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SUPPLEMENTARY GROUNDWATER ASSESSMENT

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Supplementary Groundwater Assessment
Arrow Energy Bowen Gas Project
Supplementary Report to the EIS
Report Date: 17 April 2014
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Arrow Energy Bowen Gas Project
Supplementary Report to the EIS

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ABBREVIATIONS

AAPG	American Association of Petroleum Geologists
ACARP	Australian Coal Association Research Program
ALOS	Advanced Land Observation Satellite
ANZECC	Australian and New Zealand Environmental Conservation Council
API	American Petroleum Institute
ATP	Authority to Prospect
BOM	Bureau of Meteorology
CMA	Cumulative Management Area
CGPF	Central Gas Processing Facility
DA	Drainage Area
DERM	Queensland Department of Environment and Resource Management (currently known as Department of Environment and Heritage Protection)
DEEDI	Department of Employment, Economic Development and Innovation
DNRM	Department of Natural Resources and Mines
DEHP	Department of Environment and Heritage Protection
DoE	Department of the Environment
EFO	Environmental Flow Objectives
EIS	Environmental Impact Statement
EPBC	Environment Protection and Biodiversity Conservation
EPP	Environmental Protection Policy
ET	Evapotranspiration
FCCM	Fort Cooper Coal Measures
FCF	Field Compression Facility
GA	Geoscience Australia

ABBREVIATIONS

GAB	Great Artesian Basin
GDE	Groundwater Dependent Ecosystem
GIS	Geographic Information System
GMA	Groundwater Management Area
GMP	Groundwater Monitoring Program
IAA	Immediately Affected Area
InSAR	Interferometric Synthetic Aperture Radar
JV	Joint Venture
KCB	Klohn Crippen Berger
LAA	Long-term Affected Area
MBL	Multi-branch lateral
MCM	Moranbah Coal Measures
MGP	Moranbah Gas Project
MNES	Matters of National Environmental Significance
NCA	Nature Conservation Act
NSMC	Null Space Monte Carlo
NTEC	Environmental Technology
OGIA	Office of Groundwater Impact Assessment
QGC	Queensland Gas Company
QWC	Queensland Water Commission
RCM	Rangal Coal Measures
SAR	Sodium Adsorption Ratio
SEWPaC	Sustainability Environment, Water, Population and Communities

ABBREVIATIONS

SIMS	Spring Impact Management Strategy
SKM	Sinclair Knight Merz
SPE	Society of Petroleum Engineers
SREIS	Supplementary Report to the Environmental Impact Statement
TDS	Total Dissolved Solids
ToR	Terms of Reference
TMR	Telescopic Mesh Refinement
UWIR	Underground Water Impact Report
WERD	Water Entitlements Registration Database
WMS	Water Monitoring Strategy
WRP	Water Resource Plan

GLOSSARY

Abstraction	The removal of water from a resource e.g. the pumping of groundwater from an aquifer.
Aeolian	Deposited by wind driven processes.
Adsorption	The adherence of gas molecules, ions or molecules in solution to the surface of solids.
Alluvium	Unconsolidated deposits such as sands, gravels and clays deposited by flowing water such as rivers and streams.
Anisotropy	Conditions where hydraulic properties of an aquifer vary according to the direction of flow.
Anthropogenic	Caused by human activity.
Aquifer	A saturated geological layer or formation that is permeable enough to yield economic quantities of water.
Aquitard	A geological formation having low (but not zero) permeability to water, such as a silty or clayey layer.
Baseflow	Sustained flow of a stream in the absence of direct run-off, due to groundwater discharge.
Bedding Plane	A distinct surface of contact between two sedimentary rock layers
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.
Bulk Density	The measure of mass per volume.
Catchment	An area which discharges to a common point.
Coal cleat	A natural fracture in coal.

GLOSSARY

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).
Compressibility	A measure of the relative volume change of a fluid or solid as a response to a pressure (or mean stress) change.
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.
Damage Zone	The area of rock around a fault that has undergone alteration as a result of the faulting activity.
Deformation	A geological process in which the application of a force causes a change in geometry, such as the production of a fold, fault or fabric, often associated with metamorphic reactions.
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’.
Dissolved Solids	Soluble compounds such as salts which are in solution.
Drawdown	The drop in the watertable or potentiometric level when water is being pumped from a well.
Ductile Deformation	Behaviour where rocks, at a critical stress, become permanently deformed by bending or flowing.
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.
Elastic Properties	The measurement of the tendency of a rock to deform non-permanently in various directions when stress is applied.
Fault	A fracture or fracture zone in rock along which movement has occurred.

GLOSSARY

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.
Freshwater	Water containing low salt concentrations, typically less than 1,000 mg/L. (Compare Brackish, Saline and Brine).
Geospatial	Information associated with a particular location.
Groundwater	Any sub-surface water, generally present in an aquifer or aquitard.
Groundwater Flow	The movement of water in an aquifer.
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 Stimulation	The process of injecting fluid into a low permeability rock mass to induce or enhance permeability via fracturing.
Hydrogeology	The study of the inter-relationships of geologic materials and processes with water, especially groundwater.
Hydrothermal alteration	Alteration of minerals or rocks by the action of superheated mineral-rich fluids, usually water that has been heated to very high temperatures within a crystallizing magma.
Igneous rock	A rock formed by the crystallization of magma or lava.
Igneous Intrusion	An igneous rock body that formed from magma that forced its way into, through or between subsurface rock units.
Induced hydraulic fracture	See **hydraulic stimulation**.
Inter-bedded	Have beds lying between other beds with different characteristics.
Interburden	Material of any nature that lies between two or more bedded ore zones or coal seams.
Isotopic analysis	Determination of stable isotope ratios to age date groundwater.
Lacustrine	Pertaining to, produced by or formed in a lake.

GLOSSARY

Lineament	A regional topographic feature that is believed to reflect crustal structure.
Lithology	The physical composition of a rock.
Microseismic	A vibration in the earth that is unrelated to an earthquake. It may be produced by other natural activity (wind, waves etc) or human activity.
Neotectonic	Relating to motions and deformations of the Earth's crust which are current or recent in geologic time.
Orogenic	Relating to tectonic processes that result in intense folding, reverse faulting, crustal thickening, uplift and deep plutonic activity.
Outcrop	An exposure of bedrock.
Perched Aquifer	An unconfined aquifer of limited extent located above the true watertable.
Permeability	The ability to transmit fluids through a porous medium.
Palustrine	Pertaining to an inland wetland or marsh that lacks flowing water and is non-tidal.
Porosity	The ratio of the volume of voids in a rock or a solid to the total volume. Porosity is dimensionless.
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.
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.
Proppant	A proppant is a solid material, typically treated sand or man-made ceramic materials, designed to keep an induced hydraulic fracture open, during or following a hydraulic stimulation treatment.
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.
Riparian	Pertaining to or located on the bank of a water body, in particular a stream or river.
Runoff	Rain water that flows across the land surface without entering the sub-surface.

GLOSSARY

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.
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.
Spring Factor	An estimate of the change in pressure at a spring resulting from a water licence decision, as established under resource operations plans.
Stratigraphy	The sequential classification of geological materials based on their age of formation.
Stress Direction	The direction in which a force is acting upon or within a mass or rock, expressed in terms of unit weight per surface area such as tons per square inch.
Stress Field	A region where stress is defined at every point.
Subcrop	An occurrence of strata beneath the surface of an inclusive stratigraphic unit that succeeds and unconformity on which there is marked overstep.
Subsidence	The downward settling or sinking of the Earth's surface with little or no horizontal motion.
Total Dissolved Solids	Concentration of total dissolved salts (TDS).
Transmissivity	A measurement of the capability of the entire thickness of an aquifer to transmit water, defined by the rate of flow through a unit width of aquifer, normal to flow under a unit gradient. Transmissivity is the product hydraulic conductivity and aquifer thickness.
Unconfined Aquifer	An aquifer with no confining layer between the watertable and the ground surface where the watertable is free to rise and fall.
Uplift	The relative upward movement of rocks due to tectonic forces.

GLOSSARY

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’.

UNIT

℃	Degrees Celcius
GL	Gigalitres
GL/yr	Gigalitres per year
km	Kilometres
km^2	Kilometres squared
kPa	Kilopascal
m	Metres
mAHD	Metres Australian Height Datum
mbgs	Metres below ground surface
mm	Millimetres
mg/L	Milligrams per litre
ML	Megalitres
ML/day	Megalitres per day
m/day	Metres per day
m^3/day	Metres cubed per day
mm/yr	Millimetres per year
Mtpa	Mega-tonne per annum
Mw	Moment magnitude
μS/cm	Micro-siemens per centimetre

UNIT

EXECUTIVE SUMMARY

Arrow Energy Pty Ltd submitted an Environmental Impact Statement (EIS) for the Bowen Gas Project (the Project) in December 2012. The EIS was approved by the Queensland Government for public release in March 2013. This Supplementary Report to the EIS (SREIS) completes Arrow's response to public and government comments and submissions received on the EIS. The SREIS presents further information on the project and its potential impacts, and provides confirmation or updates to the conclusions of the EIS.

Scope of Work

The scope of work undertaken for the supplementary groundwater assessment was:

- Identification of groundwater-related revisions to the project description;
- Review of new information available since the preparation of the EIS in 2012;
- Further consideration of certain information used to inform the EIS;
- Consideration of additional information not presented in the EIS, specifically relating to comments made in government and general public submissions on the EIS;
- Re-application of the significance assessment process to confirm or update the conclusions of the EIS; and
- Review of the mitigation measures proposed in the EIS to evaluate their relevance given changes to the project description and present any additional mitigation measures where required.

