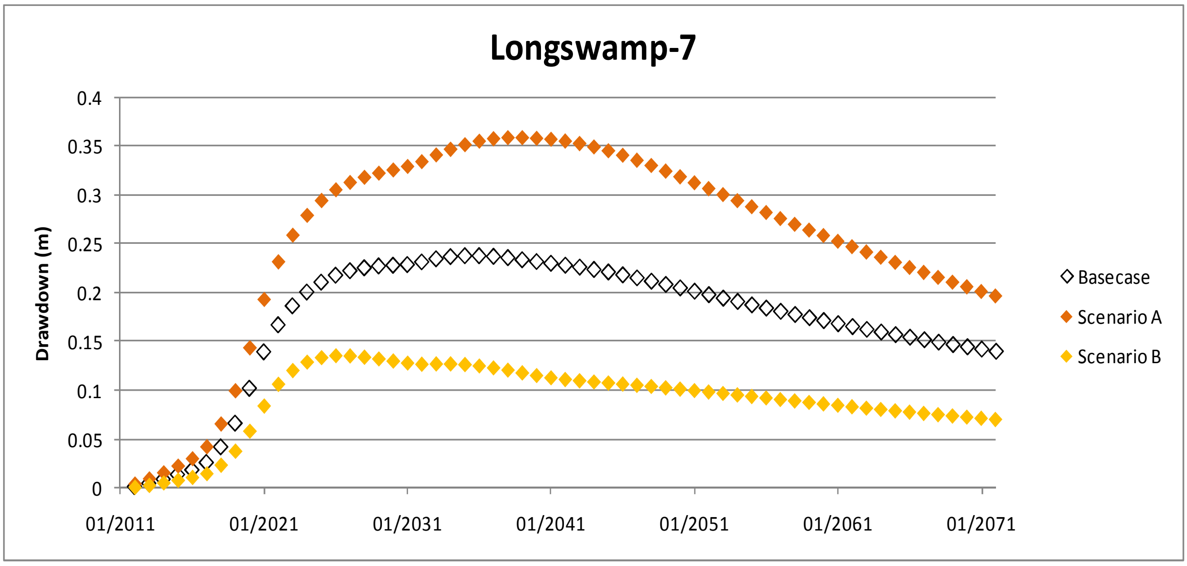
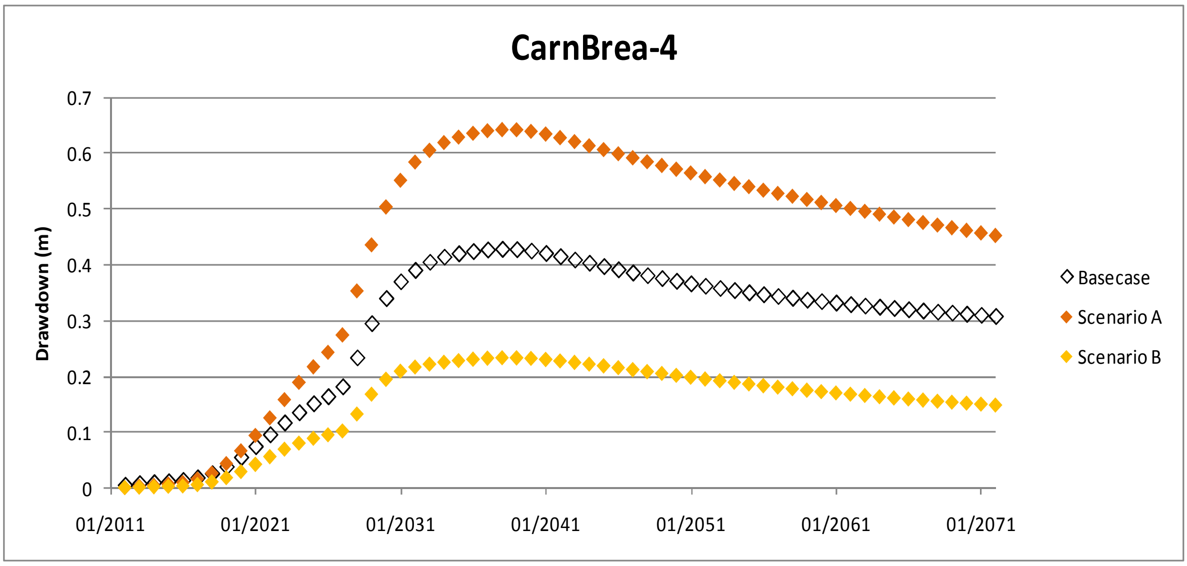
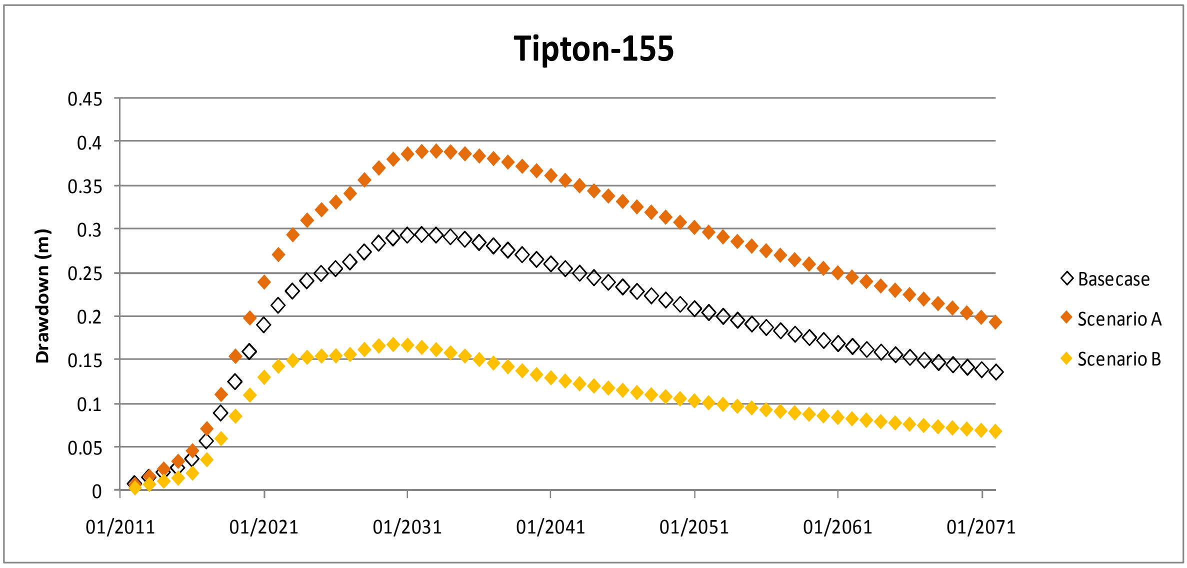
Figure 5.16 Sensitivities A and B. Predicted drawdown (Condamine Alluvium locations)







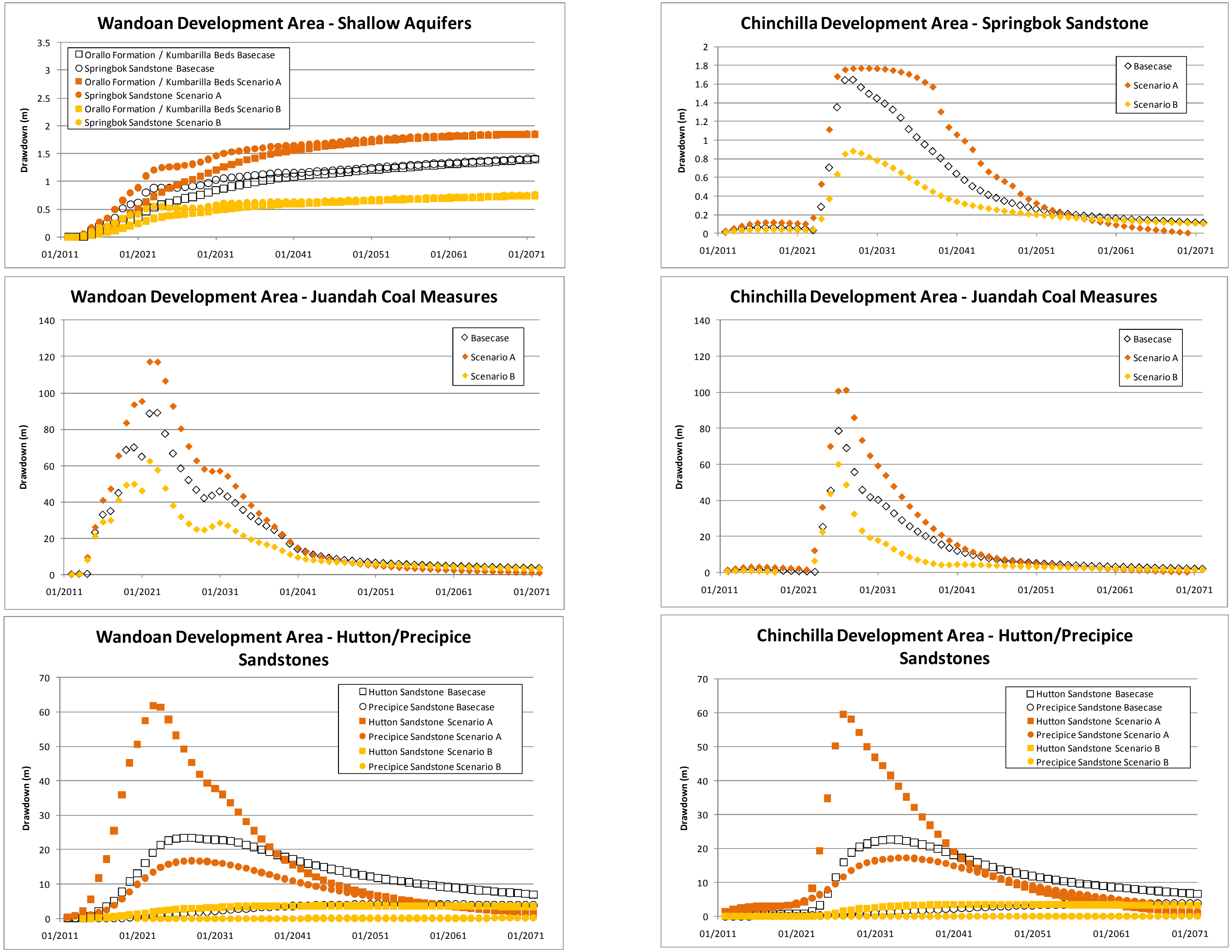


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Figure 5.17 Sensitivities A and B. Predicted drawdown (Wandoan and Chinchilla locations)

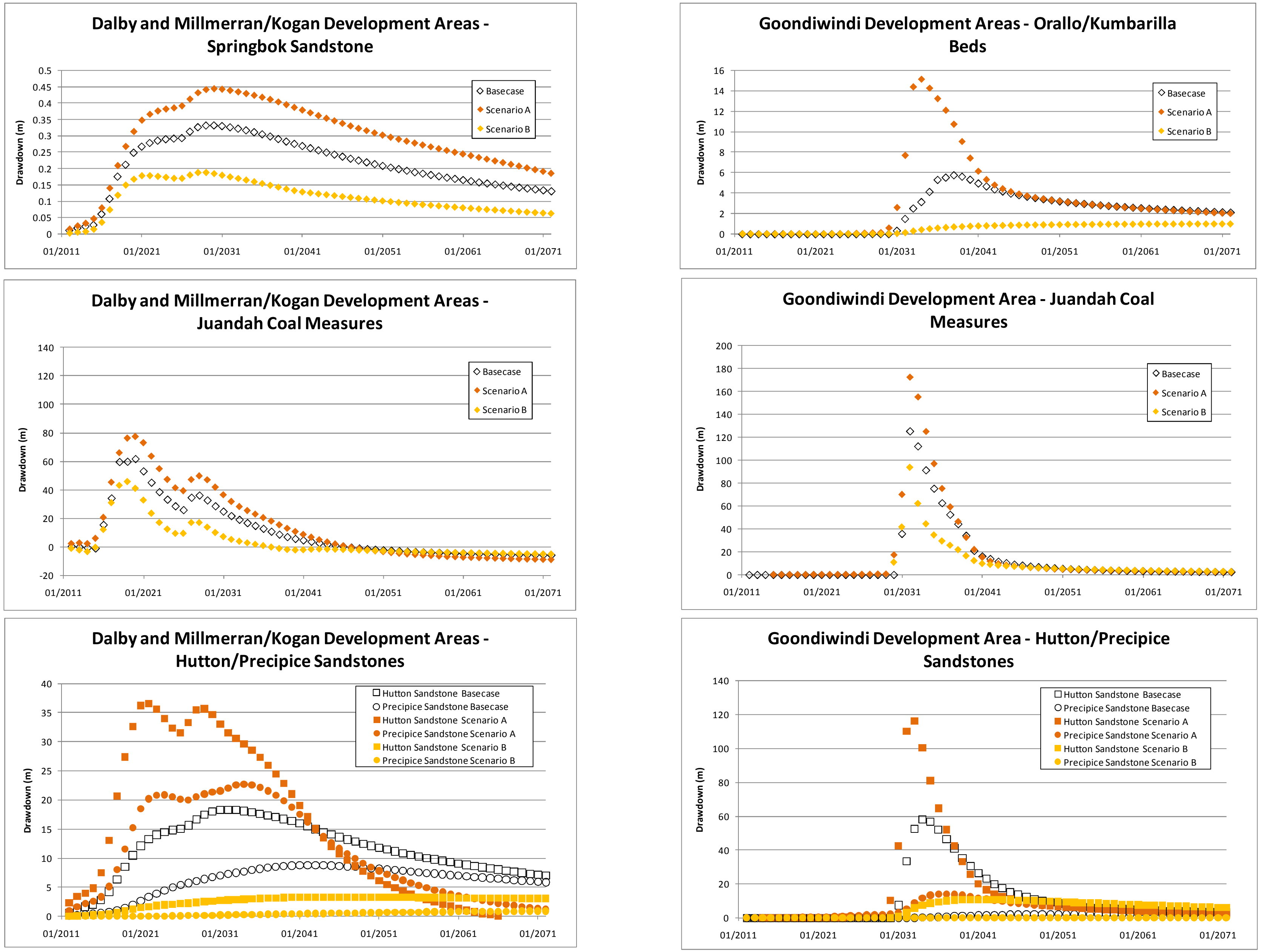

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Figure 5.18 Sensitivities A and B. Predicted drawdown (Dalby and Millmerran / Kogan locations)