Impact Assessment

The impact assessment method adopted for the SREIS is as follows:

- Review of the environmental values and potential impacts identified in the EIS, and definition of the environmental values and potential impacts to be considered in the SREIS;
- Review of the magnitude of potential impacts presented in the EIS prior to the implementation of mitigation measures;
- Review of the mitigation and management measures presented in the EIS including confirmation of relevance to the SREIS, and identification of any new mitigation and management measures;
- Application of the significance assessment methodology to assess the unmitigated and mitigated impacts associated with the Project; and
- Assessment of any new impacts identified.

Mitigation and Management Measures

A review of mitigation and management measures identified in the EIS showed that the measures are still relevant for the management of groundwater-related impacts subject to the minor revisions detailed in this report.

EXECUTIVE SUMMARY

1 INTRODUCTION

1.1 Background to the Supplementary Report to the EIS

Coffey Environments Australia Pty Ltd (Coffey Environments) was commissioned by Arrow Energy Pty Ltd (Arrow) to provide the groundwater component of the Supplementary Report to the EIS (SREIS) for the Bowen Gas Project (the Project). The supplementary groundwater assessment was developed to provide additional information in response to submissions received from the government and general public on the groundwater impact assessment included in the EIS, completed by URS Australia Pty Ltd (URS) in December 2012 (URS, 2012).

A conceptual description of the Project (the project description) was developed to inform the Bowen Gas Project EIS. The project description formed the basis upon which all impact assessment studies were conducted and as of March 2012 was fixed, to allow studies to be undertaken.

The scope of work included in the groundwater assessment component of the EIS completed by URS is listed below:

- Review of the available geological and hydrogeological information for the Bowen Basin and associated coal seam gas literature;
- Describe the hydrogeological environment (aquifer properties, flow directions, recharge / discharge mechanisms, etc.) of the Bowen Basin within and adjacent to the Project area;
- Identify groundwater systems and their environmental values in the Project area;
- Provide data and geographic information system (GIS) maps to support the development of a regional groundwater numerical model of the Bowen Basin by Ausenco-Norwest;
- Identify and assess likely impacts of the Project coal seam gas activities on groundwater environmental values and to assess the significance of these impacts on the groundwater systems;
- Provide an unmitigated impact significance ranking to the identified groundwater systems as a function of their sensitivity and the potential magnitude of impact;
- Review currently implemented management measures and identify optimum measures for management and mitigation of groundwater impacts;
- Provide a residual impact significance ranking to the identified groundwater systems as a function of their sensitivity and the potential magnitude of impact after mitigation measures are implemented; and
- Provide monitoring and commitment recommendations that support the above measures.

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 the EIS, which considered both the sensitivity of the environmental values and the magnitude of the identified impact.

Potential groundwater related impacts associated with the proposed Project field development and production program identified during the EIS process generally fell 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 this and other projects requiring the dewatering and depressurisation of the Permian coal measures.

Management and mitigation measures were identified to minimise the identified impacts. These were considered appropriate for the reduction of impacts as demonstrated by the assessment of residual impacts, which ranged from very low to low. A robust groundwater baseline assessment and groundwater monitoring program (GMP) was proposed to underpin the assessment of management and mitigation measure effectiveness.

Arrow lodged the draft EIS for the Bowen Gas Project in December 2012, which was approved by the State Government for public release in March 2013. The period for public review and comment closed on 23 April 2013.

1.2 Objectives of the Supplementary Report to the EIS

The SREIS completes Arrow's responses to comments received on the EIS, provides further information on the Project and the potential impacts, and provides confirmation or updates to the conclusions of the EIS as necessary.

The SREIS has been prepared to:

- Present any revisions to the project concept;
- Present the findings of any further impact assessment deemed necessary as a result of these changes; and
- Respond to the public and government submissions made on the EIS.

1.3 Supplementary Groundwater Assessment Scope of Works

For the purpose of the supplementary groundwater assessment report, the following major tasks were completed:

- Identification of groundwater-related revisions to the project description;
- Review of new information available since preparation of the EIS in November 2012 and further consideration of some information used to inform the EIS;
- Consideration of additional information not presented in the EIS;
- Description of the environmental values associated with groundwater for the Project area and rank the sensitivity of those values based on the information presented in the EIS and SREIS;
- Review the unmitigated impact magnitude rankings presented in the EIS through application of the regional numerical groundwater modelling developed by Ausenco-Norwest and consideration of new information available since the release of the EIS;
- Application of the significance assessment process to assess the significance of the unmitigated impacts on environmental values;

- Review of the management and mitigation measures proposed in the EIS based on the revised impact assessment, to evaluate their relevance and present additional management and mitigation measures where required;
- Assess the residual impact significance on environmental values after the application of management and mitigation measures;
- Review of the monitoring and commitment requirements set out in the EIS based on the SREIS impact assessment, to evaluate their relevance and present additional measures where required; and
- Review and assess potential cumulative impacts of the project.

1.4 Supplementary Groundwater Assessment Study Method

Details of the study method and key information sources considered for the supplementary groundwater assessment are presented in Section 4. The Project area is defined as Arrow tenements Authority to Prospect (ATP) 742, 749, 759, 1031, 1025 and 1103, consistent with the Project area defined for the EIS. For the supplementary groundwater assessment the study area is constrained to the groundwater model domain for the assessment of potential impacts to groundwater values with the exception of the assessment of groundwater dependent ecosystems (GDEs), where a study area of 50 km surrounding the Project area has been adopted (refer Figure 1.1).

In summary, the assessment contained four stages, including:

- Review of new information available since the release of the EIS and information sources not included in the EIS;
- Definition of the environmental values and potential impacts to be considered in the SREIS;
- Review of the potential impacts identified in the EIS and identification of new impacts; and
- Application of the significance assessment methodology to assess the unmitigated and mitigated impacts associated with the Project.

2 GROUNDWATER-RELATED UPDATES AND REVIEW OF THE PROJECT DESCRIPTION

The information below presents the key groundwater-related changes to the project description for assessment in the SREIS as well as further information relating to hydraulic stimulation to support the assessment of potential impacts to groundwater.

2.1 Drainage Areas

Refinement of the indicative development sequence for the Project reflects Arrow's understanding of the pressure regime in the target coal seams within the Project area. As a result, a greater number of drainage areas (DAs) with a smaller radius of influence are required to maximise gas recovery over the life of the Project. In the EIS project reference case, a total of 17 DAs were defined, each with a drainage radius of 12 km whereas in the SREIS project reference case, a total of 33 DAs are defined each with a drainage radius of approximately 6 km (Figure 2.1).

Each DA will contain a field compression facility (FCF) to boost the gas pressure for export to a central gas processing facility (CGPF). Comparison of the development sequence presented in the EIS with the revised indicative development sequence presented in the SREIS shows that a similar project phasing is anticipated. Initial development will be focussed along the western extent of the Project area, followed by areas in the east, with the last phases of development anticipated near Blackwater to the south.

2.2 Production Well Design, Configuration and Produced Water

The EIS proposed production well types including surface-in-seam chevron wells and multi-seam hydraulically stimulated vertical wells. The default well type has changed since the EIS to that of multi-branch lateral (MBL) wells. Each MBL well consists of a vertical production well and a lateral well. Further to this multi-well pads will also be utilised, where up to 6 MBL production wells may be positioned together, resulting in 12 well heads on a single pad (2 well heads per MBL well). Multi-seam hydraulically stimulated vertical wells remain a potential production well design in the SREIS project description. Figure 2.2 presents typical schematics of the proposed production well types for the EIS and SREIS.

The MBL production well configuration reduces the surface footprint area due to both additional dedicated horizontal wells with individual well head pads no longer being required and the ability to co-locate multiple wells at one location, resulting in a significantly less number of well pads across the Project area. Similarly, the expected overall number of production wells has reduced from the development case presented in the EIS (6,625 production wells) to approximately 4,000 production wells under the SREIS development case. While the number of individual well heads has reduced, the use of MBL wells means that the same "in-coal" well spacing can be achieved, given that each lateral branch will be terminated in different sections of the coal seam to enhance gas recovery.

Progression of the field development plan has included more effective well placement to target areas of high gas yield. Furthermore, refinement to the reservoir modelling shows lower water extraction rates are expected from the production wells. The combination of improved well placement, the requirement for fewer wells through well design, and lower extraction rates has resulted in a significant reduction in the anticipated overall water production. Water production is anticipated to decline from 264,300 ML over the life of the project presented in the EIS, to 153,000 ML over the life of the project currently projected for the SREIS (Figures 2.3 and 2.4).

2.3 Hydraulic Stimulation Process

Hydraulic stimulation is a process used in areas where the properties of the coal seam impede the flow of gas to a well. Where coals have low permeability, stimulation may be required to enhance the flow of gas.

Hydraulic stimulation is a process that may not be required for the Project, however further information to that presented in the EIS regarding the process of hydraulic stimulation is presented here to support the supplementary assessment of potential impacts to groundwater, should hydraulic stimulation be required.

Hydraulic stimulation is designed to stimulate fracturing in coal seam formations using geomechanical stress principles and is designed using site-specific information gathered during the well completion activities. The most current industry recommended practices for design, construction, installation, testing, and monitoring of coal seam gas wells have been incorporated into Arrow's management strategies. Arrow's design engineering team analyses the borehole logging data and evaluates the geophysical and geomechanical properties of the target coal seam areas as part of planning a hydraulic stimulation event.

The goal of hydraulic stimulation design is to maximise the extent, direction, and density of fractures within the target coal seam to provide the linear pathways for efficient gas recovery. Properly directed and connected fractures within the coal seams increase the effective porosity and permeability of the coal, releasing more gas from the adsorption sites to flow to the well. Containment of fractures within the boundaries of the targeted coal seam is also a primary goal for hydraulic stimulation. Fractures that extend into overlying siltstone, mudstone, or sandstone can potentially drain additional water from those layers into the target formation and reduce the operational efficiency of the coal seam gas well. On this basis, a detailed hydraulic stimulation design is developed and monitoring conducted to ensure that the fracturing is contained within the stimulation impact zone.

The hydraulic stimulation process occurs under varying positive high hydraulic pressures in order to physically fracture the coal matrix (ranging from approximately 7,000 to 30,000 kilopascal (kPa)). During hydraulic fracturing activities, fluid is pumped into perforations within the production casing, and into the targeted coal seam gas formation. The perforations are approximately 5 to 15 millimetre (mm) diameter holes created in the steel well casing and surrounding cement seal. The hydraulic stimulation fluids are pressurised and pumped through the perforations to cause the host rock within the formation to fracture. The fracture continues to propagate as sufficient pressure is sustained during fluid injection activities. Fine grained sand or other proppant is added to the fluid to fill the fractures. Once the injection process stops, the pressure decreases and the fracture begins to close. The physical structure of the proppant holds the fracture open, allowing both liquid and gas to flow more readily.

The fractures provide open and connected pathways for the water and gas in the coal seam to more efficiently flow to the gas well than would otherwise be the case. Geomechanical laws show that fractures generated during hydraulic stimulation occur perpendicular to the least principal stress. In a compressive stress regime, such as the Bowen Basin, the least principal stress is in the vertical direction. Hence, fractures generated by hydraulic stimulation are predominantly in a horizontal plane, thereby limiting potential for out of zone vertical propagation.

Design features that are analysed to assist in optimising gas production rates and are considered in both the well and hydraulic stimulation design include:

- Inter-bedded formation properties;

- Bedding plane configuration;
- Coal cleat properties;
- Thickness of the coal seam;
- Stress field analysis to determine the maximum and minimum principle stress direction; and
- Bulk density, elastic properties and compressibility of the coal seams and interburden layers.

Hydraulic stimulation through cemented casings is the most widespread completion technique employed in vertical coal seam gas wells globally (CSIRO, 2012). This well type is ideally suited to regions with thinner and multiple target coal seams, as is the case in parts of the Bowen Basin, and if required may be employed in such areas as an alternative to the proposed MBL wells (Figure 2.2). Recent publications (Groundwater 52 no, 1-19 Flewelling and Sharma) indicate that hydraulic stimulation in large sedimentary basins does not allow for rapid upward migration of stimulation fluids.

The assumption presented in the EIS that up to 25 percent of all coal seam gas production wells will require hydraulic simulation has been retained for the SREIS. The other key characteristics of hydraulic stimulation have also been retained for the SREIS, specifically, that approximately 99.5 percent of the material pumped into the well during hydraulic stimulation is made up of water and sand. The remaining 0.5 percent consists of additives commonly found in many house hold products. A list of the additives is provided in Appendix G of Appendix L in the EIS.

3 RELEVANT LEGISLATION, POLICIES AND GUIDELINES TO THE SREIS

The following sections describe updates to legislation, policies and guidelines relevant to the groundwater assessment for the SREIS since the release of the EIS.

3.1 Commonwealth Legislation

3.1.1 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). Any action with the potential for significant impacts to these must be referred to the Minister for the Department of the Environment (DoE), and may require approval under this Act.

3.1.1.1 EPBC Act Protected Matters: Water Resources

In 2013 the Commonwealth Government introduced and passed water resources as a controlling provision for the referral of projects under the EPBC Act. This amendment to the EPBC Act requires coal seam gas and large coal mining developments that have, will have, or are likely to have a significant impact on a water resource be referred to DoE for assessment and approval.

The DoE (formerly the Department of Sustainability, Environment, Water, Population and Communities (SEWPaC)) prepared draft significant impact guidelines in June 2013 to assist proponents in their determination whether a proposed coal seam gas or large coal mining development has, or is likely to have a significant impact on a water resource (SEWPaC, 2013).

On 17 October 2013 the federal Environment Minister advised that water resources is a controlling provision for the Bowen Gas Project.

3.1.1.2 EPBC Act Protected Matters: Nationally Important Wetlands

Wetlands considered to be of national importance have been mapped and can be accessed via the DoE online Protected Matters Search Tool. Supporting documentation (Environment Australia, 2001) provides a description of each listed wetland including ecological and hydrological characteristics. From this, and in conjunction with additional data sources where required, an assessment of whether the wetland may be groundwater dependent can be made.

3.2 Queensland Legislation

3.2.1 Petroleum and Gas (Production and Safety) Act (P&G Act) 2004 (reprinted as in force on 31 March 2013)

Under Section 185 of the P&G Act, a petroleum tenure holder 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, including coal seam gas extraction. The right to take water for or during petroleum purposes as defined in the P&G Act considers the following details:

- 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 groundwater and/or coal seam gas water within this report).

The aforementioned underground water rights attract certain obligations described as underground water obligations. These are defined in Chapter 3 of the Water Act (Qld) (2000) (Water Act).

Petroleum tenure holders 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, including coal seam gas extraction. On 22 November 2013, certain sections of the *Land Water and Other Legislation Amendment Act 2013* that amend the petroleum legislation, including the P&G Act, commenced which permit the holder of an authority to prospect, a petroleum lease or a water monitoring authority to drill a water observation bore or water supply bore in the area of the respective authority or lease. Further discussion as to how the amendment affected the requirements for drilling water bores is discussed in Section 3.3.2 and Section 3.4.3.

3.2.2 **Petroleum and Gas (Production and Safety) Regulation (P&G Regulation) 2004** (current as at 22 November 2013)

The P&G Regulation details the requirements for the holder of a petroleum tenure to provide a notice of intention to carry out hydraulic stimulation activities and a notice of completion of hydraulic stimulation activities. These requirements are detailed in Division 2 Sections 30 to 35.

The holder of a petroleum tenure must also lodge a report at the completion of hydraulic stimulation activities. The report requirements are further detailed in Subdivision 6 Sections 46A.

3.2.3 **Environmental Protection Act (EP Act) 1994** (current as at 1 December 2013)

The objective of the EP Act is to protect the Queensland environment while allowing for development that improves the total quality of life, both now and in the future, in a way that maintains the ecological processes on which life depends.

3.2.3.1 Environmental Approvals and Risk Assessment Process

The EP Act requires an application for Environmental Authority (EA) for petroleum activities to identify potential impacts on environmental values and propose environmental protection commitments. For the groundwater related aspects of the Bowen Gas Project this includes development of a GMP and management of non-spring based GDEs.

The EP Act also describes the application process to permit hydraulic stimulation through an environmental authority. The application must describe the environmental values that may be potentially, or actually, impacted from hydraulic stimulation activities. This should include a description of the environmental values of groundwater resources on, and beyond, the relevant petroleum tenures that are found where stimulation activities are to be carried out.

If well stimulation is planned as part of the petroleum activities, the application must include an assessment in order for the administering authority to assess and condition the activity. If well stimulation is not planned or the assessment is not supplied in the application, the environmental authority may condition that well stimulation activities cannot be undertaken.

Based on the assessment, the administering authority will develop necessary and desirable environmental authority conditions, which will include baseline and impact monitoring conditions as part of the authorisation to undertake the activity.

In addition to the assessment, the application must be supported by evidence that fluids used in stimulation will not include restricted stimulation fluids (as identified in Section 206 of the EP Act). The results of any landholder bore and well water quality analyses that may be included in the assessment should describe the overall condition of these waters in relation to the environmental values of the groundwater resource and water quality objectives as provided for in guidelines such as the Environmental Protection (Water) Policy 2009 (EPP Water) and Australian and New Zealand Environmental Conservation Council (ANZECC).

The application must include environmental protection commitments and objectives in relation to stimulation activities. This should include a commitment to take all reasonable and practical measures to ensure that stimulation activities do not negatively affect water quality, other than that within the stimulation impact zone of the target formation, and that stimulation activities will be carried out so as to not cause a connection of the target gas producing formation and another aquifer.

3.2.4 **Water Act (Qld) 2000** (reprinted as in force 31 March 2013)

The overall purpose of the Water Act is to provide for the sustainable management of water and other resources, the establishment and operation of water authorities, and for other purposes. In particular, the Act:

- Provides a comprehensive regime for the planning and management of all 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;
- 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); and
- 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 provides for the management of impacts on underground water caused by the exercise of underground water rights by petroleum tenure holders. This is achieved by defining several key underground water obligations that tenure holders must discharge, specifically:

- Undertaking Baseline Assessments to identify the location, construction, groundwater level and groundwater quality of existing water bores.
- Preparing underground water impact reports (UWIRs) which includes:
    - Description of the regional geology and hydrogeology (including aquifers, their quality and connections to formations from which coal seam gas water is extracted) based on the existing information.
    - Description of the petroleum and gas production in the tenure.
    - Prediction of groundwater drawdown as a result of the exercise of underground water rights by tenure holders including identification of:
        - Areas of each aquifer in the tenure where groundwater drawdown is predicted to exceed the bore trigger threshold (defined in the Water Act as 2 metres (m) for an unconsolidated aquifer and 5 m for a consolidated aquifer):
            - In the next three years (an Immediately Affected Area (IAA)).