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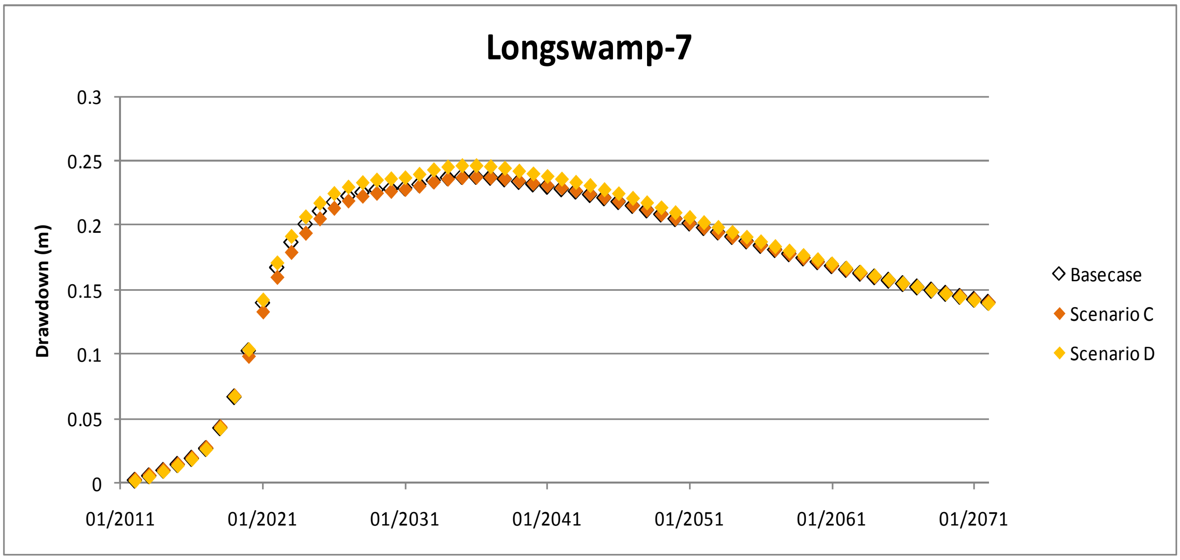
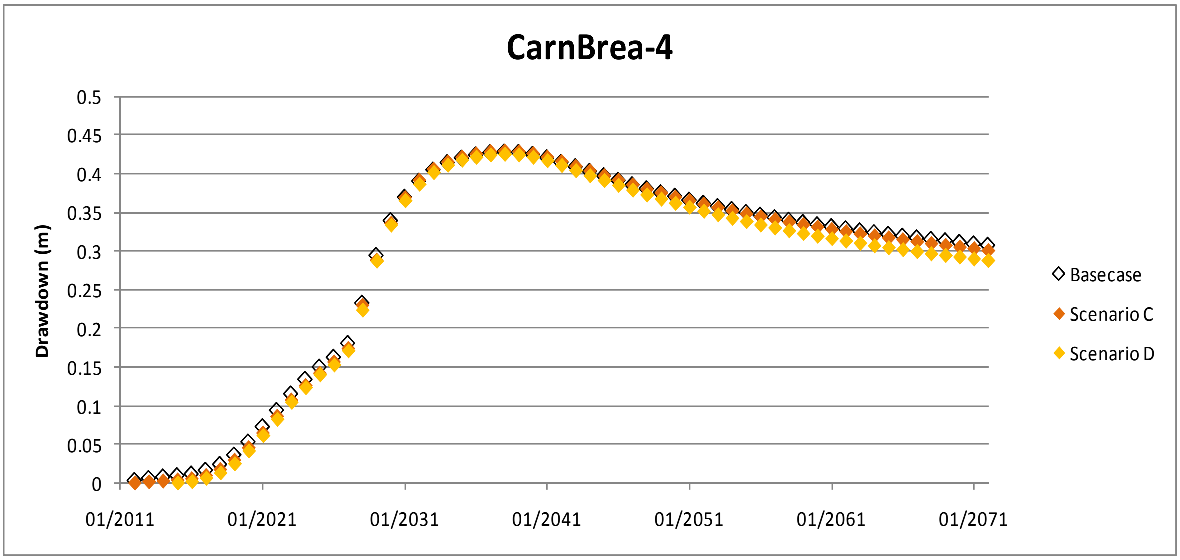
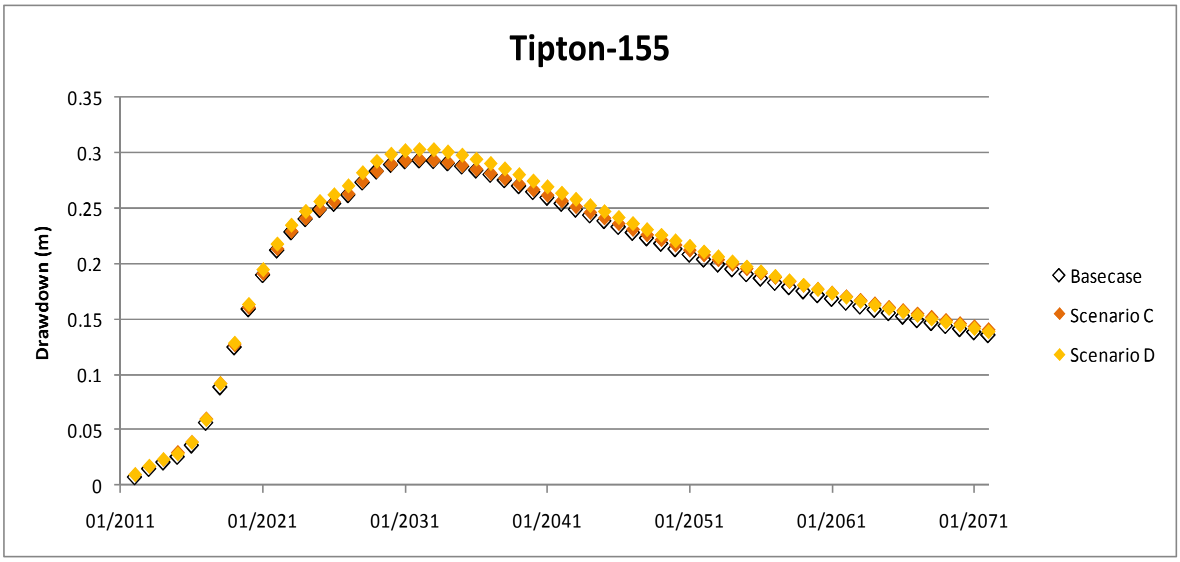
Figure 5.19 Sensitivities C and D. Predicted drawdown (Condamine Alluvium locations)







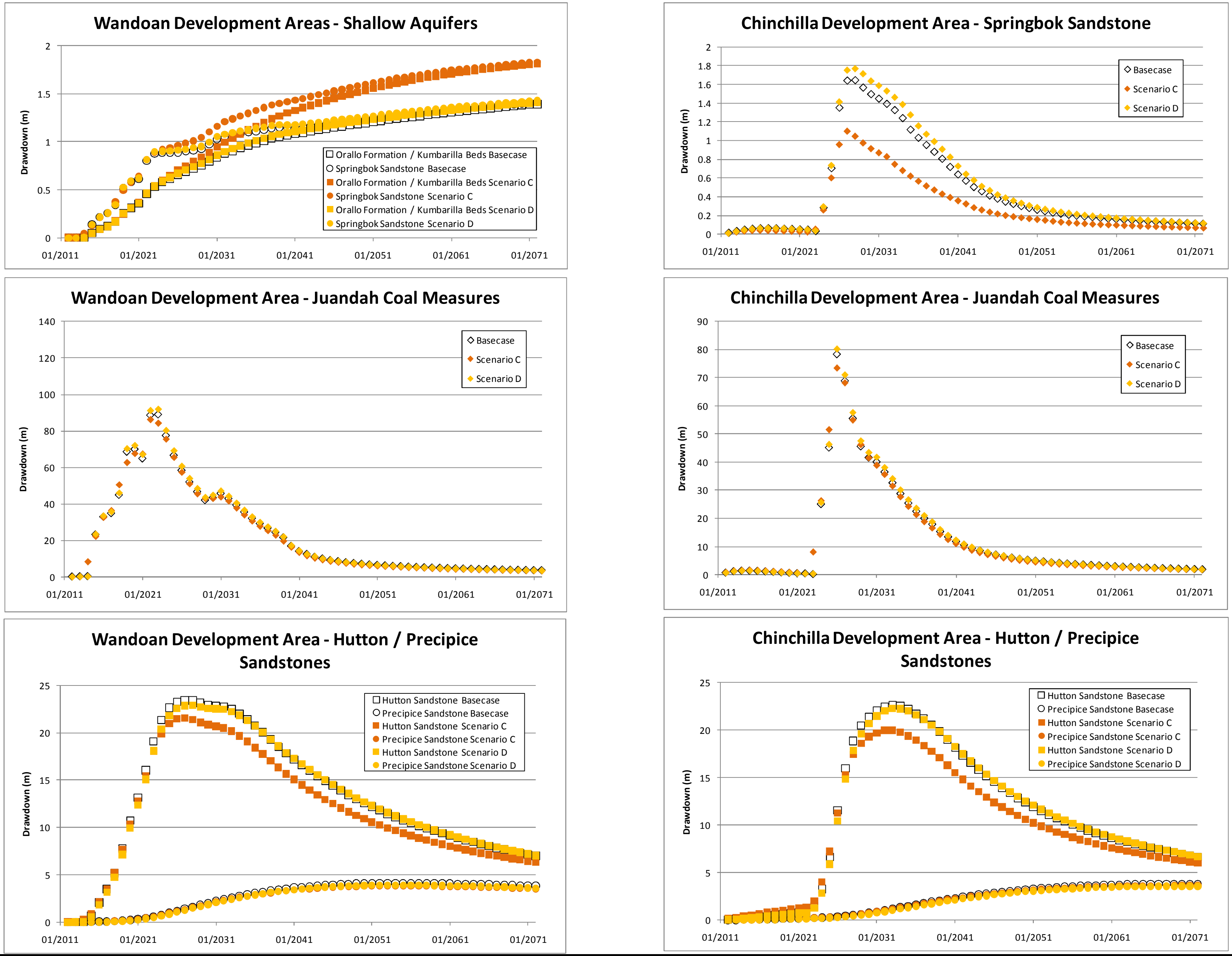


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Figure 5.20 Sensitivities C and D. Predicted drawdown (Wandoan and Chinchilla locations)

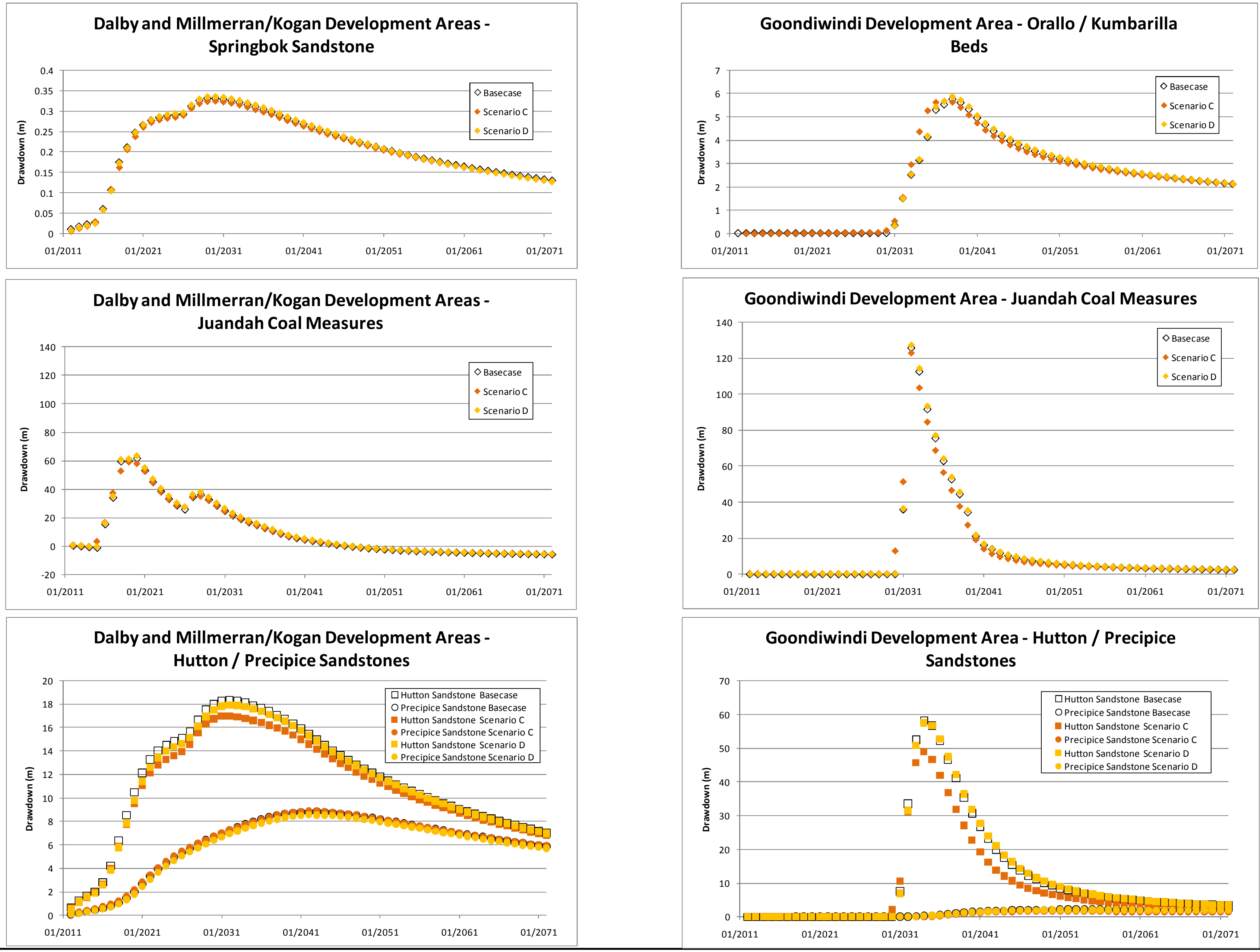

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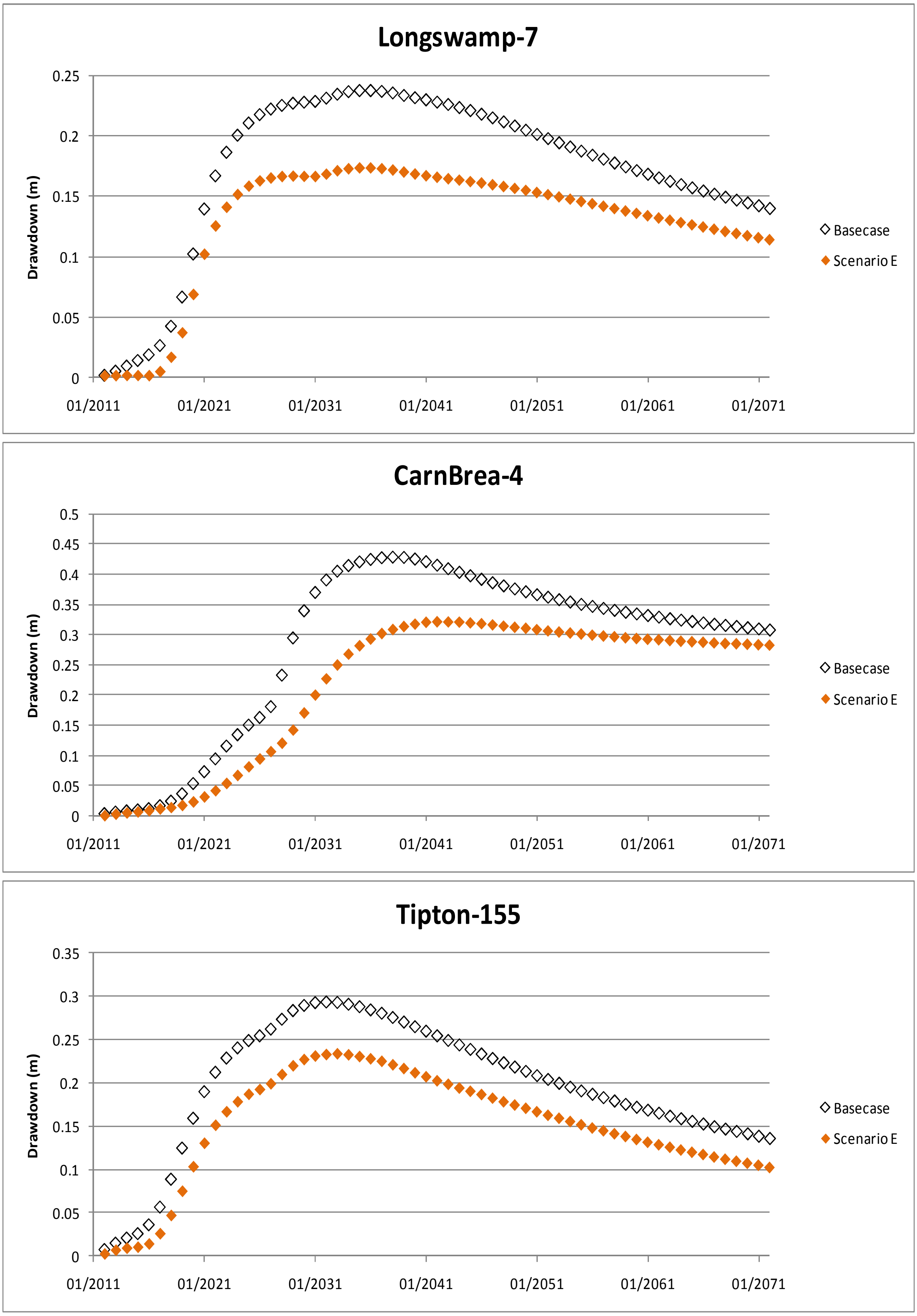
Figure 5.21 Sensitivities C and D. Predicted drawdown (Dalby and Millmerran / Kogan locations)

Figure 5.22 Sensitivity E. Predicted drawdown (Condamine Alluvium locations)