            - At any time (a Long-term Affected Area (LAA)).

        - Potentially affected springs. A potentially affected spring is defined as a spring overlying an aquifer where the water level in the aquifer is predicted in a UWIR to decline by more than the spring trigger threshold, at the location of the spring, at any time due to the exercise of underground water rights. The spring trigger threshold is 0.2 m.

    - Report obligations including:

        - Water Monitoring Strategy (WMS) including a program for monitoring changes in groundwater levels and water quality.

        - Spring Impact Management Strategy (SIMS) including:

            - Details of potentially affected springs in the tenure,

            - Assessments of the connectivity of the spring to the underlying aquifers,

            - A prediction of risk and likely impact to the ecosystem and cultural and spiritual values of the spring.

            - Development of a strategy (where required) to mitigate impacts to the spring based on information gathered from the aforementioned studies.

    - Assignment of responsible tenure holder for report and make good obligations if the report is prepared for a cumulative management area (CMA).

    - Program for annual review.

- Make good obligations including the requirement to:

    - Undertake a bore assessment for all bores located in an IAA to determine whether the bore has, or is likely to start having, an impaired capacity i.e. the bore can no longer provide a reasonable quantity or quality of groundwater due to a decline in groundwater level because of the exercise of underground water rights by petroleum tenure holders; and

    - Enter into a make good agreement with the owner of the bore which documents the outcome of the bore assessment and defines make good measures for the bore to be undertaken by the tenure holder including any of the following:

        - Ensuring the bore owner has access to a reasonable quantity and quality of water.

        - Monitoring the bore.

        - Compensating the bore owner.

3.2.4.1 Declaration of a Cumulative Management Area

A CMA may be declared where the impacts on water levels caused by multiple individual petroleum and gas projects overlap. Currently there is no CMA declared for the northern Bowen Basin and the majority of the Project area.

ATP 1025, the southern-most tenement within the Project area is situated within the Surat CMA. The Surat CMA was declared by the Queensland Government in March 2011. The Office of Groundwater Impact Assessment (OGIA) (formerly the Queensland Water Commission (QWC)) prepared a draft UWIR for the Surat CMA, and it was released for public consultation on 17 May 2012. The draft UWIR was subsequently revised and submitted to the Department of Environment and Heritage Protection (DEHP) on 18 July 2012. The Chief Executive of DEHP approved the final UWIR for the Surat CMA, and the requirements in the endorsed report took effect from 1 December 2012.

3.2.5 Water Supply (Safety and Reliability) Act 2008 (Reprinted as in force 14 May 2013)

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; and
- 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).

3.2.6 Great Artesian Basin Resource Operations Plan (2007) (amended November 2012)

The Great Artesian Basin (GAB) resource operations plan overlaps the project area in the very south of ATP 1025 near Blackwater. The GAB resource operations plan was finalised in December 2006 and commenced by public notice in February 2007 after a public consultation and review process. The GAB resource operations plan was amended on 16 November 2012 to streamline the process for release of unallocated water, as outlined in Chapter 2 of the plan.

On 30 May 2013, the chief executive of the Department of Natural Resources and Mines (DNRM) commenced a process to release general reserve unallocated water from three management areas identified in the water resource plan (WRP). Up to a combined total of 7,200 ML of unallocated water has been made available from the Surat, Surat East and Surat North management areas. The Project area is not located within any of these management areas.

The resource operations plan created a spring register listing the GAB springs that support significant cultural and environmental values. The WRP and resource operations plan protects the flow of groundwater to these springs. The spring register contains information about the spring type, the management units that are connected or supplying water to the springs, decisions made about water licenses that could impact the flow of water to the springs, and the cumulative spring factor for each spring.

Spring factors are estimates of the change in pressure at a spring resulting from a water licence decision, as established under the GAB resource operations plan. They are determined for new water licences granted from the unallocated water reserves (identified in the GAB WRP), and for water licence relocations, amendments, surrenders, and cancellations; and added to the pre-existing cumulative spring factors for each relevant spring in the register.

The spring register is currently unavailable due to the tendering process that is in progress for the release of general reserve unallocated water in the Surat, Surat East and Surat North management areas. It is assumed that all springs listed in the register are also contained in DEHP (Queensland Herbarium) springs database.

On commencement of the GAB resource operations plan, all cumulative spring factors were zero. The reason for calculating cumulative spring factors is to monitor the cumulative impact of water licence decisions on spring flows over time. The resource operations plan establishes that no cumulative spring factor can exceed 400 (equivalent to a pressure reduction of 0.4 m head of water), thus limiting any cumulative impact of water licence decisions on flow to springs.

Water licensees in the GAB WRP area are able to relocate water by transferring, amending or amalgamating all or part of their water licences. Relocations can occur provided these dealings are consistent with the rules in the resource operations plan regarding protection of entitlements of existing users and flow to springs.

Furthermore, a five-year review of the GAB WRP was completed in March 2013 to assess whether the plan was fulfilling its objectives, and whether the plan needs to be amended. No changes were made to the GAB WRP as a result of the five-year review.

3.2.7 Environmental Protection (Water) Policy 2009 (current as at 16 August 2013)

The purpose of the EPP Water is to achieve the objectives of the EP Act in relation to Queensland waters while allowing for ecologically sustainable development.

The environmental values are to be enhanced or protected (Section 6 of the EP Act). The relevant environmental values vary depending on the ecological value of the water, level of disturbance and intended use of the water.

The management controls/ mitigation measures in this study were prepared to meet the requirements of this policy.

The Policy has been amended since the release of the EIS however the amendments do not relate to the Project area.

3.2.8 Sustainable Planning Act 2009 (current as at 7 November 2013)

The purpose of this Act is to regulate the development of infrastructure outside petroleum tenures.

The Project is located within the Isaac Connors Groundwater Management Area (GMA) where any works for taking or interfering with water for purposes other than stock or domestic use (other than small diameter groundwater monitoring bores) are assessable activities and require a development permit.

The Act has been amended since the release of the EIS to align with the Greentape Reduction Act (2012), however the changes do not relate to groundwater.

3.2.9 **Water Resource (Fitzroy Basin) Plan 2011** (current as at 27 September 2013)

The Fitzroy Basin WRP provides a framework for the allocation and management of water in the area. Tenements in the northern portion of the Project area are located within the declared Isaac Connors GMA, as defined under Chapter 2, Section 7, Schedule 3, Schedule 4, and Schedule 7 of the Fitzroy Basin WRP 2013.

The plan was amended in 2013 to update a reference made to the Water Act, specifically regarding taking or interfering with groundwater. Any long-term water take or interference from groundwater sources requires authorisation by way of a licence.

The Fitzroy Basin Resource Operation Plan (2004) was established to provide guidance on the implementation of the Water Resource (Fitzroy Basin) Plan 1999. A new Fitzroy Basin Resource Operation Plan that will implement the Water Resource (Fitzroy Basin) Plan 2011 is currently being developed and is expected to be released in late 2014. A resource operations plan is developed under the Water Act 2000 and establishes rules that guide the allocation and management of water within all or certain parts of the associated WRP to achieve the objectives set out in the WRP.

3.2.10 **Water Resource (Burdekin Basin) Plan 2007** (current as at 27 September 2013)

This WRP provides a framework for sustainably managing water and the taking of water within the plan area. The Project is located a long distance upstream from the closest Burdekin WRP environmental flow objectives (EFO) node and the Project area is a small portion of the total catchment to the closest EFO.

The WRP was amended in 2013 to update a reference made to the Water Act, specifically regarding taking or interfering with groundwater. Any long-term water take or interference from groundwater sources requires authorisation by way of a licence.

3.2.11 Nature Conservation Act (NCA) 1992

The NCA is legislation that provides for the conservation of nature through the development of an integrated and comprehensive conservation strategy for the whole of Queensland. The NCA classifies species according to conservation status and the framework has been applied in the assessment of springs across the Surat CMA to identify biologically important springs. The Surat CMA incorporates the southern Bowen Basin, which includes ATP1025, the southern-most tenement within the Project area.

3.3 Queensland Policies, Codes of Practice and Guidelines

3.3.1 Coal Seam Gas Water Management Policy

A Coal Seam Gas Water Management Policy was prepared by DEHP and released in December 2012. The objective of the policy document is to encourage the beneficial use of coal seam gas water and brine/salt in a way that protects the environment and maximises productive use of these resources. To achieve this objective, the policy identifies priorities for the management of coal seam gas water and brine/salt. Arrow’s coal seam gas water and salt management strategy reflects the priorities outlined in the policy, thereby facilitating compliance with the government’s objective for the management of coal seam gas water and brine/salt. Arrow’s revised Coal Seam Gas Water and Salt Management Strategy is presented in Appendix D of the SREIS.

The policy identifies that the management and use of coal seam gas water should be consistent with the following priorities:

- **Priority 1**. Coal seam gas water is used for a purpose that is beneficial to either the environment, existing or new water users or existing or new water-dependent industries.
- **Priority 2**. After feasible beneficial use options have been considered, treating and disposing coal seam gas water in a way that firstly avoids, and then minimises and mitigates, impacts on environmental values.

The policy identifies that the management and use of brine/salt should be consistent with the following priorities:

- **Priority 1**. Brine or salt residues are treated to create useable products wherever feasible.
- **Priority 2**. After assessing the feasibility of treating the brine or solid salt residues to create useable and saleable products, disposing of the brine and salt residues in accordance with strict standards that protect the environment.