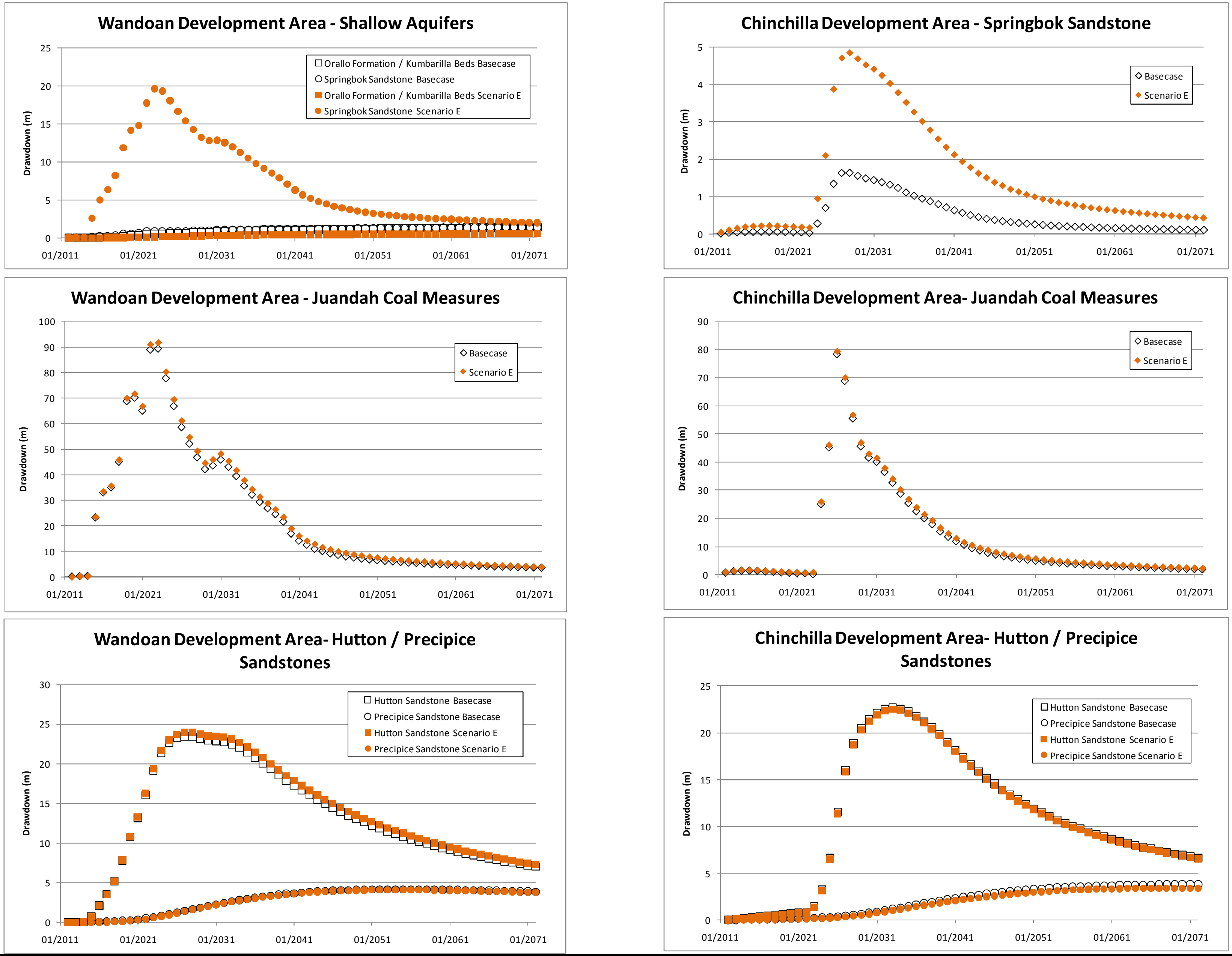


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Figure 5.23 Sensitivity E. Predicted drawdown (Wandoan and Chinchilla locations)

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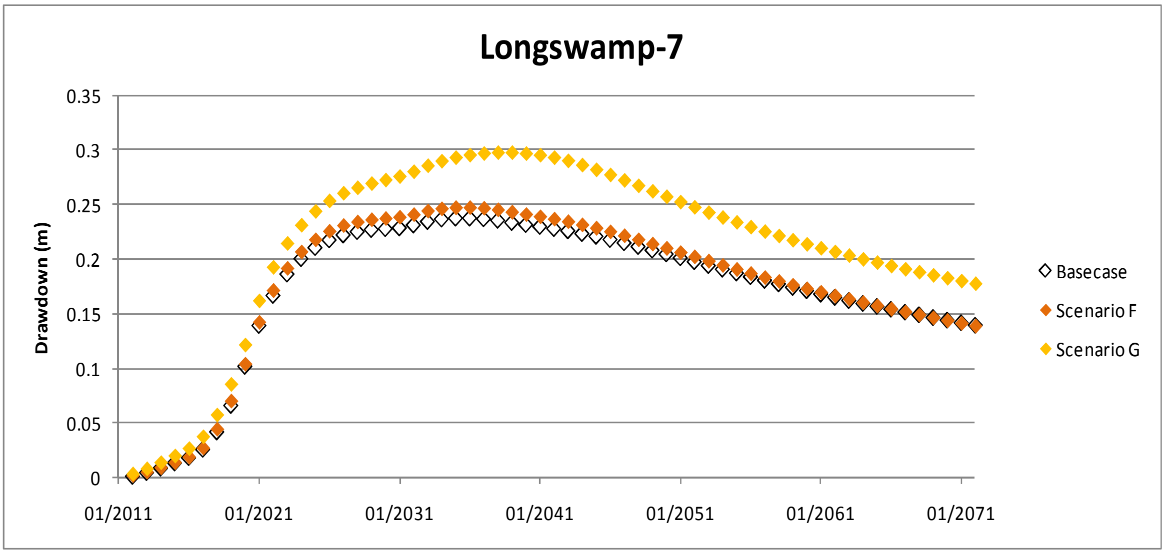
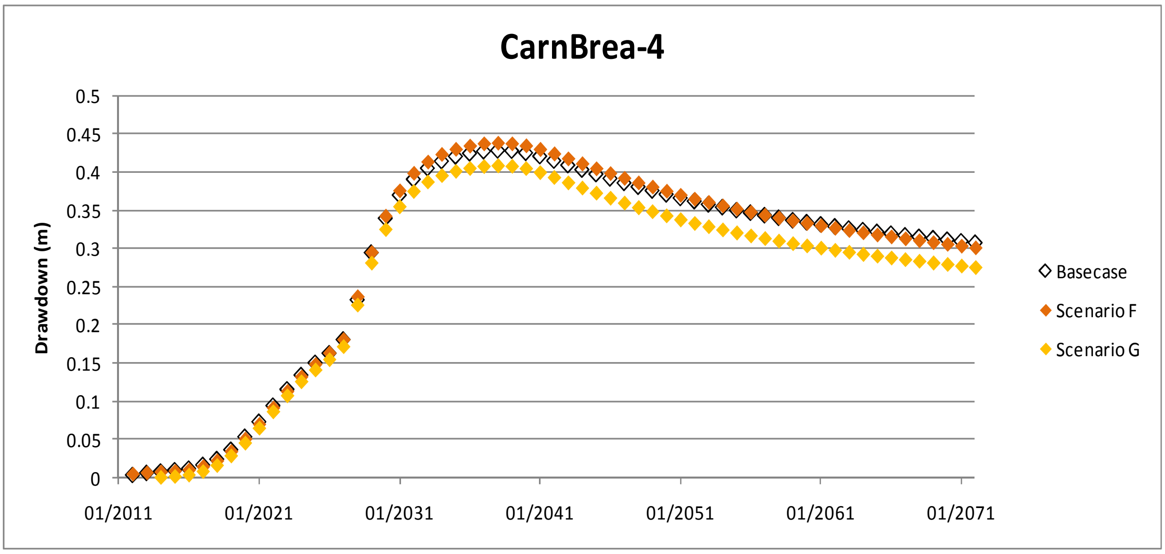
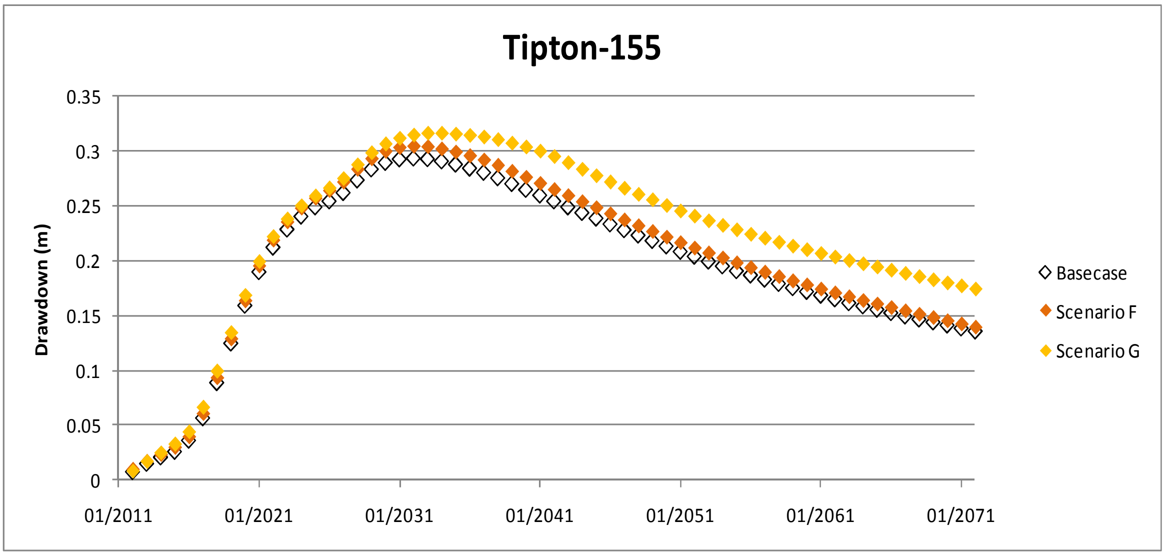
Figure 5.24 Sensitivity E. Predicted drawdown (Dalby and Millmerran / Kogan locations)

Figure 5.25 Sensitivities F and G. Predicted drawdown (Condamine Alluvium locations)







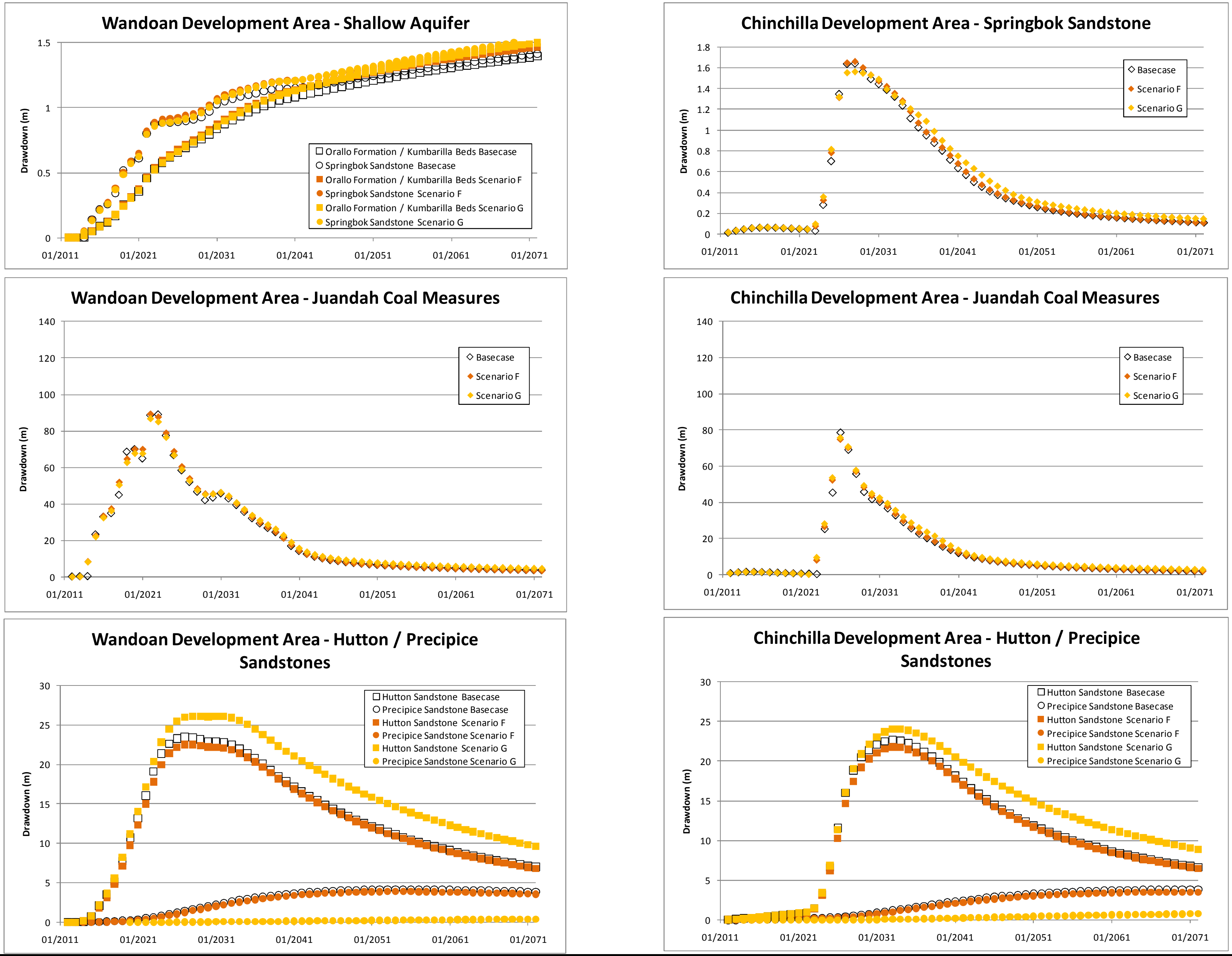


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Figure 5.26 Sensitivities F and G. Predicted drawdown (Wandoan and Chinchilla locations)

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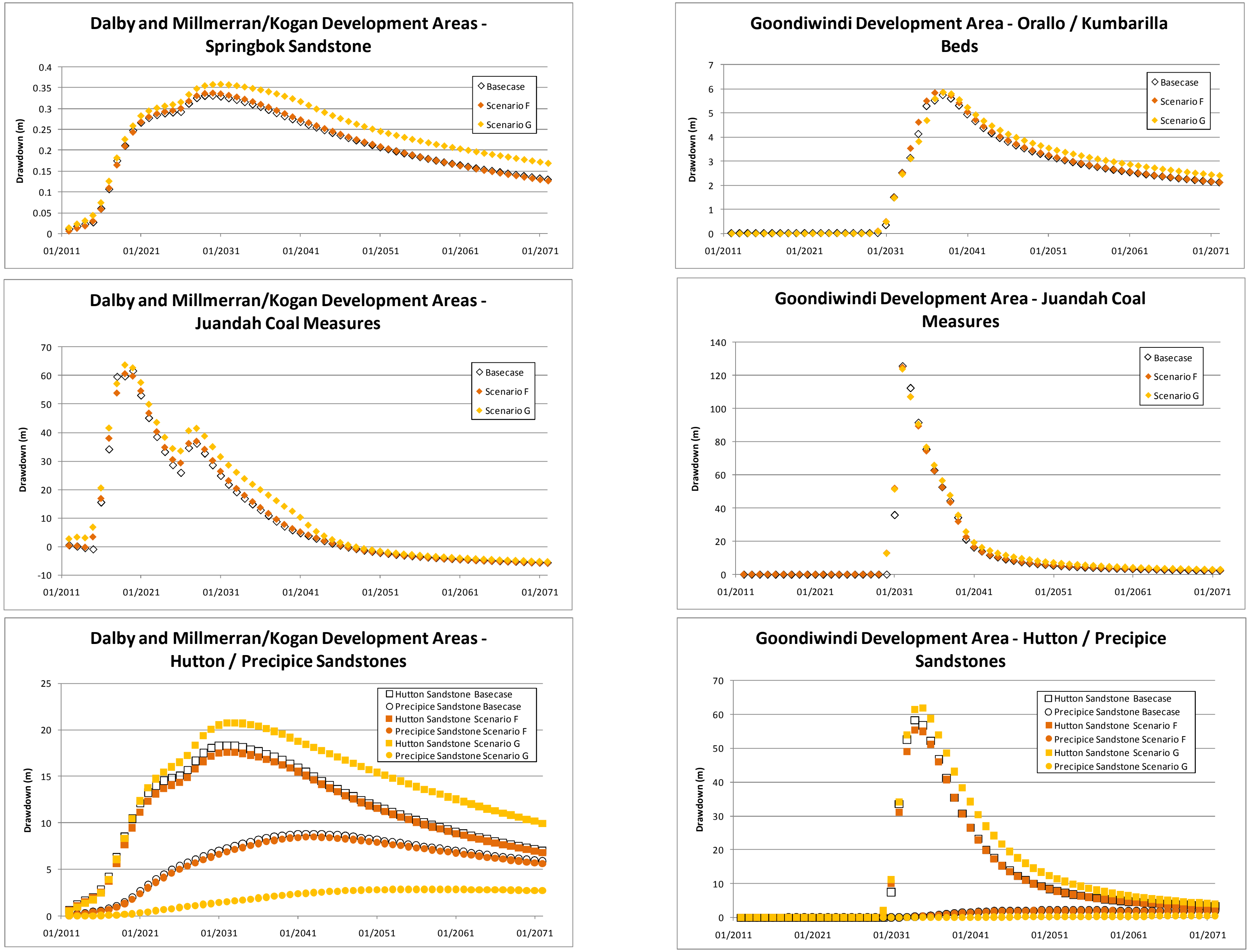

Figure 5.27 Sensitivities F and G. Predicted drawdown (Dalby and Millmerran / Kogan locations)