3.3.2 Code of Practice for Constructing and Abandoning Coal Seam Gas Wells in Queensland

The Code of Practice (DNRM, 2013) was originally facilitated by the Department of Employment, Economic Development and Innovation (DEEDI) and released in 2011. These functions within DEEDI are now administered by the Department of Natural Resources and Mines (DNRM), and in November 2013 DNRM released Version 2 of the Code of Practice. The code aims to ensure that all coal seam gas wells are constructed and abandoned to a minimum acceptable standard. This ensures that these activities are completed in a consistent manner and the processes are effectively monitored to ensure that:

- The environment, in particular underground sources of water, is protected;
- Risk to public and coal seam gas workers is managed to a level as low as reasonably practicable;
- Regulatory and applicable Australian and International Standards, as well as the Operator's internal requirements, are complied with; and
- The life of a coal seam gas well is managed effectively through appropriate design and construction techniques, ongoing monitoring and end of life decommissioning.

The Code also provides for the drilling and installation of groundwater monitoring bores. The petroleum tenure holder must determine whether the bore will be drilled as per the requirements of the petroleum legislation (where there is significant gas hazard), or whether it is safe to drill the bore under the Water Act. If the bore is to be drilled under the petroleum legislation (and in accordance with the Code), there is no need for the presence of a licensed water bore driller to supervise drilling.

Version 2 of the Code was released after the release of the EIS and includes provision for the specification of coal seam gas well control equipment and additional and alternative requirements for the construction of water bores by coal seam gas tenure holders.

It is intended that this Code of Practice will have enforceable effect in Queensland by being called up under the P&G Regulation as a "safety requirement". However the provisions of the P&G Act and the P&G Regulation will take precedence over the Code should any cases occur where conflict arises.

3.3.3 Guideline on Application Requirements for Petroleum Activities

This guideline (DEHP, 2013) was prepared by DEHP in March 2013 and provides information on the requirements of an environmental authority (EA) or an amendment to an EA application on petroleum tenures, including coal seam gas activities. The guideline provides information to assist proponents in the identification of environmental values and associated environmental protection commitments. Use of the guideline when preparing the application document will assist the administering authority in determining the most appropriate set of conditions to be set out in the environmental authority.

Arrow will apply for an environmental authority for the Project. The document provides guidance on the content of an application for a range of environmental factors, including groundwater. The document also provides guidance on the content of the application in relation to hydraulic stimulation activities and waste management.

3.4 Other Guidelines, Industry Tools and Frameworks

3.4.1 Australian Groundwater-Dependent Ecosystems Toolbox

The Australian GDE toolbox was developed to provide an intuitive framework for the identification and management of GDEs as well as to better understand ecological groundwater requirements. The classification of GDE type presented in the toolbox is consistent with the GDE Atlas (Richardson et al, 2011; Bureau of Meteorology (BoM), 2013) described in Section 3.4.2 including:

- Type 1: Aquifer and cave ecosystems;
- Type 2: Ecosystems dependent on surface expression of groundwater; and
- Type 3: Ecosystems dependent on subsurface expression of groundwater.

The GDE toolbox contains two parts: Part 1 Assessment Framework (Richardson et al, 2011) and Part 2 Assessment Tools (Richardson et al, 2011a). The GDE Assessment Framework (Part 1) consists of three stages:

- Stage 1: Baseline understanding of GDE location, classification of ecosystem type and basic conceptualisation of eco-hydrogeological setting;
- Stage 2: Characterisation of groundwater reliance, which can be achieved through the collection of physical parameters including groundwater levels, hydraulic gradients and fluxes, as well as geochemical and isotopic analysis; and
- Stage 3: Characterisation of ecological response to change in groundwater conditions, achieved only through analysis of detailed monitoring data to provide a quantified understanding. This may not be achieved in the short-term (such as the typical timeline for the preparation of management plans and approvals processes). Stage 3 assessment may take years to decades of research and monitoring (Richardson et al, 2011).

Part 2 of the GDE Toolbox defines the assessment tools as a suite of practical and technically robust methods for the collation and assessment of data as described by the requirements of the framework (Part 1). Ultimately through the application of appropriate tools, GDE landscapes may be identified and water requirements for the maintenance of ecosystems may be established.

The primary focus for the development of the GDE toolbox was to provide a framework through which ecological water requirements could be established. This framework sets out a logical sequence of assessment stages that can also be applied to identify potential GDE landscapes that may be impacted by petroleum tenure activities (equivalent to Stage 1). From this, appropriate management and mitigation measures can be established, including further assessment in line with Stages 2 and 3 of the GDE Toolbox assessment framework where appropriate.

3.4.2 Atlas of Groundwater Dependent Ecosystems

The National Atlas of Groundwater Dependent Ecosystems (GDE Atlas) (BoM, 2013) presents the current understanding of GDEs across Australia and provides a national scale mapped database of the locations of known and potential GDEs, supported by hydrogeological and ecological lines of evidence.

The GDE Atlas provides regional scale data that can form the starting point for the identification of potential GDE landscapes to allow GDEs to be considered in groundwater management, and specifically for this project, the management of potential impacts to GDEs.

The GDE Atlas includes ecosystem types that are relevant to the groundwater components of the Project Terms of Reference (ToR) and may be present within the Project area and immediate surrounds including:

- The surface expression of groundwater (springs, wetlands, rivers).
- The subsurface presence of groundwater (vegetation).

Subterranean GDEs are presented in the GDE Atlas however the extent of mapping for this GDE type is limited to Tasmania only therefore has not been considered further here. Subterranean GDEs are discussed in more detail in the aquatic ecology sections of the EIS (Chapter 16 and Appendix O).

The GDE Atlas classifies ecosystems based on multiple lines of scientific evidence including previous fieldwork, literature and mapping, combined with analysis of nation-wide layers of satellite remote sensing data. The physical characteristics that describe each ecosystem are also provided. Where a potential for dependence on groundwater has been identified, ecosystems have been mapped as:

- Identified in previous field study;
- Identified in previous desktop study;
- High potential for groundwater interaction (indicating a strong possibility the ecosystem is interacting with groundwater);
- Moderate potential for groundwater interaction; and
- Low potential for groundwater interaction (indicating it is relatively unlikely the ecosystem will be interacting with groundwater, and will include ecosystems that are not interacting with groundwater).

The GDE Atlas contains further attribute data to assist with the assessment of whether the ecosystems are actually dependent on groundwater, including a field that assigns a level of confidence in the assessment of high, moderate or low potential based on the number of lines of evidence use to generate the classification.

3.4.3 Minimum standards for the construction and reconditioning of water bores

The right to take groundwater is established under the Water Act 2000, or granted under a licence or water allocation. A driller’s licencing requirements under the Water Act 2000 ensures that all water bore drillers are properly skilled and that their work meets minimum standards.

All water bores (including groundwater monitoring bores) must be constructed in accordance with the Minimum Construction Requirements for Water Bores in Australia (National Uniform Drillers Licensing Committee, 2012). Bores in artesian basins must also comply with Minimum Standards for the Construction and Reconditioning of Water Bores that intersect the sediments of artesian basins in Queensland (DNRM, 2013a). This relates only to a small portion of the southern part of ATP1025.

4 ASSESSMENT METHOD AND INFORMATION SOURCES

The EIS defined the Project area as a contiguous parcel of tenements that includes all or parts of ATP1103 and 1031, and ATP(A)742, 749 and 759. In addition it also included ATP1025. For the SREIS the Project area remains unchanged, noting that ATP(A)742, 749 and 759 have now been granted and are therefore referred to as ATP742, 749 and 759.

The study area defined for the EIS groundwater assessment extended beyond the Project area and included the outer geological and hydrogeological boundary of the Bowen Basin. The study area also encompassed the numerical groundwater model domain. For the supplementary groundwater assessment the study area is defined by the groundwater modelling domain and for the assessment of GDEs a 50 km buffer around the Project area was applied.

While the Project area has not changed since the EIS, a more focused study area has been used for the SREIS.

To inform the development of the supplementary groundwater impact assessment, the study method comprised five main components:

- A detailed desktop review of information available since the release of the EIS covering additional government and industry research and studies (refer Sections 5 and 6). Some information sources considered in the EIS were re-visited in light of the new information available, and additional information was sought;
- Review of the groundwater environmental values identified for the Project area (refer Section 7);
- Review and assessment of additional numerical model outputs, geological, structural and subsidence information to allow re-assessment of potential impacts (refer Section 8);
- Review of the potential impacts identified in the EIS (refer Section 8) to assess adequacy with respect to the changed project description and current development plan. Additional impacts and/or impacts no longer relevant to the Project were identified; and
- Review and revision of the impact assessment including management and mitigation measures to capture any additional impacts or changes to (either increase or decrease) impact significance as reported in the EIS (refer Sections 8 and 9).

4.1 Desktop Assessment Information Sources

The supplementary groundwater assessment builds on the information provided in the EIS through the detailed review and analysis of some key information sources. Specifically, the following areas have been focussed on with respect to improving understanding to inform the impact assessment process:

- The role faulting and folding has on the movement of groundwater and how the drawdown associated with depressurisation of the coal seam gas targets may be influenced by these features;
- Areas where the alluvial and sedimentary aquifers may be directly underlain by coal formations (i.e. there is the absence of a confining layer such as the Rewan Formation) and there is the potential for increased hydraulic connectivity between the groundwater systems;
- Mechanisms associated with induced seismicity in response to coal seam gas extraction and hydraulic stimulation; and

- The types of GDEs present within the Project area and immediate surrounds, their potential connectivity to various aquifer units, groundwater chemistry characteristics and ecological values.

A summary of the key data and information sources used to inform the assessment is provided in Table 4.1 below. A full reference list is provided in Section 11.

Table 4.1: Summary of Key Information Sources

Document	Author / Source	Format	Status since EIS	Relevance / Application
InSAR Historical Study of the Moranbah Gas Project	Altamira (2013)	Report	New	Presents the results of the study and analysis of ground motion across the Moranbah Gas Project (MGP) area using interferometric synthetic aperture radar (InSAR) technology. The baseline study used data collected over the period of December 2006 to January 2011 to establish baseline ground motion for comparison with surface deformation monitoring during approved coal seam gas extraction from the MGP area.
Simulating faults as preferential pathways for groundwater flow in the Bowen Basin – Hypothetical Study	Arrow (2013)	Report	New	This technical note presents a hypothetical study looking at groundwater drawdown near fault zones in response to coal seam gas extraction and the potential for aquifer interconnectivity, and reports on internal modelling developed from prior work as part of ongoing model studies.
Hydraulic Testing Program, Moranbah Gas Project	Arrow (2013a)	Report	New	Summarises a hydraulic testing program completed by Arrow on 21 groundwater monitoring wells located within the MGP area to assess hydraulic conductivity at each well location.
Groundwater Model, Northern Bowen Basin Regional Model Impact Predictions, Queensland Australia	Ausenco – Norwest (2012)	Report	Existing. Additional information reviewed for current assessment.	Numerical simulation of the groundwater produced in association with coal seam gas operations and predictions on the cumulative impacts. Predictions of the modelling were used to underpin the EIS and the development of mitigation measures. Further discussion is presented in Section 6. This report was included as Appendix M of the EIS.
Collation and Assessment of Groundwater Geochemical Data, Northern Bowen Basin, Queensland Australia	Ausenco-Norwest (2013)	Report	New	Currently available groundwater quality data for the northern section of the Bowen Basin, Queensland, Australia was compiled and analysed following a high level review of data quality.

Table 4.1: Summary of Key Information Sources (cont'd)

Document	Author / Source	Format	Status since EIS	Relevance / Application
Parameter and Predictive Error/Uncertainty Assessment, Northern Bowen Basin Regional Groundwater Model, Queensland, Australia	Ausenco-Norwest (2013a)	Report	New	The report presents an assessment of the Northern Bowen Basin Regional Groundwater model parameter predictive error/ uncertainty in order to better understand the model limitations and to identify data gaps. The report presents the initial assessment findings, and results from Null Space Monte Carlo (NSMC) and Pareto front analyses.
Fracking and Earthquake Hazard	British Geological Survey (2012)	Online article	Existing. New inclusion in assessment.	Summary of investigations into earthquakes near Blackpool (UK) and linkages to hydraulic fracture activities conducted at a nearby shale gas exploration site.
Atlas of Groundwater Dependent Ecosystems (GDE Atlas)	Bureau of Meteorology (2013) (custodian)	Online interactive webpage	New	Provides mapped potential GDE landscapes and data on the physical setting of GDEs.
Bowen Basin EIS Groundwater Model Review	CDM Smith (2013)	Report	New	Review of the numerical model developed by Ausenco-Norwest for the BGP EIS with reference to the Australian Groundwater Modelling Guidelines.
Australia's seismogenic neotectonic record.	Clark et al (2011)	Report	Existing. New inclusion in assessment.	Over the last decade knowledge of Australian intraplate faults has advanced significantly. This report reviews this knowledge and proposes six preliminary seismicity source zones (domains) based upon neotectonic data.
EPBC Act Protected Matters: Nationally Important Wetlands	DoE (2013) (custodian)	Online interactive webpage	Existing. Additional information reviewed for current assessment.	Provides locations and site specific information on wetlands listed as nationally important.

Table 4.1: Summary of Key Information Sources (cont'd)

Document	Author / Source	Format	Status since EIS	Relevance / Application
Australian Coal Association Research Program (ACARP) Project C9021 Exploration and Mining Report 976C. Bowen Basin Supermodel 2000	Esterle et al (2002)	Report	Existing. New inclusion in assessment.	Regional 3-D model of the coal measures associated with Bowen Basin coal seam gas targets. The report provides a snapshot of the data available and presents a series of regional maps showing coal seam thickness and interburden distribution, regional and local structure of the main mineable seams and where available, the sedimentary character of the interburden.
Representation of Fault Zone Permeability in Reservoir Flow Models. Society of Petroleum Engineers (SPE) Annual Technical Conference and Exhibition, New Orleans, Louisiana	Flodin E.A., Aydin A., Durlofsky L.J., and Yeten B. (2001)	Journal Article	Existing. New inclusion in assessment.	To improve the representation and influence of faults in reservoir flow simulations this study computes the effective flow characteristics of faults using fine-scale field-based data. To assess the bulk flow characteristics of fault zones an upscaling methodology was established. The study also established a relationship between fault slip magnitude and permeability, including variation in permeability along a fault. The study compares modelled scenarios using the results of the newly established permeability estimates from fault slip correlation to a standard case of constant permeability and fault width.
Geoscience Australia earthquake database.	Geoscience Australia (2013)	Online database	New	Database of historical earthquakes for Australia and the region, and any significant international earthquakes.
Summary of advice in relation to the potential impacts of coal seam gas extraction in the Surat and Bowen Basins, Queensland.	Geoscience Australia and Habermehl, M.A., (2010)	Report	Existing. New inclusion in assessment.	Summary of expert advice provided to SEWPaC (now DoE) in relation to the likely groundwater impacts of proposed and potential future coal seam gas extraction activities in the Surat and Bowen Basins in Queensland.

Table 4.1: Summary of Key Information Sources (cont'd)

Document	Author / Source	Format	Status since EIS	Relevance / Application
In Situ Stress Field of Eastern Australia. Australian Journal of Earth Sciences, Volume 46, p. 813-825	Hillis R.R., Enever J.R., and Reynolds D. (1999)	Journal Article	Existing. New inclusion in assessment.	Presents results of in-situ stress analysis available for eastern Australia, in particular the Bowen and Sydney Basins, following an extensive program of hydraulic fracture testing and overcoring. The information is used to assess the extent to which plate boundary forces and other local stress sources are responsible for the stress field of the area.
Computing permeability of fault zones in aeolian sandstone from outcrop measurements. American Association of Petroleum Geologists (AAPG) Bulletin, v. 86, no. 7, p. 1187–1200	Jourde H, Flodin E.A., Aydin A., Durlofsky L.J., and Wen X.H. (2002)	Journal Article	Existing. New inclusion in assessment.	Analysis and determination of fault-zone permeabilities for use in large scale reservoir simulation using fine scale outcrop measurements, estimates of fault zone properties and numerical modelling. The analysis method considered trends in fault zone permeability as a function of fault slip.
Hydraulic Fracturing and Induced Seismicity in Kansas	Kansas Geological Survey (2013)	Memo	Existing. New inclusion in assessment.	Provides responses to public questions regarding the potential for seismic activity to be related to hydraulic fracturing and other oil-field related activities.
Analysis of Gas and Water Production Pathways in Coal Seams.	Kinnon, E. C. (2010)	Masters of Philosophy thesis.	Existing. New inclusion in assessment.	Detailed assessment of data obtained from an existing coal seam gas project in the northern Bowen Basin to assess well pathways, production performance and water and gas origins.
Evaluation of the April 2011 Bowen ML 5.3 earthquake and aftershock sequence. Australian Earthquake Engineering Society 2011 Conference.	Mathews et al (2011)	Conference paper	Existing. New inclusion in assessment.	This paper describes the largest earthquake to strike Queensland in decades, the preliminary aftershock distribution from the first two weeks of recorded data, the response spectra, isoseismal radius and focal mechanism of the main shock..

Table 4.1: Summary of Key Information Sources (cont'd)

Document	Author / Source	Format	Status since EIS	Relevance / Application
Geomechanical study of Bowland Shale seismicity - Synthesis report.	Pater, C.J. and Baisch, S. (2011)	Report	Existing. New inclusion in assessment.	This study assessed the relationship between Cuadrilla Resources Ltd shale gas hydraulic fracture activities and two small earthquakes that occurred near the Preese Hall wellsite in Lancashire, UK. The probable mechanism of the events is described based on analysis of all available data. It was shown that many factors coincided to induce the seismic events, which are unusual for stimulation treatments.
Fluid Flow in a Fractured Reservoir Using a Geomechanically Constrained Fault-Zone-Damage Model for Reservoir Simulation. SPE Reservoir Evaluation & Engineering, Volume 12, Number 4, p. 562-575	Paul P.K, Zoback M.D, and Hennings P.H. (2009)	Journal Article	Existing. New inclusion in assessment.	This study uses the principles of dynamic rupture propagation from earthquake seismology to predict the nature of fractured zones associated with reservoir-scale faults to calculate the extent of the damage zone along the fault plane. The modelling carried out provides a first order approximation of damage zones in terms of permeability and permeability anisotropy.
Fracture Mapping Results - Red Hill 060F, 050F, and 052F	Pinnacle (2013)	Report	Existing. New inclusion in assessment.	Presents the results of microseismic mapping services provided to Arrow during the hydraulic fracture stimulation of the Red Hill 060F, 050F, and 052F vertical wells, which are located 38 km north of Moranbah, Queensland. The mapping aimed to characterise the down-hole conditions, monitor the Project in real time to prevent significant out-of-zone height growth into known area water aquifers and provide information that can be used for future well placement and infill drilling strategies.