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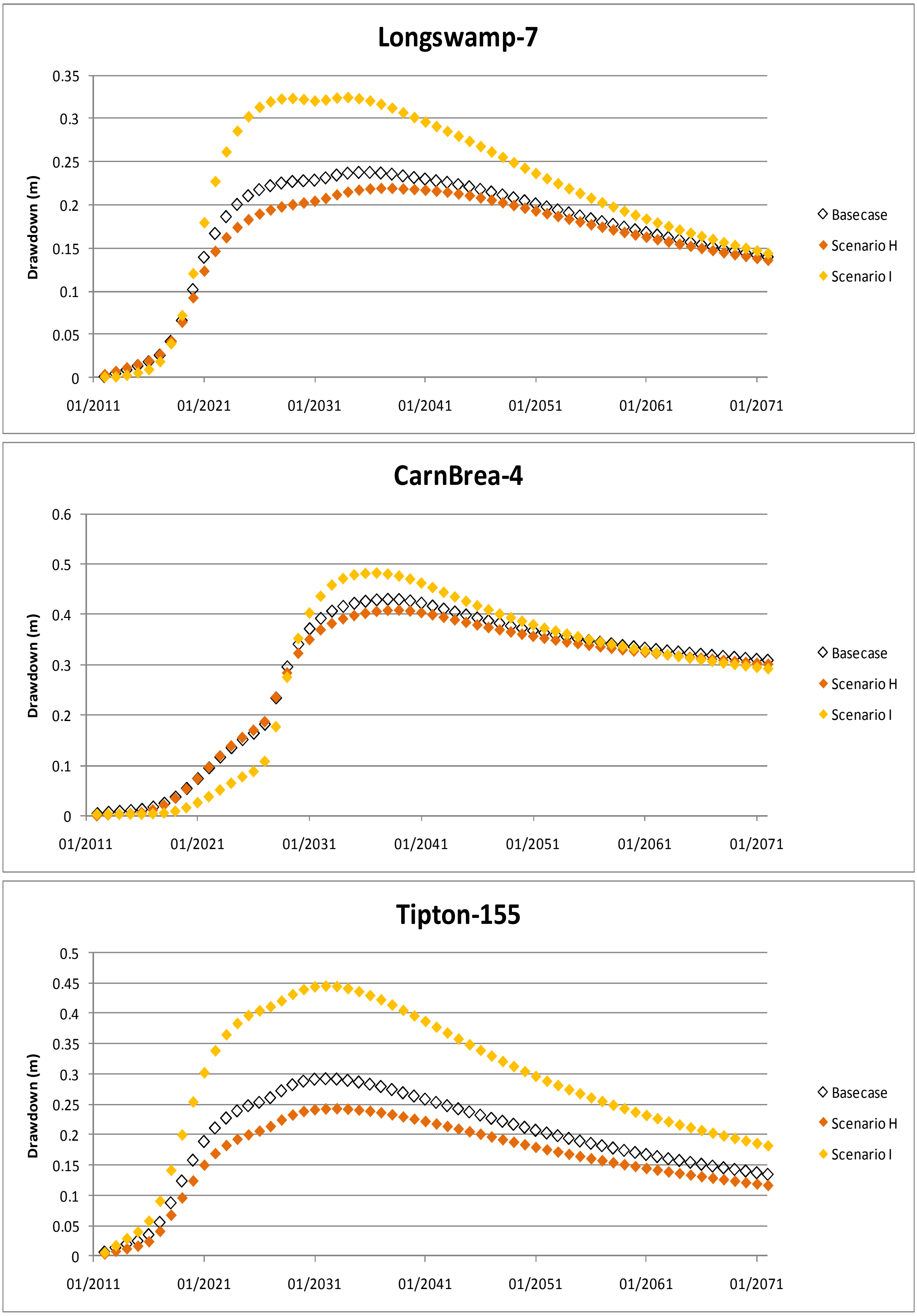
Figure 5.28 Sensitivities H and I. Predicted drawdown (Condamine Alluvium locations)



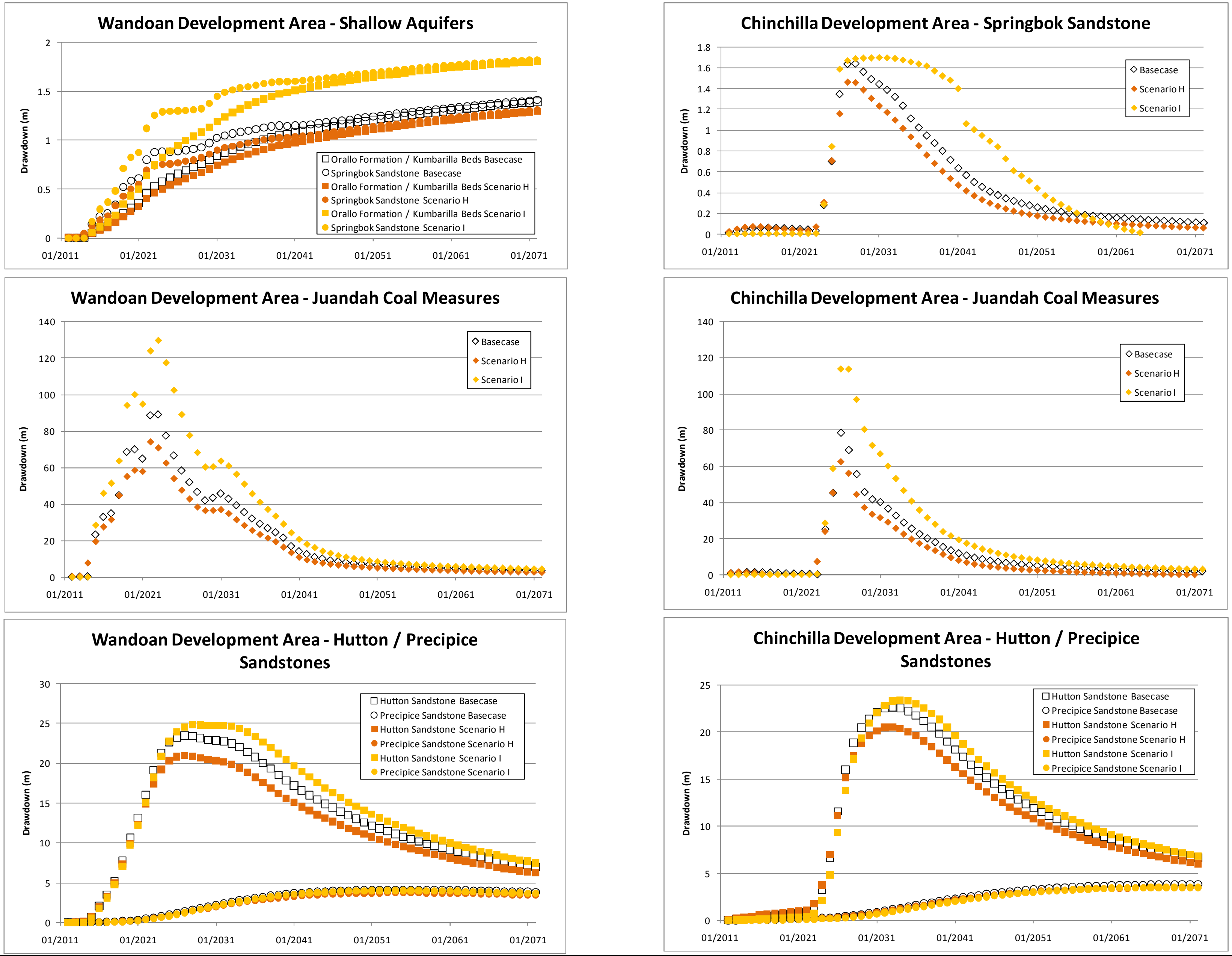


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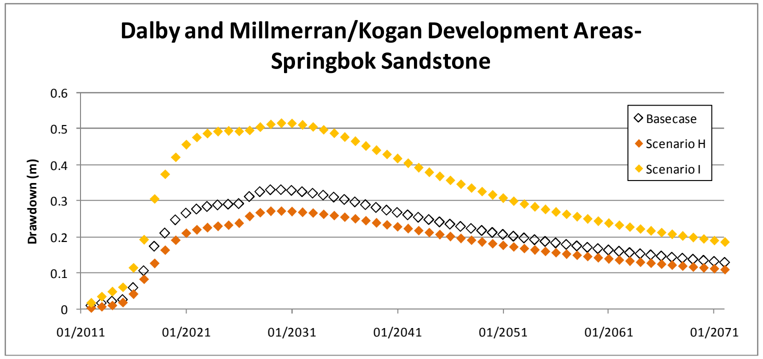
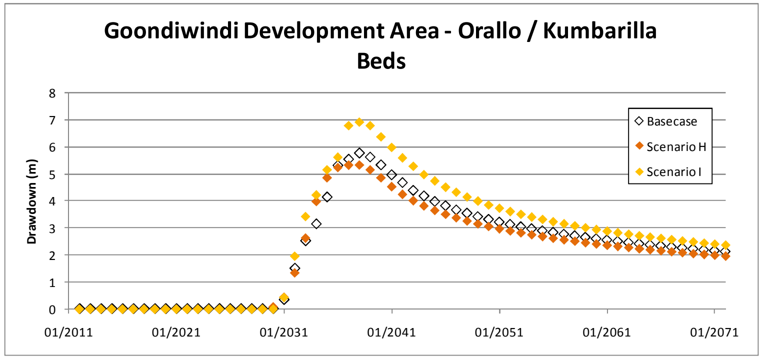
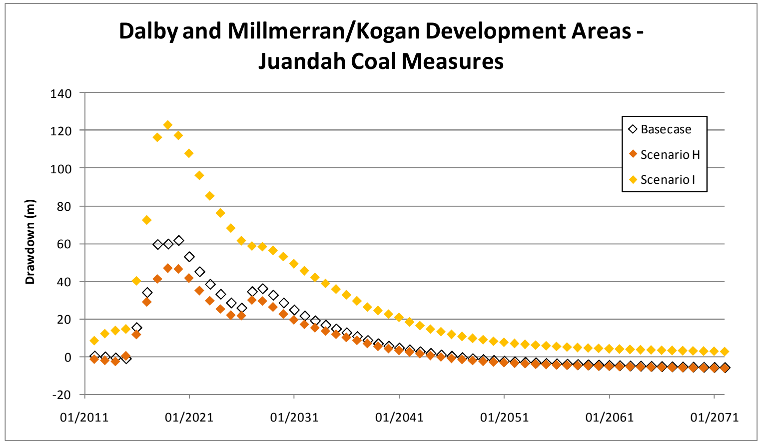
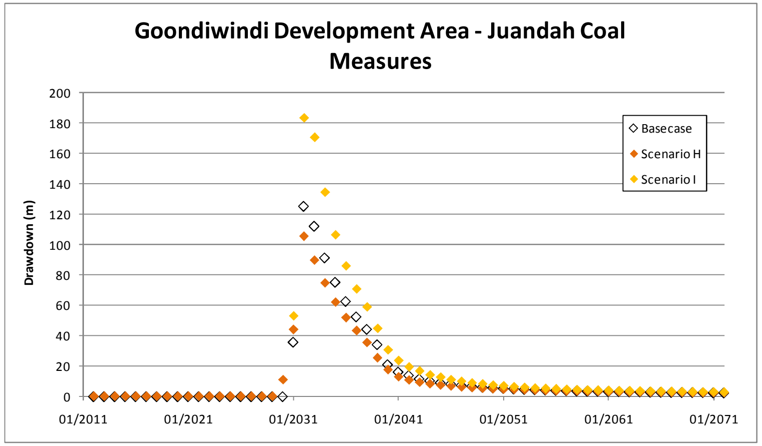
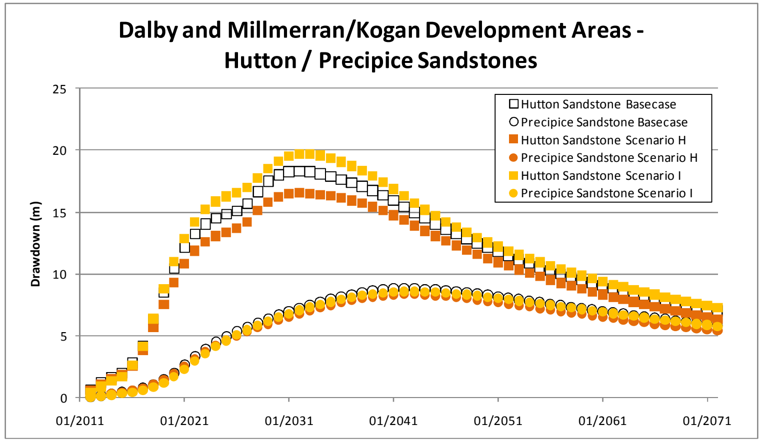
Figure 5.29 Sensitivities H and I. Predicted drawdown (Wandoan and Chinchilla locations)











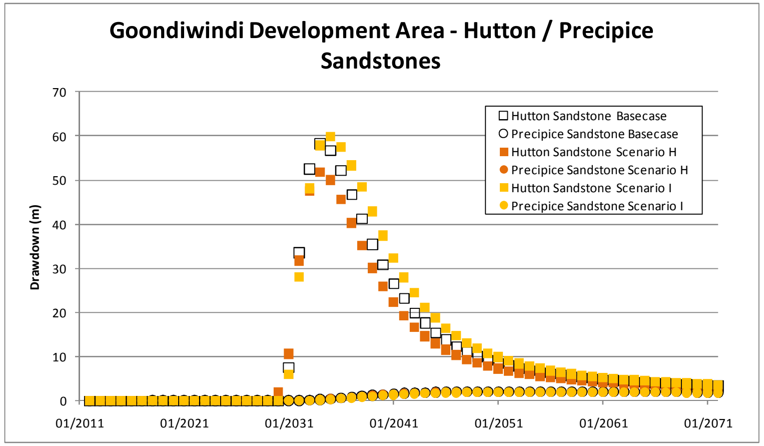


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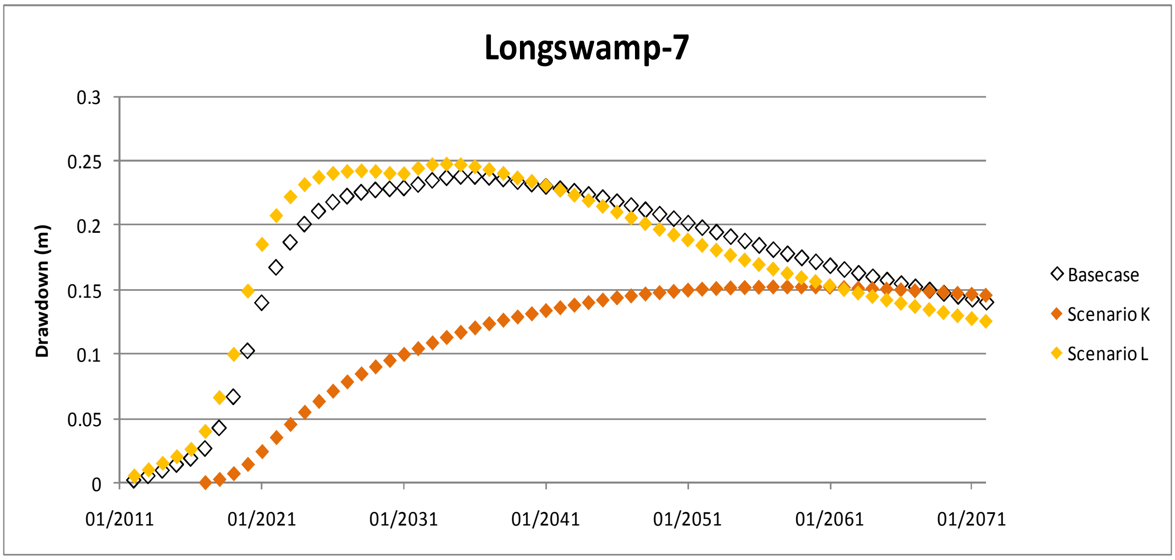
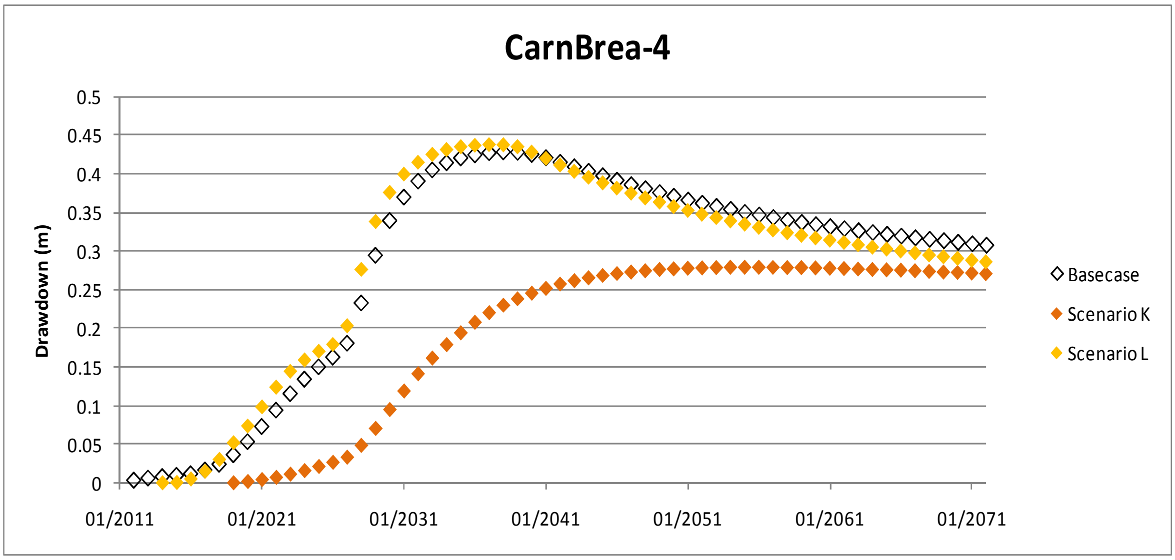
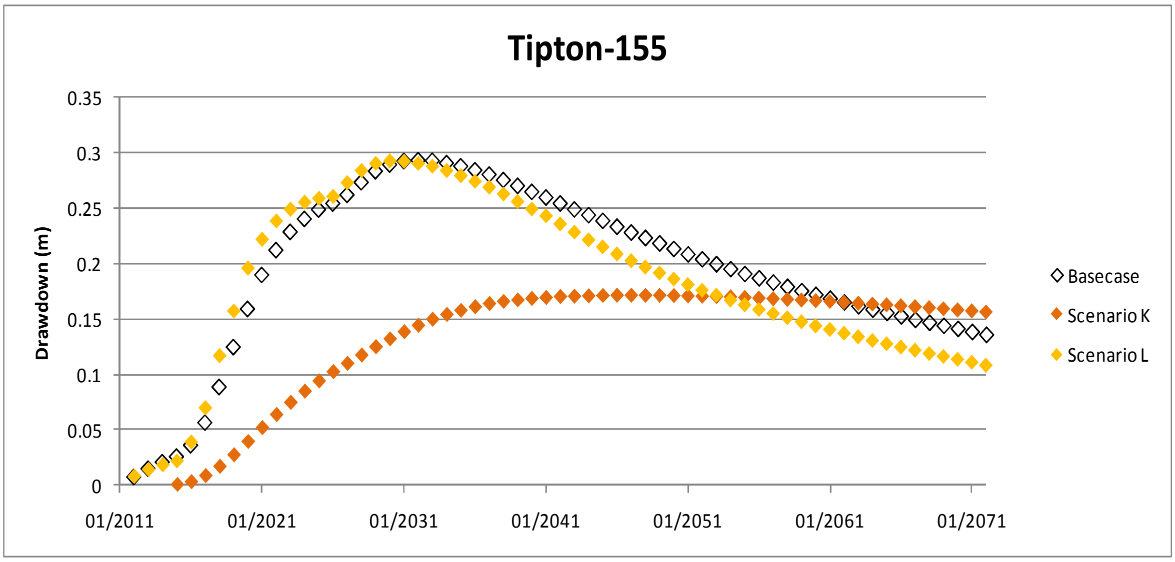
Figure 5.30 Sensitivities H and I. Predicted drawdown (Dalby and Millmerran / Kogan locations)