Table 4.1: Summary of Key Information Sources (cont'd)

Document	Author / Source	Format	Status since EIS	Relevance / Application
Isaac Connors Groundwater Project Part A: Conceptual Model for Groundwater and Part B: Assessment of Groundwater Dependent Ecosystems. Technical reports for the Fitzroy Basin Water Resource Plan Amendment.	SKM (2009 and 2009a)	Report	Existing	Detailed conceptualisation of the Isaac Connors groundwater systems, including development of a water balance, conceptualisation of groundwater-surface water interaction and assessment of the types and likely dependence of GDEs within the Isaac Connors catchment.
Northern Bowen Basin Structural Framework from 2D Seismic Interpretation	Sliwa (2011)	Report	Existing. New inclusion in assessment.	The report peer reviews and expands on the interpretation of 2D seismic sections for faults completed by Velseis (2011) for a regional marker equivalent of the Leichhardt seam (a seam within the Rangal Coal Measures (RCM)) as well as the GM seam (a seam within the Moranbah Coal Measures (MCM)). In addition the report identifies and characterises structural domains with consistent style of deformation.
Thermal and Fluid Flow History in the Bowen Basin. Bowen Basin Symposium 2000.	Uysal et al (2000)	Conference Paper	Existing. New inclusion in assessment.	The paper assesses the mineralogic, isotopic and geochronologic characteristics of authigenic clay and carbonate minerals of volcanogenic sandstones, mudrocks and bentonites from boreholes in the Late Permian coal measures of the Bowen Basin to explain the thermal and fluid history of the Bowen Basin.
Healthy HeadWaters Activity 1.2: Spatial Analysis of Coal Seam Gas Water Chemistry	Worley Parsons (2012)	Report	Existing	Provides unified database of historical groundwater and stratigraphic information for the Surat and Bowen basins from existing publically available data sources.

5 UPDATES TO THE UNDERSTANDING OF EXISTING ENVIRONMENT

A detailed review of information sources was completed to improve knowledge of the physical environment associated with the project, and the key sources are listed in Table 4.1. The following sections do not re-state the information presented in the EIS, but provide additional information to build on that presented in the EIS.

5.1 Regional Geology

Since completion of the EIS, additional investigations have been undertaken in order to further develop the geological understanding of the Project area, and to refine key aspects of the project knowledge. Existing information sources have also been revisited as part of the supplementary groundwater assessment to assist in characterising the existing environment. These investigations and reviews include specialist studies concerned with stratigraphy and geological structure, including the nature and extent of faulting, intrusions and lineaments, and subsidence. The results are provided as Appendices to this report and discussed in this section and in Section 6.

5.1.1 Stratigraphy

The stratigraphic model that formed the basis for the EIS and Arrow Bowen Basin EIS groundwater model is based on a detailed and comprehensive geological data set that includes sub-surface structure and formation extent characterised by borehole intersection data points (‘picks’), seismic sections, and surface mapping of outcrop geology. Because of the interest in the Bowen Basin as a coal and gas province, the stratigraphy is well characterised. Since the EIS, additional consideration of stratigraphy and formation extent has been made, in particular with respect to the extent of the Rewan Formation, a key confining layer which has implications for modelled groundwater impacts that might result from the Project.

The Rewan Formation represents the basal layer of the Bowen Basin Triassic succession of rocks (Mimosa Group) that overly the Late Permian Backwater Group (host to the target coal seams).

The Rewan Formation subcrop extent layer used in the stratigraphic model is based on the geological layers presented in the Bowen Basin Structural Geology map (CSIRO, 2008) which was developed as a collaborative research project between CSIRO Exploration and Mining and the QLD Department of Mines and Energy. The collaborative project integrated new geophysical data with existing geological and geophysical information.

Sliwa (2011) reviewed the CSIRO geological mapping with respect to the distribution of Triassic rocks, and used the Leichhardt seam of the Rangal Coal Measures (RCM) to define the subcrop of the overlying Triassic succession, of which the Rewan Formation is the lower-most unit. The review provided a revised extent and mapping of the Triassic succession and hence the Rewan Formation, and showed that in the CSIRO mapping overall the Rewan Formation (particularly in the south) is under-represented in the earlier conceptualisation of the model region geology (Sliwa, 2011). The implication of this, from a modelling perspective, is that in these areas drawdown impacts in overlying formations such as the shallow alluvium is likely to be over-stated.

Therefore the modelling results and the potential impacts derived from them can be considered as conservative in relation to groundwater drawdown predictions in areas where the Rewan Formation is absent.

5.1.2 Structure and Stress Regime

5.1.2.1 Regional Stress in the Northern Bowen Basin

Developing an understanding of the regional stress field in the Bowen Basin provides a basis for understanding the development of basin structural features, such as folds and faults, and has a relationship with observed seismicity. The in-situ stress field within the basin is a function of the relative stress magnitudes in the horizontal directions (regional stress caused by tectonics), and the stress in the vertical direction (overburden stress controlled by depth and rock density).

Significant work has been undertaken to characterise the in-situ stress field of the Bowen Basin. Hillis et al (1999) conducted an analysis of the stress regime in Eastern Australia, using in excess of 1000 individual stress measurements. A consistent north-northeast (016^0) mean stress orientation was found. A tectonic plate boundary control on stress orientation was concluded as the reason for this (Hillis et al, 1999).

The analysis undertaken considered:

- s_H (maximum far-field horizontal stress);
- s_h (minimum far-field horizontal stress); and
- s_v (vertical overburden stress).

In the Bowen Basin, 80% of the data indicate that vertical overburden stress (s_v) is the minimum principal stress, with the relationship $s_H > s_h > s_v$ (Hillis et al, 1999). This relationship has an important bearing on understanding of basin stress and fault development, and indicates that a compressive tectonic setting exists. This is an important factor that can influence the hydraulic behaviour of faults as closed faults, as discussed in Section 5.1.2.2 below.

5.1.2.2 Faulting and Fault History

Since preparation of the EIS, further consideration of the nature of faulting within the Project area has been undertaken, including consideration of a review of published and mapped faulting and other structures within the Bowen Basin. In addition, a study of the hydraulic properties of faults, including models for prediction of the permeability of faults, was undertaken (Appendix A).

Figure 5.1 presents an updated map of the current dataset of known or potential discontinuities from the study based on the review. The dataset includes:

- CSIRO (2008) mapped faults;
- Arrow interpreted mapped faults; and
- $70^0/250^0$ structural lineaments identified by Coffey (Appendix A).

Background and Context

To develop a reliable understanding of the behaviour of faults in the Bowen Basin, it is important to understand the technical context and the tectonic history of the basin through the available published literature.

The faulting history of the Bowen Basin is discussed at length in Esterle et al (2002). Thrust faults are reported to be related to the regional-scale Jellinbah thrust system, which propagated into the basin during the Mid Triassic (Esterle et al, 2002). Normal faults are described as completely brittle (as opposed to ductile) and propagated through fully lithified rocks, occurring at least as high in the stratigraphy as the RCM. Reactivation on structures such as normal faults, thrust faults and dykes are truncated by the Tertiary unconformity (Esterle et al, 2002). Further, it is reported that where thrust faults and normal faults interfere, the thrust faults are overprinted on the normal faults, indicating that normal faulting (a feature of extensional tectonic stress) has predated the present compressional stress regime.

Esterle et al (2002) describe how fully lithified rocks underwent first a mild extension resulting in abundant normal faults, and then compression resulting in the less abundant but more severe thrust faults by the Mid Triassic.

In considering the contemporary tectonic activity, Clark et al (2011) report that "*very few neotectonic features are known from the north-east of Australia, and most of these are less than convincing*". Based on the palaeotectonic history described by Esterle et al (2002) and the reported lack of significant neotectonism in Queensland (Clark et al, 2011) it is clear that the Bowen Basin faulting mainly predates the Tertiary, and has had low activity during the Cainozoic.

Uysal et al (2000) describe the fluid flow history in the Bowen Basin, supported by mineralogic, isotopic and geochronologic studies. The data indicate that two different extensional events affected Australia during the Mesozoic: a Late Triassic event and a younger Late Jurassic to Early Cretaceous event related to the fragmentation of Gondwana. Hydrothermal activity and fluid flow associated with these events, in particular the Late Triassic, is hypothesised to have resulted in widespread clay and carbonate mineralisation, leading to significantly reduced permeability and porosity within the basin.

Fault Occurrence and Type

Sliwa (2011) conducted a study and interpretation of faulting in the Bowen Basin to develop a regional structural model and to characterise structural domains with consistent deformational styles. The study included analysis of 212 2D seismic lines.

The study reported that major thrust faults are closely linked with folds, and that four separate structural zones can be defined with contrasting compressive deformation styles. Different folding style and occurrence is noted for each of the zones. Nearly all of the large thrust faults trend north-northwest and dip to the east, although an exception is a group of thrust faults to the south of the Cretaceous Bundarra intrusion that anomalously dip to the west (Sliwa, 2011).

Thrust fault throws range from 30 m to >500 m. Most faults with throws greater than 350 m are located north of the Cretaceous Bundarra Granodiorite intrusion.

Open folds were identified as being rare in deformation zones associated with large thrust faults, but common within zones of small thrust faults and normal faults.

5.1.2.3 Hydraulic Behaviour of Faults

A literature review of models for predicting fault permeability, including conceptual models presented by Flodin et al (2001), Jourde et al (2002) and Paul et al (2009), was completed (refer Appendix A).