Figure 5.31 Sensitivities K and L. Predicted drawdown (Condamine Alluvium locations)







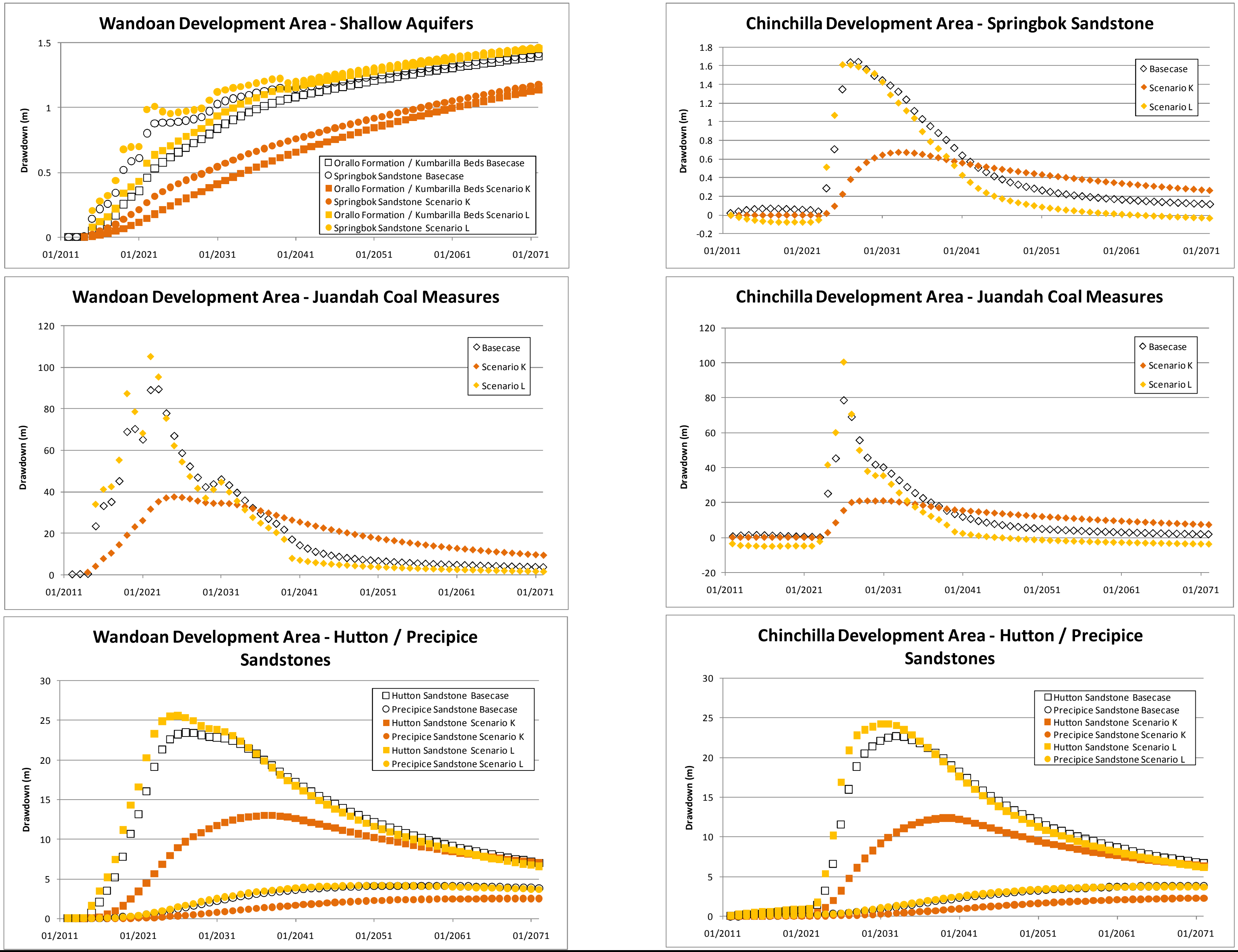


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Figure 5.32 Sensitivities K and L. Predicted drawdown (Wandoan and Chinchilla locations)

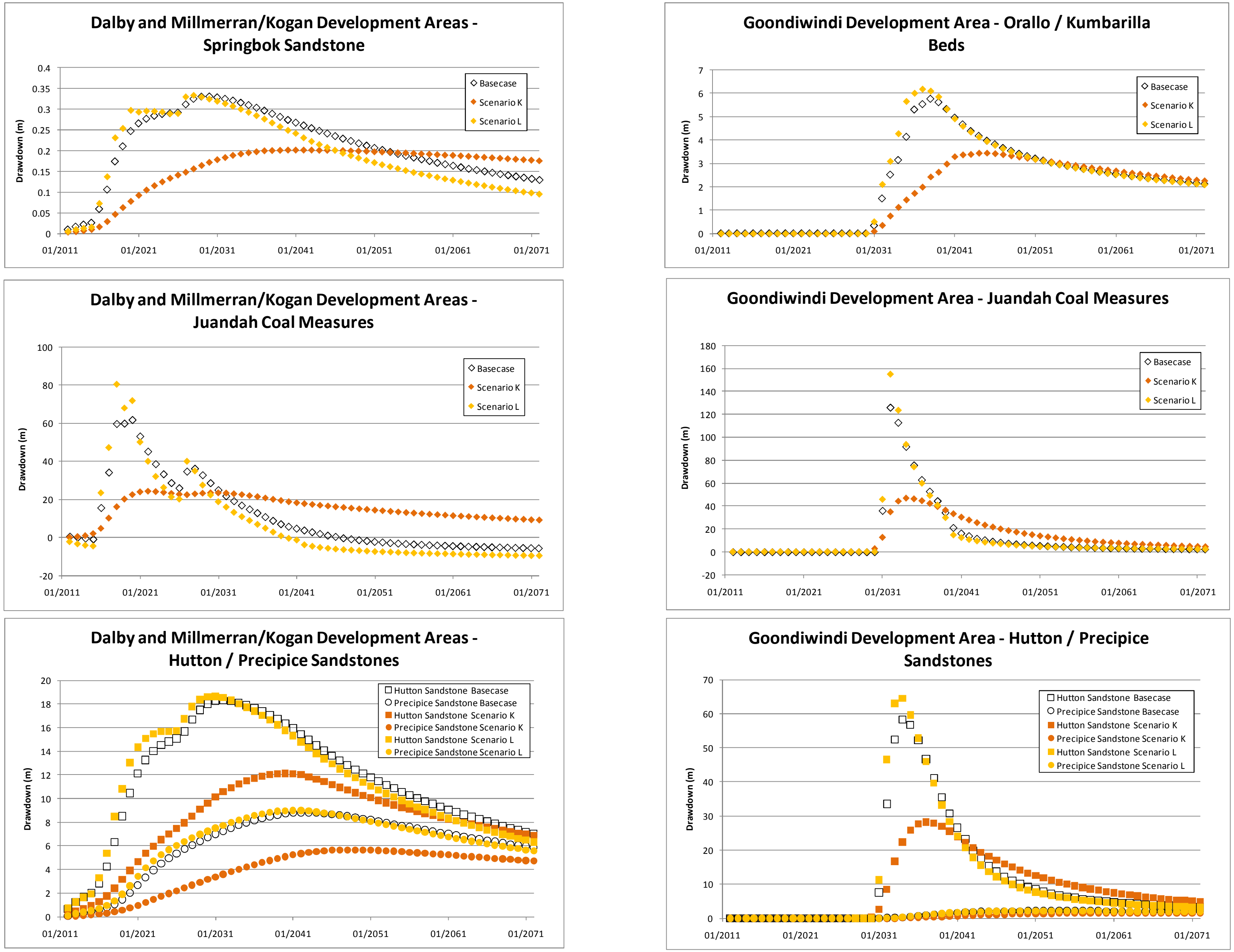

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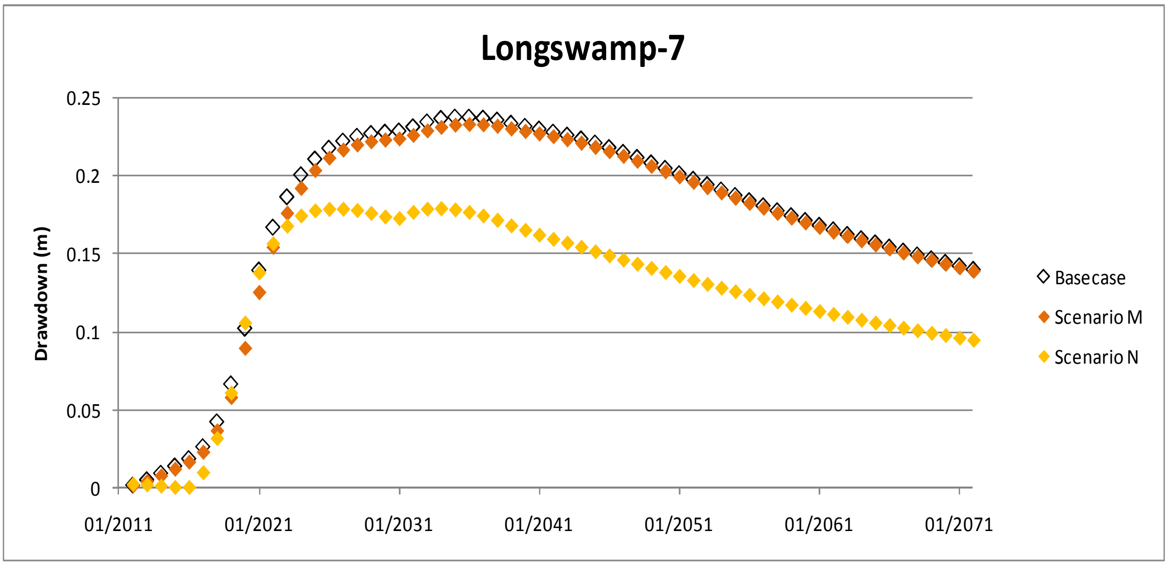
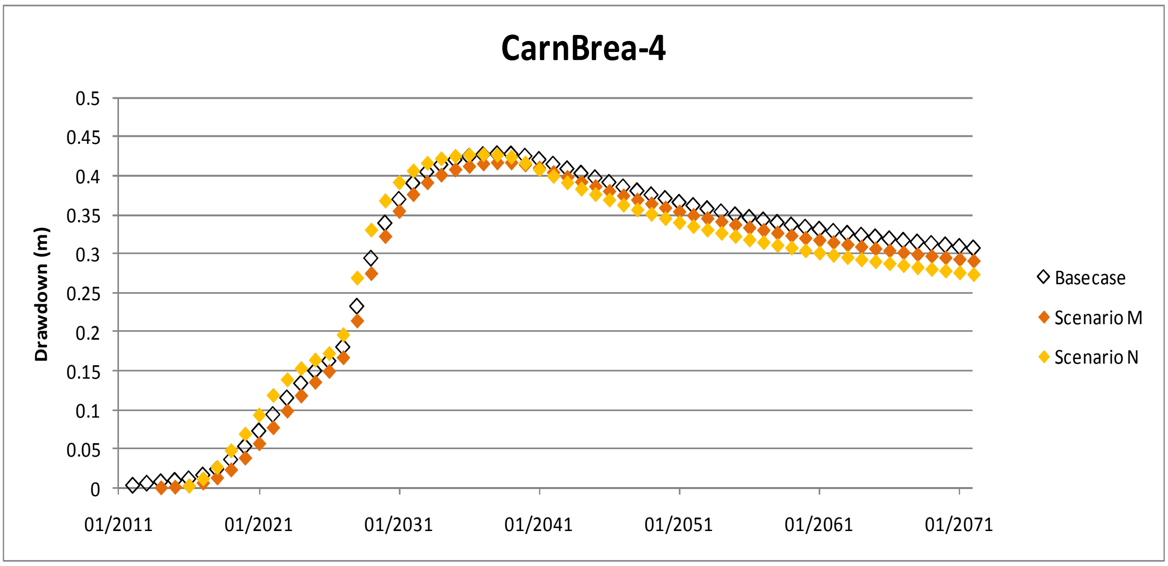
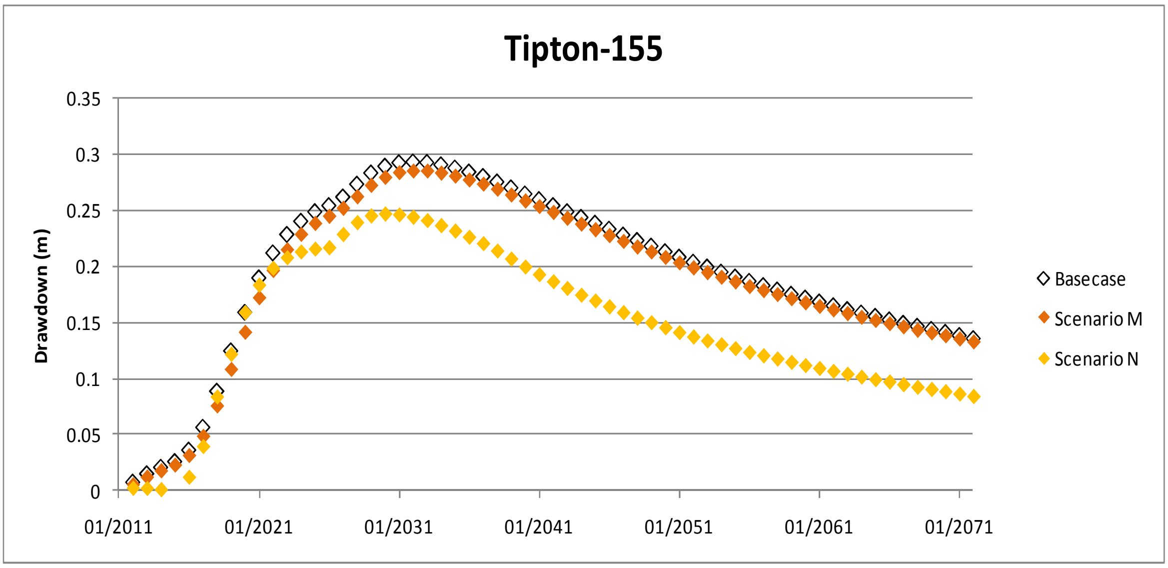
Figure 5.33 Sensitivities K and L. Predicted drawdown (Dalby and Millmerran / Kogan locations)

Figure 5.34 Sensitivities M and N. Predicted drawdown (Condamine Alluvium locations)







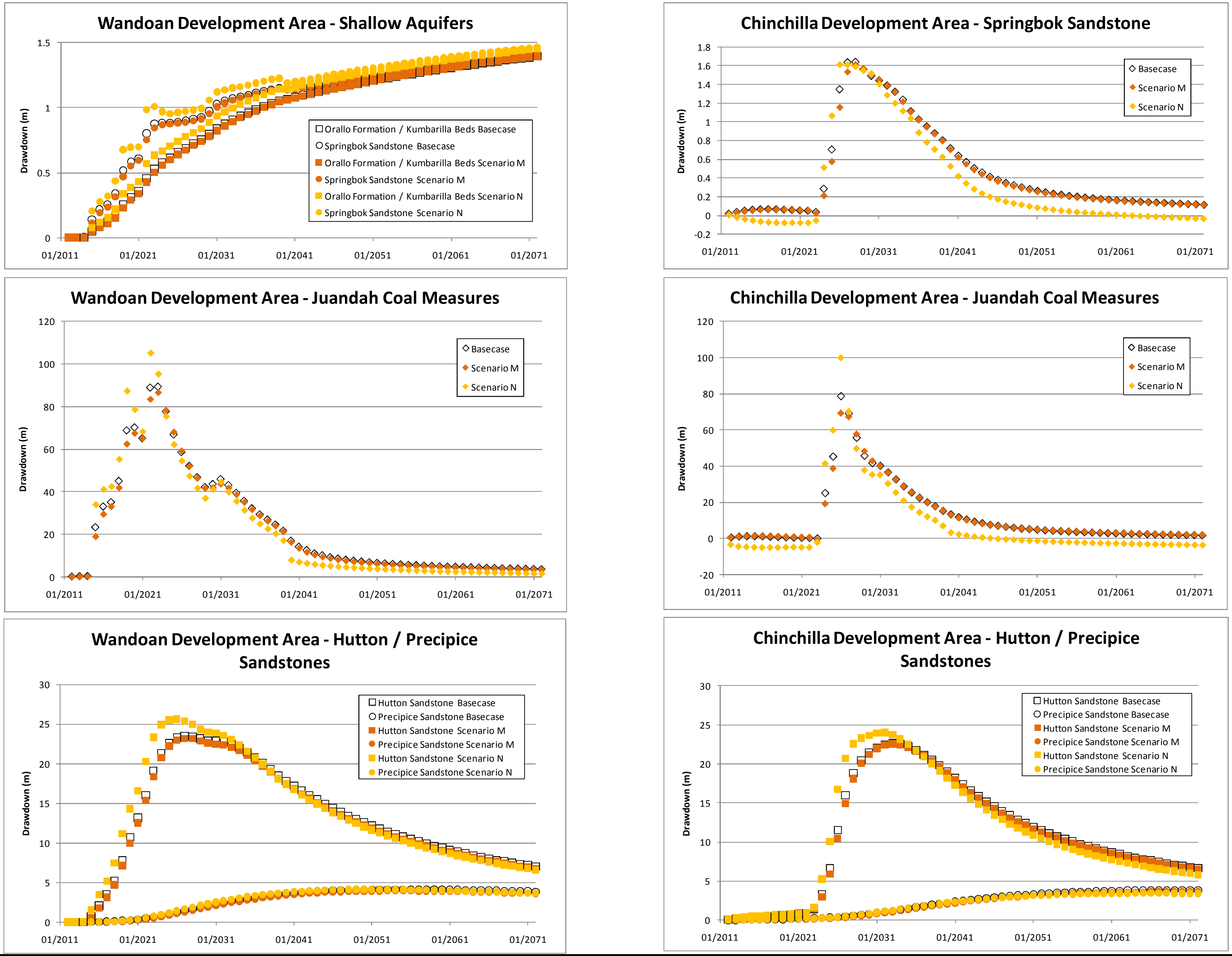


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Figure 5.35 Sensitivities M and N. Predicted drawdown (Wandoan and Chinchilla locations)

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Figure 5.36 Sensitivities M and N. Predicted drawdown (Dalby and Millmerran / Kogan locations)

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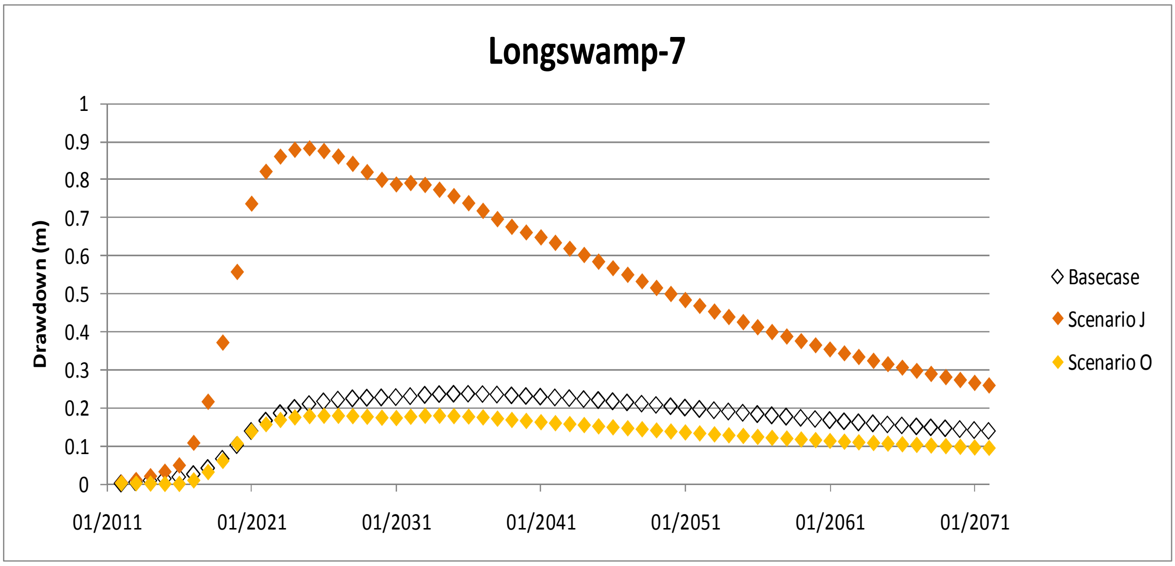
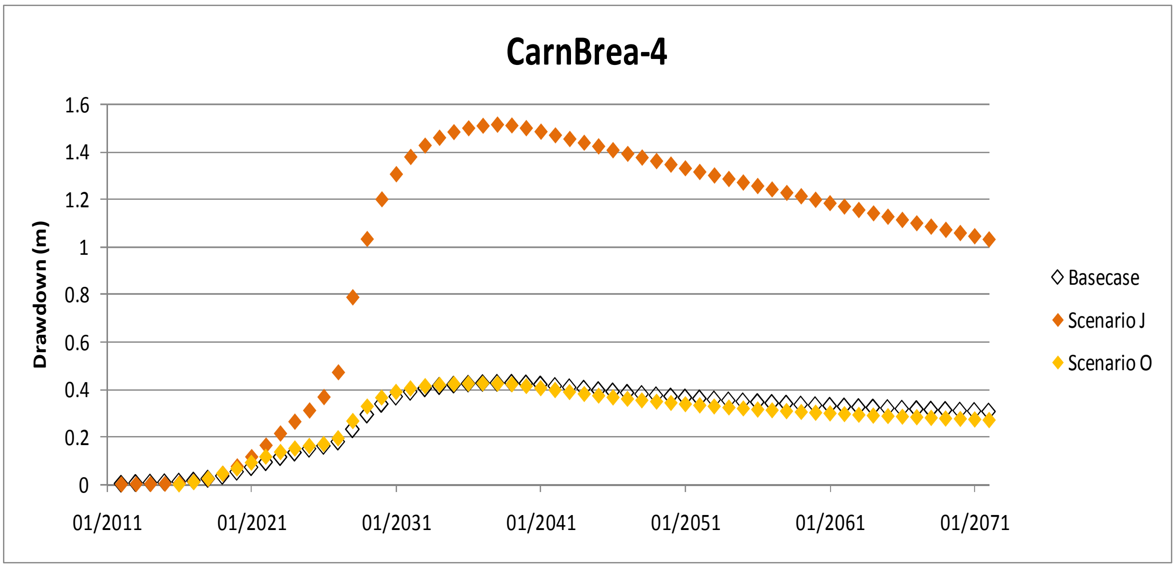
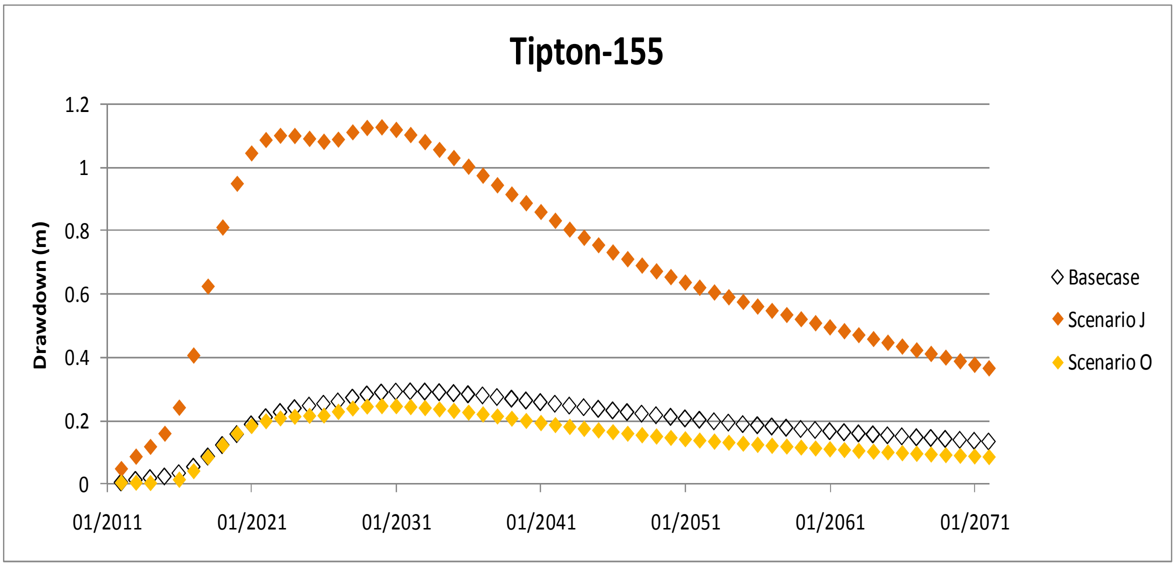
Figure 5.37 Sensitivities J and O. Predicted drawdown (Condamine Alluvium locations)







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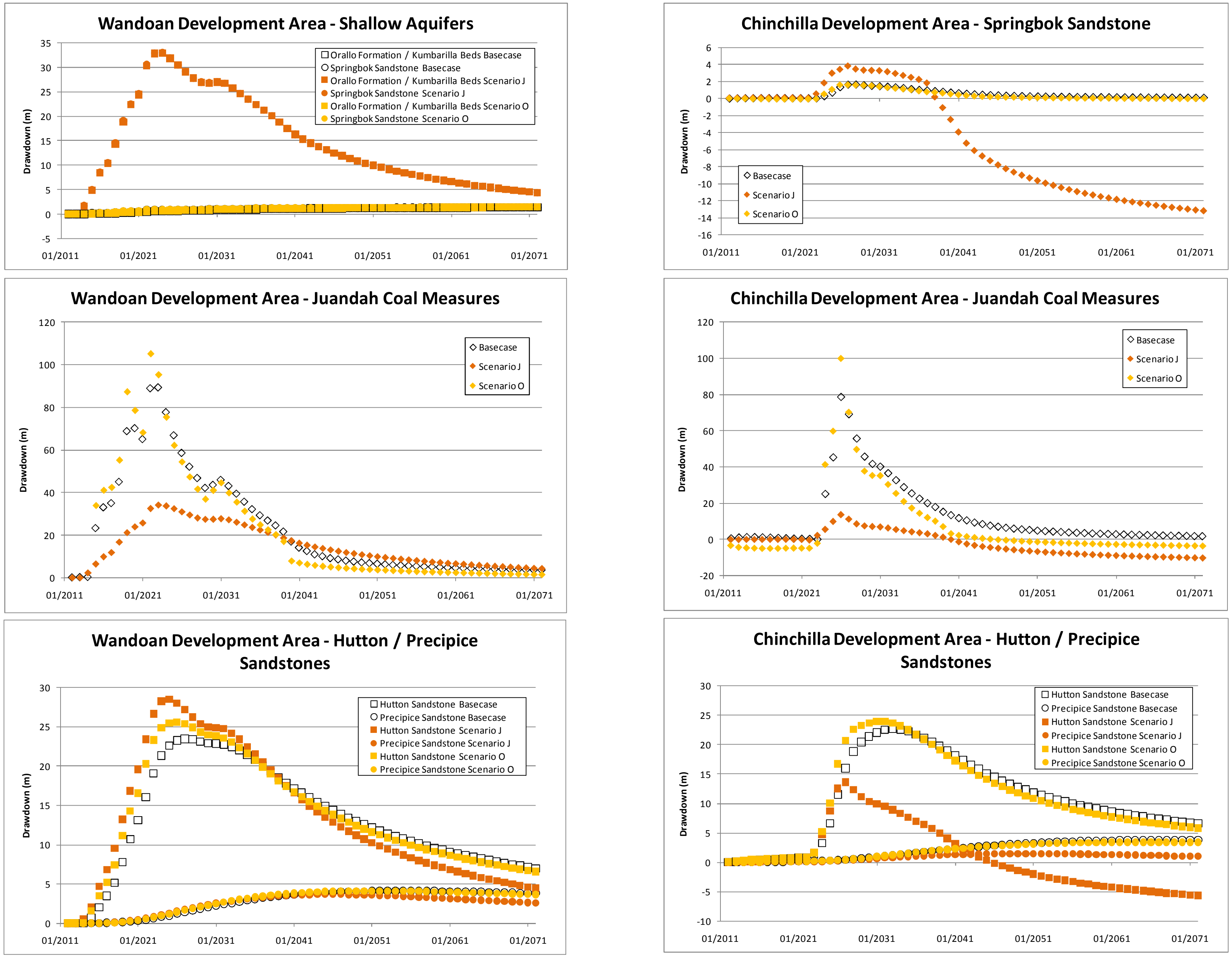

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Figure 5.38 Sensitivities J and O. Predicted drawdown (Wandoan and Chinchilla locations)

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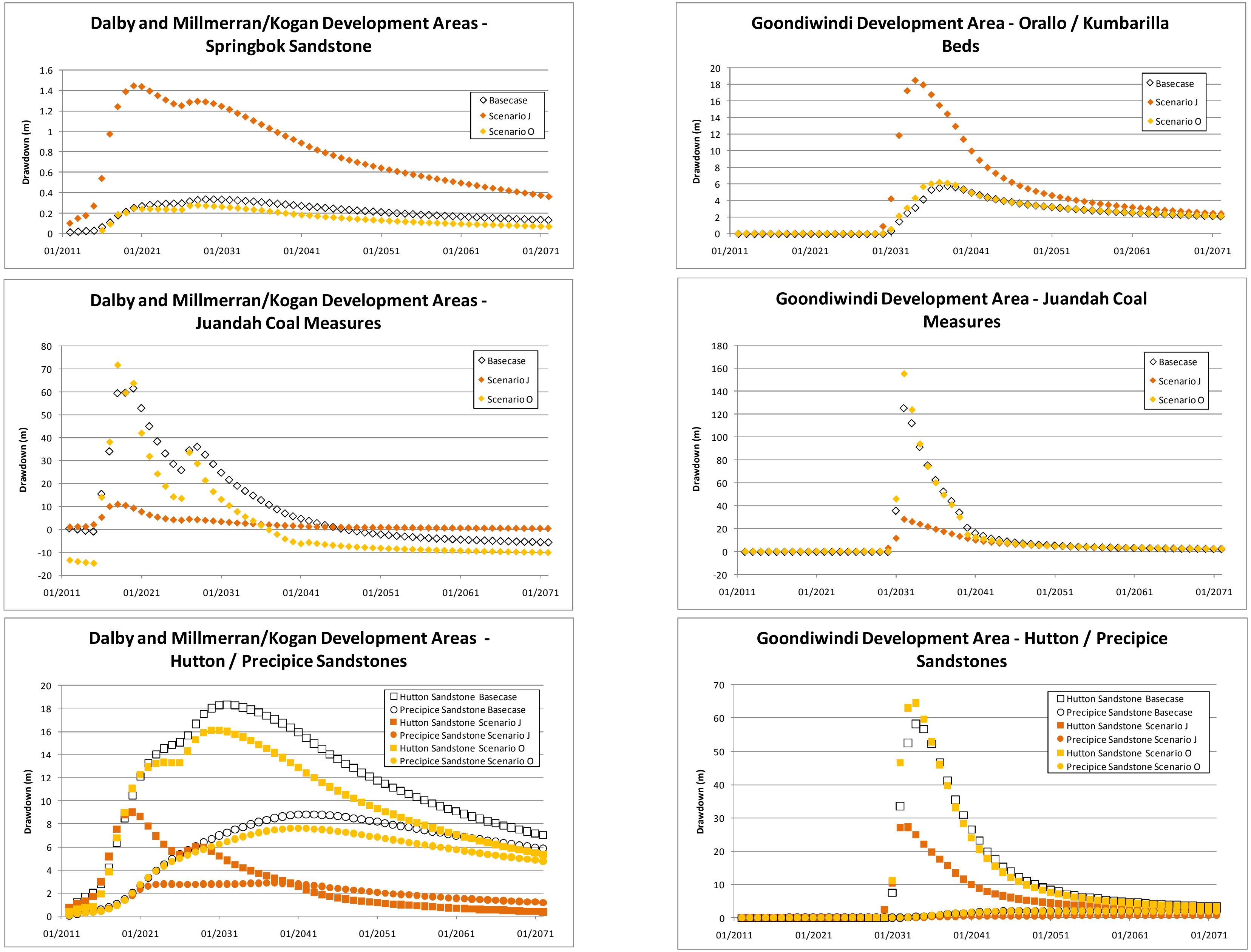

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Figure 5.39 Sensitivities J and O. Predicted drawdown (Dalby and Millmerran / Kogan locations)

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Appendix C
Springs within the model extent

Arrow Energy Surat Gas Project
Groundwater Impact Assessment Report

ID	Name	Lat GDA94	Long GDA94	Zone	XGDA94	YGDA94	EPBC	Number Active	Number Inactive	Rank	NRM Water	Current Flow	Unit	Rock Name	Age
2	DawsonRiver2	-25.5143305	150.0581143	56	204299.544	7174817.59	EPBC	1		3	Surat North	31298	Je	Evergreen Formation	EARLY JURASSIC
3	DawsonRiver3	-25.4580306	150.1315126	56	211546.529	7181218.35		10		3	Surat North	883336	Jp	Precipice Sandstone	EARLY JURASSIC
4	DawsonRiver4	-25.472997	150.1229459	56	210720.45	7179541.11		12		3	Surat North	45273	Je	Evergreen Formation	EARLY JURASSIC
5	Boggomoss	-25.4397318	150.0344732	56	201737.715	7183032.55	EPBC	25		1b	Surat North	3040250	Je	Evergreen Formation	EARLY JURASSIC
6	DawsonRiver5	-25.4414584	150.0304868	56	201340.809	7182832.25	EPBC	16		1b	Surat North	2905926	Je	Evergreen Formation	EARLY JURASSIC
7	DawsonRiver7	-25.5523321	149.8070932	55	782055.893	7170899.4		2		3	Surat North	980	Ji	Injune Creek Group	MIDDLE JURASSIC - LATE JURASSIC
8	DawsonRiver8	-25.567332	149.8020934	55	781518.159	7169247.71	EPBC	1		3	Surat North	31298	Ji	Injune Creek Group	MIDDLE JURASSIC - LATE JURASSIC
9	CockatooCrk	-25.7234716	150.2512549	56	224203.77	7152056.69	EPBC	7		1b	Surat North	43609	Je	Evergreen Formation	EARLY JURASSIC
74	Yebna	-25.6483358	149.2011053	55	720968.218	7161412.22		1		3	Surat North	0	Je	Evergreen Formation	EARLY JURASSIC
76	EdenVale	-25.1983454	148.1011217	55	610939.616	7212625.91		1		3	Surat North	0	Jh	Hutton Sandstone	MIDDLE JURASSIC
84	Conom	-24.389009	149.1374303	55	716775.987	7301024.15		3		3	Mimosa	0	TRe	Clematis Group	TRIASSIC
85	Newton	-25.3833369	149.3728481	55	738739.494	7190475.11		2	2	2	Surat North	24838	Jh	Hutton Sandstone	MIDDLE JURASSIC
229	Ponies	-25.8293361	149.0401098	55	704491.271	7141619.37		1		2	Surat North	4405	Jh	Hutton Sandstone	MIDDLE JURASSIC
230	LuckyLast	-25.8013394	148.7573158	55	676180.723	7145130.18	EPBC	5		1b	Surat North	96717	Ji	Injune Creek Group	MIDDLE JURASSIC - LATE JURASSIC
232	CrystalBall	-25.507095	147.9763766	55	598121.017	7178530.63		4		1b	Surat North	969170	Jh	Hutton Sandstone	MIDDLE JURASSIC
233	Moolayember	-25.1793422	148.570113	55	658222.186	7214261.56		1		1b	Surat North	24183	TRe	Clematis Group	TRIASSIC
234	Hellhole	-25.1038508	147.4331338	55	543671.021	7223473.29		2		2	Barcaldine East	6807	Jh	Hutton Sandstone	MIDDLE JURASSIC
235	Moffat	-25.0756808	148.0557854	55	606477.915	7226246.78		3		2	Surat North	67383	Jh	Hutton Sandstone	MIDDLE JURASSIC
236	Marlong	-24.9440142	147.9597888	55	596899.143	7240899.62		3		2	Surat North	120463	Jp	Precipice Sandstone	EARLY JURASSIC
237	Paddy's	-24.9263485	147.8271244	55	583516.753	7242943.93		1		2	Barcaldine East	3404	Jp	Precipice Sandstone	EARLY JURASSIC
238	16mile	-24.8903508	147.5251295	55	553038.27	7247081.64		1		3	Barcaldine East	349	Jp	Precipice Sandstone	EARLY JURASSIC
239	Rock Art	-24.8783503	147.8042908	55	581242.507	7248272.83		6		1a	Barcaldine East	766033	Jp	Precipice Sandstone	EARLY JURASSIC
240	BunBunc	-24.8663515	147.4431308	55	544764.897	7249768.53		1		3	Barcaldine East	31298	Jp	Precipice Sandstone	EARLY JURASSIC
241	MajorMitchell	-24.8339534	147.1969354	55	519899.412	7253414.29		5		1a	Barcaldine East	19490434	Jp	Precipice Sandstone	EARLY JURASSIC
242	Googenya	-24.8553518	147.4011314	55	540525.677	7250999.65		1		3	Barcaldine East	349	Jp	Precipice Sandstone	EARLY JURASSIC
243	Top	-24.8393523	147.3481322	55	535175.729	7252785.96		1		3	Barcaldine East	96	Jp	Precipice Sandstone	EARLY JURASSIC
244	Bunoven	-24.825852	147.4056311	55	540989.994	7254264.77		2		3	Barcaldine East	9600	Jp	Precipice Sandstone	EARLY JURASSIC
245	DenSprings	-24.8228513	147.4911295	55	549631.137	7254568.64		2		2	Barcaldine East	2027	TRm	Moolayember Formation	MIDDLE TRIASSIC
246	Ladybird	-24.7993491	147.8251233	55	583399.853	7257008.36		1		2	Barcaldine East	4405	Jp	Precipice Sandstone	EARLY JURASSIC
247	BigTreeGroup	-24.795753	147.6889218	55	569634.731	7257482.86		4	1	2	Barcaldine East	7372	Jp	Precipice Sandstone	EARLY JURASSIC
254	254	-24.9183409	148.9411041	55	696030.577	7242685.24		1		3	Mimosa	0	TRe	Clematis Group	TRIASSIC
255	EddyOwen	-25.3983484	147.5511334	55	555434.802	7190818.44		1		3	Barcaldine East	0	Jh	Hutton Sandstone	MIDDLE JURASSIC
256	DamDyke	-24.748349	147.8811219	55	589096.621	7262620.47		1		3	Surat North	0	Jp	Precipice Sandstone	EARLY JURASSIC
258	Manan	-26.2233439	147.7151377	55	571434.834	7099374.82		2		2	Surat	853			
260	Scotts Creek	-25.8908341	149.2856057	55	728987.752	7134400.54	EPBC	4		1b	Surat North	489641	Ji	Injune Creek Group	MIDDLE JURASSIC - LATE JURASSIC
261	Abercorn	-25.1228251	151.1373406	56	312204.879	7220145.98		4		1b	Surat East	315474			
262	Spa	-25.2653496	147.4681337	55	547137.782	7205578.09		1		3	Barcaldine East	0	Je	Evergreen Formation	EARLY JURASSIC
264	Cera	-25.2783241	151.1620914	56	314936.172	7202955.81		1		3	Surat East	37943			
265	Surveyor's	-25.201349	147.589131	55	559352.674	7212617.29		1		3	Barcaldine East	0	Je	Evergreen Formation	EARLY JURASSIC
266	BlackChest	-25.3983502	147.3011378	55	530289.224	7190898.46		1		3	Barcaldine East	0	Ji	Injune Creek Group	MIDDLE JURASSIC - LATE JURASSIC
267	267	-25.2313438	148.3426176	55	635236.791	7208750.31		2		3	Surat North	0	Je	Evergreen Formation	EARLY JURASSIC
268	Bevan	-25.0313507	147.451132	55	545512.51	7231495.44		1		3	Barcaldine East	0	Je	Evergreen Formation	EARLY JURASSIC
272	Unfairplay	-24.8533533	147.2061347	55	520825.715	7251264.82		2		3	Barcaldine East	0	Jp	Precipice Sandstone	EARLY JURASSIC
283	Barton	-26.2813328	149.2341101	55	723084.7	7091223.24		1		3	Surat	0			
296	Carnarvon Gorge	-25.0353982	148.1881342	55	619865.896	7230597.09		21		1a	Surat North	430546	Je	Evergreen Formation	EARLY JURASSIC
297	Carnarvetc	-24.7407518	147.7143247	55	572234.302	7263560.02		5		3	Barcaldine East	0	TRm	Moolayember Formation	MIDDLE TRIASSIC
298	SprGrove	-24.9773265	151.0420912	56	302366.113	7236127.06		1		3	Surat East	3404			
302	302	-25.1063392	149.2531011	55	727202.26	7221371.67		2		2	Surat North	235845	Jp	Precipice Sandstone	EARLY JURASSIC
304	ExpedRange	-24.2636335	149.1514216	55	718410.337	7314890.17		19		1b	Mimosa	465790	TRm	Moolayember Formation	MIDDLE TRIASSIC
306	306	-24.0903432	149.2170925	55	725383.734	7333981.42		1		3	Mimosa	0	TRm	Moolayember Formation	MIDDLE TRIASSIC
307	Eglin	-24.5473938	149.1172405	55	714459.087	7283511.11		11		3	Mimosa	266016	TRm	Moolayember Formation	MIDDLE TRIASSIC
308	308	-25.0008065	148.9881039	55	700644.465	7233481.78		1		3	Mimosa	0	TRe	Clematis Group	TRIASSIC
309	309	-25.0608927	148.8801064	55	689650.038	7226981.75		1		3	Mimosa	0	TRe	Clematis Group	TRIASSIC
310	310	-25.0133386	149.2240996	55	724446.293	7231723.15		1		3	Surat North	0	TRm	Moolayember Formation	MIDDLE TRIASSIC
311	311	-25.7160987	149.0875259	55	709444.161	7154089.92		12		2	Surat North	133988	Jp	Precipice Sandstone	EARLY JURASSIC
325	325	-24.8153479	147.9841206	55	599458.78	7255130.26		0	1	5	Surat North	0	Jp	Precipice Sandstone	EARLY JURASSIC
326	326	-25.2291839	148.6601118	55	667224.922	7208632.2		1		3	Surat North	0	TRe	Clematis Group	TRIASSIC
327	327	-25.4993379	148.9831081	55	699324.46	7178264.25		1		3	Surat North	0	TRm	Moolayember Formation	MIDDLE TRIASSIC
328	328	-24.9563376	149.4030959	55	742628.341	7237729.69		1		3	Surat North	0	TRm	Moolayember Formation	MIDDLE TRIASSIC
331	331	-25.3929924	150.1599876	56	214257.933	7188487.41		2		3	Surat North	0	TRr	Rewan Formation	TRIASSIC
332	332	-25.3175504	150.085806	56	206607.993	7196687.37		1		3	Surat North	0	Jp	Precipice Sandstone	EARLY JURASSIC
334	334	-25.423396	150.192562	56	217607.914	7185187.44		1		3	Surat North	0	TRr	Rewan Formation	TRIASSIC
335	335	-25.094343	149.5424214	55	756413.938	7222182.29		1		3	Surat North	0	Jh	Hutton Sandstone	MIDDLE JURASSIC
336	336	-24.9453363	149.6140919	55	763964.209	7238554.71		1		3	Surat North	0	Jp	Precipice Sandstone	EARLY JURASSIC
337	337	-24.9153505	147.5511292	55	555653.093	7244303.02		1		3	Barcaldine East	0	Jp	Precipice Sandstone	EARLY JURASSIC
339	LonelyEddie	-25.4783398	148.7331125	55	674222.199	7180941.19		1		3	Surat North	0	Jp	Precipice Sandstone	EARLY JURASSIC
506	SprRidge	-26.2338911	148.8694498	55	686739.146	7097056.78		3		2	Surat	11232			
507	VI_mile	-26.2600097	148.6896622	55	668739.068	7094410.12		4		4	Surat	11150			
509	Binnalong	-25.0693489	147.6771283	55	568291.689	7227192.73		1		3	Barcaldine East	120000	Je	Evergreen Formation	EARLY JURASSIC
561	SpRockCrk	-25.7623383	148.7701143	55	677522.171	7149433.28		1		3	Surat North	931	Je	Evergreen Formation	EARLY JURASSIC

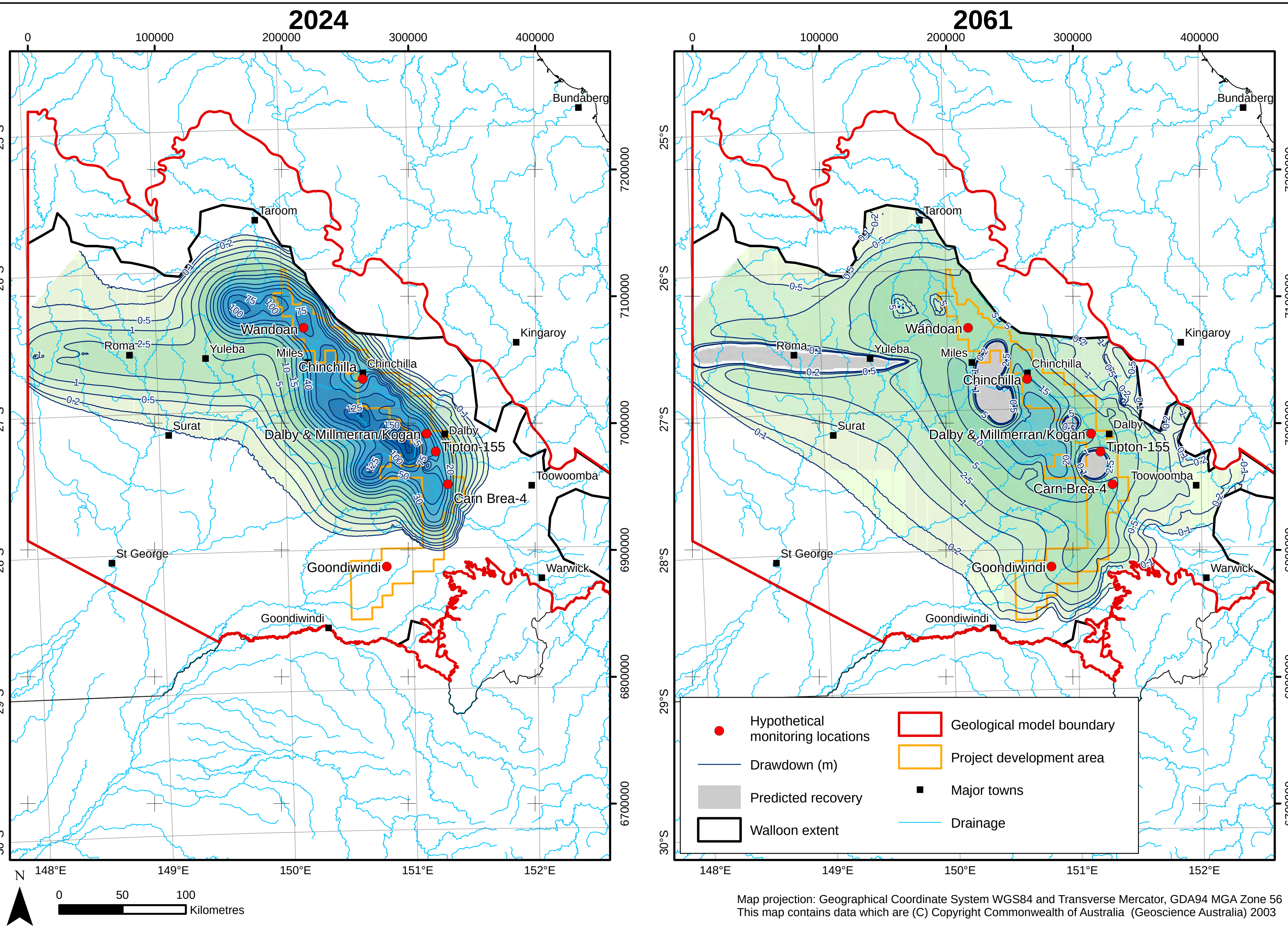
ID	Name	Sequence Number	Dominant Rock	Map Symbol	Unit	Rock Name	Age	Sequence Number	Dominant Rock	Map Symbol
2	DawsonRiver2	1510	ARENITE-MUDROCK	Je	Jle	Evergreen Formation	EARLY JURASSIC	1510	ARENITE-MUDROCK	Je
3	DawsonRiver3	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
4	DawsonRiver4	1510	ARENITE-MUDROCK	Je	Jle	Evergreen Formation	EARLY JURASSIC	1510	ARENITE-MUDROCK	Je
5	Boggomoss	1510	ARENITE-MUDROCK	Je	Jle	Evergreen Formation	EARLY JURASSIC	1510	ARENITE-MUDROCK	Je
6	DawsonRiver5	1510	ARENITE-MUDROCK	Je	Jle	Evergreen Formation	EARLY JURASSIC	1510	ARENITE-MUDROCK	Je
7	DawsonRiver7	1370	SEDIMENTARY ROCK	Ji	Ji	Injune Creek Group	MIDDLE JURASSIC - LATE JURASSIC	1370	SEDIMENTARY ROCK	Ji
8	DawsonRiver8	1370	SEDIMENTARY ROCK	Ji	Qa	Qa-NSB	QUATERNARY	100	ALLUVIUM	Qa
9	CockatooCrk	1510	ARENITE-MUDROCK	Je	Jle	Evergreen Formation	EARLY JURASSIC	1510	ARENITE-MUDROCK	Je
74	Yebna	1510	ARENITE-MUDROCK	Je	Jle	Evergreen Formation	EARLY JURASSIC	1510	ARENITE-MUDROCK	Je
76	EdenVale	1390	ARENITE	Jh	Jlh	Hutton Sandstone	MIDDLE JURASSIC	1390	ARENITE	Jh
84	Conom	1730	SEDIMENTARY ROCK	Re				0		
85	Newton	1390	ARENITE	Jh	Jlh	Hutton Sandstone	MIDDLE JURASSIC	1390	ARENITE	Jh
229	Ponies	1390	ARENITE	Jh	Jlh	Hutton Sandstone	MIDDLE JURASSIC	1390	ARENITE	Jh
230	LuckyLast	1370	SEDIMENTARY ROCK	Ji	Ji	Injune Creek Group	MIDDLE JURASSIC - LATE JURASSIC	1370	SEDIMENTARY ROCK	Ji
232	CrystalBall	1390	ARENITE	Jh	Jlh	Hutton Sandstone	MIDDLE JURASSIC	1390	ARENITE	Jh
233	Moolayember	1730	SEDIMENTARY ROCK	Re	TRe	Clematis Group	TRIASSIC	1730	SEDIMENTARY ROCK	Re
234	Hellhole	1390	ARENITE	Jh	Jlh	Hutton Sandstone	MIDDLE JURASSIC	1390	ARENITE	Jh
235	Moffat	1390	ARENITE	Jh	Jlh	Hutton Sandstone	MIDDLE JURASSIC	1390	ARENITE	Jh
236	Marlong	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
237	Paddy's	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
238	16mile	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
239	Rock Art	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
240	BunBunc	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
241	MajorMitchell	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
242	Googenya	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
243	Top	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
244	Bunoven	1510	ARENITE	Jp	TRm	Moolayember Formation	MIDDLE TRIASSIC	1700	ARENITE-MUDROCK	Rm
245	DenSprings	1700	ARENITE-MUDROCK	Rm	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
246	Ladybird	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
247	BigTreeGroup	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
254	254	1730	SEDIMENTARY ROCK	Re	TRe	Clematis Group	TRIASSIC	1730	SEDIMENTARY ROCK	Re
255	EddyOwen	1390	ARENITE	Jh	Jle	Evergreen Formation	EARLY JURASSIC	1510	ARENITE-MUDROCK	Je
256	DamDyke	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
258	Manan	0			JKh	Hooray Sandstone	JURASSIC - CRETACEOUS	1430	ARENITE	JKh
260	Scotts Creek	1370	SEDIMENTARY ROCK	Ji	Ji	Injune Creek Group	MIDDLE JURASSIC - LATE JURASSIC	1370	SEDIMENTARY ROCK	Ji
261	Abercorn	0			Jlh	Hutton Sandstone	MIDDLE JURASSIC	1390	ARENITE	Jh
262	Spa	1510	ARENITE-MUDROCK	Je	Jle	Evergreen Formation	EARLY JURASSIC	1510	ARENITE-MUDROCK	Je
264	Cera	0			Jle	Evergreen Formation	EARLY JURASSIC	1510	ARENITE-MUDROCK	Je
265	Surveyor's	1510	ARENITE-MUDROCK	Je	Jle	Evergreen Formation	EARLY JURASSIC	1510	ARENITE-MUDROCK	Je
266	BlackChest	1370	SEDIMENTARY ROCK	Ji	Jmb	Birkhead Formation	JURASSIC	1450	ARENITE-MUDROCK	Jib
267	267	1510	ARENITE-MUDROCK	Je	Jle	Evergreen Formation	EARLY JURASSIC	1510	ARENITE-MUDROCK	Je
268	Bevan	1510	ARENITE-MUDROCK	Je	Jle	Evergreen Formation	EARLY JURASSIC	1510	ARENITE-MUDROCK	Je
272	Unfairplay	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
283	Barton	0			Jug	Gubberamunda Sandstone	JURASSIC	1450	ARENITE	Jg
296	Carnarvon Gorge	1510	ARENITE-MUDROCK	Je	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
297	Carnarvetc	1700	ARENITE-MUDROCK	Rm	Tob	Tob-NSB	TERTIARY	990	BASALT	Tob
298	SprGrove	0			Jle	Evergreen Formation	EARLY JURASSIC	1510	ARENITE-MUDROCK	Je
302	302	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
304	ExpedRange	1700	ARENITE-MUDROCK	Rm				0		
306	306	1700	ARENITE-MUDROCK	Rm				0		
307	Eglin	1700	ARENITE-MUDROCK	Rm	TRe	Clematis Group	TRIASSIC	1730	SEDIMENTARY ROCK	Re
308	308	1730	SEDIMENTARY ROCK	Re	TRe	Clematis Group	TRIASSIC	1730	SEDIMENTARY ROCK	Re
309	309	1730	SEDIMENTARY ROCK	Re	TRe	Clematis Group	TRIASSIC	1730	SEDIMENTARY ROCK	Re
310	310	1700	ARENITE-MUDROCK	Rm	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
311	311	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
325	325	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
326	326	1730	SEDIMENTARY ROCK	Re	TRm	Moolayember Formation	MIDDLE TRIASSIC	1700	ARENITE-MUDROCK	Rm
327	327	1700	ARENITE-MUDROCK	Rm	TRm	Moolayember Formation	MIDDLE TRIASSIC	1700	ARENITE-MUDROCK	Rm
328	328	1700	ARENITE-MUDROCK	Rm	TRm	Moolayember Formation	MIDDLE TRIASSIC	1700	ARENITE-MUDROCK	Rm
331	331	1730	ARENITE-MUDROCK	Rr	Qa	Qa-NSB	QUATERNARY	100	ALLUVIUM	Qa
332	332	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
334	334	1730	ARENITE-MUDROCK	Rr	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
335	335	1390	ARENITE	Jh	Jlh	Hutton Sandstone	MIDDLE JURASSIC	1390	ARENITE	Jh
336	336	1510	ARENITE	Jp	Jle	Evergreen Formation	EARLY JURASSIC	1510	ARENITE-MUDROCK	Je
337	337	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
339	LonelyEddie	1510	ARENITE	Jp	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp
506	SprRidge	0			Jug	Gubberamunda Sandstone	JURASSIC	1450	ARENITE	Jg
507	VI_mile	0			Jug	Gubberamunda Sandstone	JURASSIC	1450	ARENITE	Jg
509	Binnalong	1510	ARENITE-MUDROCK	Je	Jle	Evergreen Formation	EARLY JURASSIC	1510	ARENITE-MUDROCK	Je
561	SpRockCrk	1510	ARENITE-MUDROCK	Je	Jlp	Precipice Sandstone	EARLY JURASSIC	1510	ARENITE	Jp

Appendix D
Additional numerical model outputs

Arrow Energy Surat Gas Project
Groundwater Impact Assessment Report

The two additional figures included in this appendix were produced by Schlumberger Water Services (Australia) Pty Ltd in October 2011 (after the finalisation of their report in June 2011, as included in Appendix B)

6-114 Arrow Energy CSG Investigations\GIS\Figures\6-114 R4 Figures



Schlumberger WATER SERVICES

Figure 1 Scenario 2 predicted drawdown contours, Juandah Coal Measures (2024 & 2061)

6-114/R4

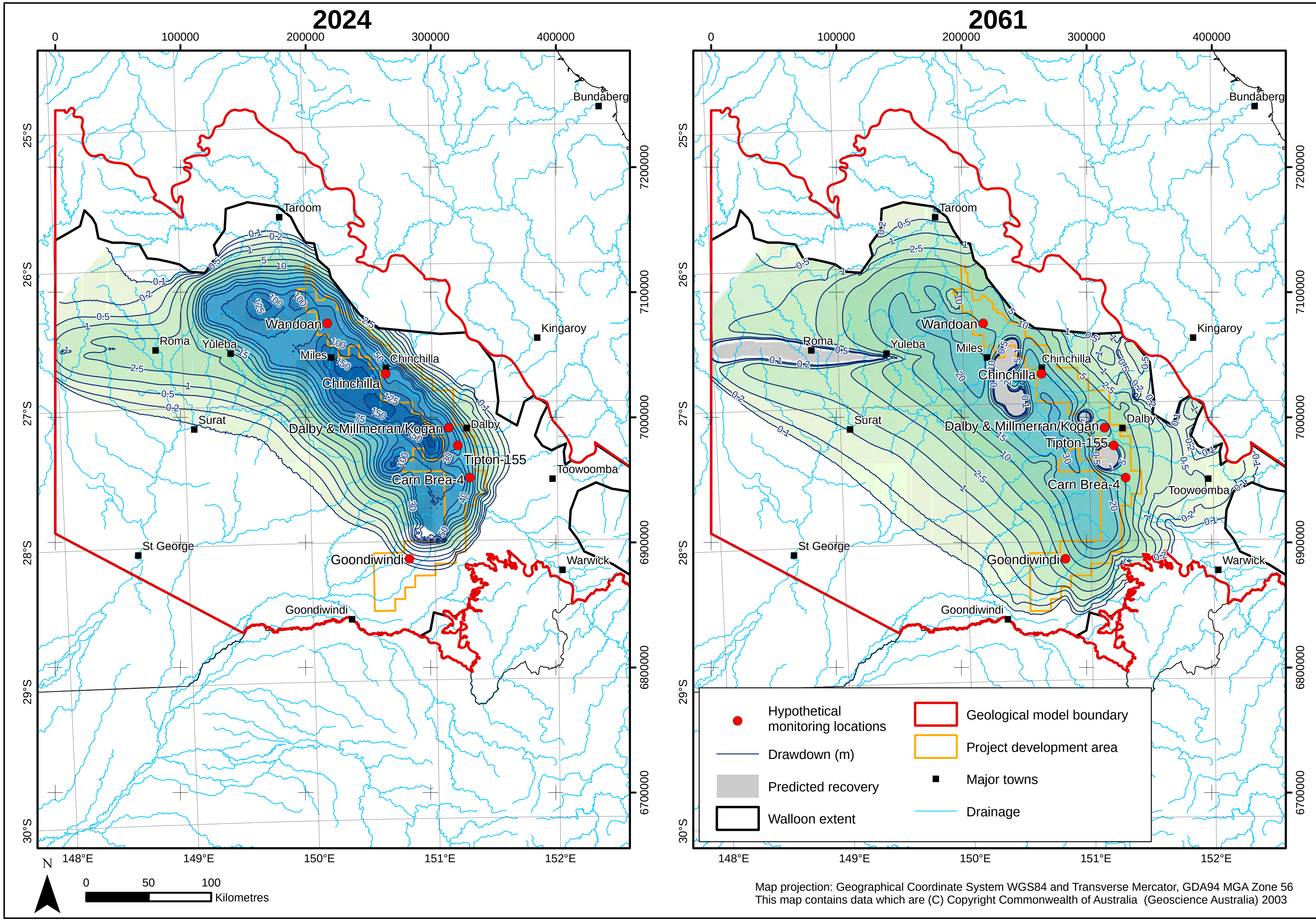


Figure 2 Scenario 3 predicted drawdown contours, Juandah Coal Measures (2024 & 2061)

Appendix E
Important information about your Coffey report

Arrow Energy Surat Gas Project
Groundwater Impact Assessment Report

Important information about Coffey Environmental Report

Uncertainties as to what lies below the ground on potentially contaminated sites can lead to remediation costs blow outs, reduction in the value of the land and to delays in the redevelopment of land. These uncertainties are an inherent part of dealing with land contamination. The following notes have been prepared by Coffey to help you interpret and understand the limitations of your report.

Your report has been written for a specific purpose

Your report has been developed on the basis of a specific purpose as understood by Coffey and applies only to the site or area investigated. For example, the purpose of your report may be:

- To assess the environmental effects of an on-going operation.
- To provide due diligence on behalf of a property vendor.
- To provide due diligence on behalf of a property purchaser.
- To provide information related to redevelopment of the site due to a proposed change in use, for example, industrial use to a residential use.
- To assess the existing baseline environmental, and sometimes geological and hydrological conditions or constraints of a site prior to an activity which may alter the sites environmental, geological or hydrological condition.

For each purpose, a specific approach to the assessment of potential soil and groundwater contamination is required. In most cases, a key objective is to identify, and if possible, quantify risks that both recognised and unrecognised contamination pose to the proposed activity. Such risks may be both financial (for example, clean up costs or limitations to the site use) and physical (for example, potential health risks to users of the site or the general public).

Scope of Investigations

The work was conducted, and the report has been prepared, in response to specific instructions from the client to whom this report is addressed, within practical time and budgetary constraints, and in reliance on certain data and information made available to Coffey. The analyses, evaluations, opinions and conclusions presented in this report are based on those instructions, requirements, data or information, and they could change if such instructions etc. are in fact inaccurate or incomplete.

Subsurface conditions can change Interpretation of factual data

Subsurface conditions are created by natural processes and the activity of man and may change with time. For example, groundwater levels can vary with time, fill may be placed on a site and pollutants may migrate with time. Because a report is based on conditions which existed at the time of the subsurface exploration, decisions should not be based on a report whose adequacy may have been affected by time. Consult Coffey to be advised how time may have impacted on the project and/or on the property.

Interpretation of factual data

Environmental site assessments identify actual subsurface conditions only at those points where samples are taken and when they are taken. Data derived from indirect field measurements and sometimes other reports on the site are interpreted by geologists, engineers or scientists to provide an opinion about overall site conditions, their likely impact with respect to the report purpose and recommended actions. Actual conditions may differ from those inferred to exist, because no professional, no matter how well qualified, can reveal what is hidden by earth, rock and time. The actual interface between materials may be far more gradual or abrupt than assumed based on the facts obtained. Nothing can be done to change the actual site conditions which exist, but steps can be taken to reduce the impact of unexpected conditions. For this reason, parties involved with land acquisition, management and/or redevelopment should retain the services of Coffey through the development and use of the site to identify variances, conduct additional tests if required, and recommend solutions to unexpected conditions or other problems encountered on site.

Your report will only give preliminary recommendations

Your report is based on the assumption that the site conditions as revealed through selective point sampling are indicative of actual conditions throughout an area. This assumption cannot be substantiated until project implementation has commenced and therefore your report recommendations can only be regarded as preliminary. Only Coffey, who prepared the report, is fully familiar with the background information needed to assess whether or not the report's recommendations are valid and whether or not changes should be considered with redevelopment or on-going use of the site. If another party undertakes the implementation of the recommendations of this report there is a risk that the report will be misinterpreted and Coffey cannot be held responsible for such misinterpretation.

Your report is prepared for specific purposes and persons

To avoid misuse of the information contained in your report it is recommended that you confer with Coffey before passing your report on to another party who may not be familiar with the background and the purpose of the report. In particular, a due diligence report for a property vendor may not be suitable for satisfying the needs of a purchaser. Your report should not be applied for any purpose other than that originally specified at the time the report was issued.

Interpretation by other professionals

Costly problems can occur when other professionals develop their plans based on misinterpretations of a report. To help avoid misinterpretations, retain Coffey to work with other professionals who are affected by the report. Have Coffey explain the report implications to professionals affected by them and then review plans and specifications produced to see how they have incorporated the report findings.

Data should not be separated from the report

The report as a whole presents the findings of the site assessment and the report should not be copied in part or altered in any way. Logs, figures, laboratory data, drawings, etc. are customarily included in our reports and are developed by scientists, engineers or geologists based on their interpretation of field logs (assembled by field personnel), field testing and laboratory evaluation of field samples. This information should not under any circumstances be redrawn for inclusion in other documents or separated from the report in any way.

Contact Coffey for additional assistance

Coffey is familiar with a variety of techniques and approaches that can be used to help reduce risks for all parties to land development and land use. It is common that not all approaches will be necessarily dealt with in your environmental site assessment report due to concepts proposed at that time. As a project progresses through planning and design toward construction and/or maintenance, speak with Coffey to develop alternative approaches to problems that may be of genuine benefit both in time and cost.

Responsibility

Environmental reporting relies on interpretation of factual information based on judgement and opinion and has a level of uncertainty attached to it, which is far less exact than other design disciplines. This has often resulted in claims being lodged against consultants, which are unfounded. To help prevent this problem, a number of clauses have been developed for use in contracts, reports and other documents. Responsibility clauses do not transfer appropriate liabilities from Coffey to other parties but are included to identify where Coffey's responsibilities begin and end. Their use is intended to help all parties involved to recognise their individual responsibilities. Read all documents from Coffey closely and do not hesitate to ask any questions you may have.