Flodin et al (2001) identifies that faults can act as fluid flow barriers, conduits, or barrier/conduit systems. The flow and properties of faults are complex however, and may display both flow and barrier characteristic signatures in different time and place (Jourde et al, 2002).

Flodin et al (2001) focus on faults in porous aeolian sandstone to establish bulk flow characteristics, utilise an upscaling methodology, and present a modelled relationship between fault slip and permeability. Jourde et al (2002), considering the same porous sandstone, found that the permeability development associated with fault-zone slip was strongly anisotropic, with enhancement (relative to the host rock) of nearly one order of magnitude in the fault-parallel plane, and by contrast reduced permeability normal to the fault up to two orders of magnitude (relative to the host rock) due to the presence of low hydraulic conductivity core rock within the faults.

Paul et al (2009) studied reservoir-scale faults in the CS field, located in the Timor Gap between Australia and Indonesia, and use the principles of dynamic rupture propagation from earthquake seismology to predict the nature of fracture/damage zones associated with reservoir-scale faults. In the CS field, the petroleum reservoir shows significant permeability anisotropy associated with flow parallel to large reservoir-scale faults. The paper found that the fault damage zones have an optimal orientation for shear failure in the present day stress state.

When considering the development of models for fault permeability in the Bowen Basin, it should be noted that the faults studied by Flodin et al (2001) and Jourde et al (2002) were observed at surface outcrop in the North Muddy Mountains of Southern Nevada, USA. It is important to further consider that not only is the tectonic setting different, but also that the porous aeolian sandstone (Aztec Sandstone) does not have an analogue in the Bowen Basin.

Basin stress and tectonics must also be considered when making fault behaviour comparisons with other basins. As noted in Section 5.1.2.1, in the Bowen Basin vertical overburden stress (s_v) is the minimum principal stress, and the relationship $s_{H} > s_{h} > s_{v}$ applies (Hillis et al, 1999) indicating a present day compressive (reverse faulting) stress regime. The Bowen Basin stress relationship is fundamentally different from the CS field. Paul et al (2009) report a strike-slip/normal faulting for the CS field, where the relationship $s_{H} >= s_{v} > s_{h}$ applies. This stress relationship in the Bowen Basin has an important bearing on fault permeability, because of the potential for compressive tectonic stress to close fractures associated with faults, in contrast to faulting under a less compressive or partly extensional tectonic regime.

Based on an assessment of the above, the argument that faults in the Bowen Basin are generally of low permeability both parallel to and normal to the fault planes is compelling from a structural standpoint. This is consistent with and supported by other important lines of evidence, summarised below:

- **Field Evidence** – based on Arrow's field experience, including drill stem tests from the Bowen Basin, including the Moranbah Gas Project, water losses through structure have either not occurred or not been significant.
- **Fault Sealing and Limited Re-Activation** – based on the geological history of the Bowen Basin (Esterle et al (2002), Sliwa, 2011) fault development primarily occurred during the Mesozoic (Triassic and Jurassic) associated with earlier orogenic events. Hydrothermal alteration and mineralisation (Uysal et al, 2000) will have led to the sealing of fault damage zones associated with these earlier tectonic events. Faulting and fault re-activation has been limited through the Late Mesozoic and Cainozoic.
- **Age of Faulting** - Paul et al (2009) identify that [permeable] damage zones caused by slip on existing faults are important "…*especially when faults are active in present-day stress conditions*…" compared with the Bowen Basin where the faulting is predominantly Mesozoic and inactive in the present day.

- **Lack of Neotectonism** – Tectonism drives faulting and fault re-activation. The lack of neotectonic events in Queensland (Clark et al, 2011) supports the hypothesis that the Bowen Basin faulting predates the Cainozoic, and is largely inactive.
- **Basin Stress Regime** – The contemporary compressive stress regime (reverse faulting) has the potential for basin stress to close fractures associated with faults, compared with extensional tectonics.
- **Low Permeability Fault Core Rock** – field evidence from other basins and literature reviews indicate the presence of low hydraulic conductivity fault core rock in between host rock damage zones. This indicates faults act as barriers to horizontal flow regardless of whether mineralisation of damage zones has occurred or not.

5.2 Regional Hydrogeology

The regional hydrogeological setting was presented in the EIS and remains relevant for the current assessment. This section presents further detail on the physical hydrogeological setting of the Bowen Basin within the study area, including detail on aquifer parameters and potential interconnectivity of coal seam targets with overlying aquifers.

5.2.1 Aquifer Parameters

Following the EIS, a review was undertaken by Coffey to consider the aquifer parameters adopted for the Bowen Basin EIS groundwater model. The review considered the process presented in Ausenco-Norwest (2012) and the referenced data sources, parameters adopted for the OGIA Surat CMA groundwater model (GHD, 2012), and the results of hydraulic testing associated with the Moranbah Gas Project (Arrow, 2013a). In addition, a revised calibration and parameter set has been developed, as described in Section 6.3.

5.2.1.1 Bowen Basin EIS Groundwater Model Parameters

The parameterisation process adopted for the Arrow Bowen Basin EIS groundwater model is provided in "*Technical Note: Groundwater Model Parameterisation and Calibration, Northern Bowen Basin Regional Model*" (Appendix C of Ausenco-Norwest, 2012). The parameterisation effort involved the compilation of data from literature, government databases, and Arrow in-house datasets, and is presented in Section 4.4 of Appendix L Groundwater and Geology Technical Report in the EIS (URS, 2012).

Parameters were then adjusted during the calibration process iteratively to result in a final base-case set of parameters (the calibrated parameter set). An important part of this process is ensuring that the calibrated parameter set contains values that are realistic, and could reasonably be expected to occur in natural settings. Calibration targets adopted for the Arrow Bowen Basin EIS groundwater model comprised:

- Measured potentiometric groundwater levels;
- Surface water baseflow; and
- Model areas where calibrated heads should approach the ground surface and springs could occur.

A description of the primary hydrogeological parameters (hydraulic conductivity, specific storage and specific yield) is provided in Section 2 of Appendix C of Ausenco-Norwest (2012). Hydraulic conductivity is the primary aquifer parameter describing permeability. Specific storage is the primary storage parameter for confined aquifers. Specific yield is the primary storage parameter for unconfined aquifers. It is noted that parameter data is more refined and developed for the coal seams within and near the coal seam gas tenements, and is primarily focussed on permeability.

Hydraulic conductivity

Table 2.2 in Appendix C of Ausenco-Norwest (2012) provides reference and comment justifying the adopted initial hydraulic conductivity ranges, and vertical anisotropy ratios. It is noted that hydraulic conductivity values were further assessed as part of the model uncertainty analysis and the model peer review (refer Sections 6.2 and 6.3).

An important consideration is that hydraulic conductivity in coal formations has a relationship with depth, whereby deeper coals are more compacted and have reduced hydraulic conductivity. Shallower coals, due to reduced overburden pressure, have higher developed porosity and permeability. Understanding this depth dependent relationship is important for reservoir engineering purposes and development planning, and has been established by Arrow from field data and testing in the Bowen Basin. This hydraulic conductivity relationship has also been integrated in the Bowen Basin EIS groundwater model.

The calibrated model hydraulic conductivity values were reviewed and compared with modelling previously undertaken by the OGIA in the adjacent Surat Basin. Modelling undertaken in this basin, the OGIA Surat CMA groundwater model, is reported in GHD (2012). It is not possible to make direct comparison between the Bowen Basin EIS groundwater model and the OGIA Surat CMA groundwater model, as the formations are not direct equivalents and the general characteristics of the older Bowen Basin are different from the younger and typically higher porosity Surat Basin. Nevertheless similar values are seen for comparable lithologies (for example coals, sandstone aquifers and confining layers), and comparison indicates that the calibrated anisotropy ranges are appropriate.

Storage

Calibrated storage values are provided in Table 7.2 of Appendix C of Ausenco-Norwest (2012). Specific yield is reported for areas where the zone is unconfined, such as in Layer 1, and specific storage is reported for confined zones. Storage values were a calibration parameter and final values assigned during transient calibration.

The specific storage values for the coal seam interburden and confining units are the least well-defined in terms of available storage data, but important in terms of controlling drawdown. The final base-case specific storage values for the interburden layers were selected by verification analysis using the Moranbah Gas Project production and pressure data (Ausenco-Norwest, 2012). The calibrated values were at the lower end of the initial ranges based on literature review, and this may relate to the in-basin carbonate and clay mineralisation reported by Uysal et al (2000) that is a key feature of the northern Bowen Basin sediments. Importantly, specific storage does not appear unrealistically high, which would lead to under-representation of predicted drawdown impacts.

Field measurements of formation storage parameters are less readily available than for hydraulic conductivity. One key reason for this is that although single well tests may be useful for obtaining hydraulic conductivity data, establishment of storage data requires observations from separate monitoring wells installed close to pumping test bores. Due to the high cost of installing such wells in deep basin formations, this data is infrequently obtained. However literature values are useful as an initial estimate, followed by establishment of final values during model calibration, as adopted by Ausenco-Norwest (2012).

For the Arrow Bowen Basin EIS groundwater model, the calibrated values of specific storage for the confined formations range from $5x10^{-5}$ to $5x10^{-6}$ (Ausenco Norwest, 2012). These are within the typical range of storage values adopted for the OGIA Surat CMA groundwater model (GHD, 2012).

Other Parameters

The adopted base case recharge parameters are described in Section 2.4.2 of Ausenco-Norwest (2012). The lower base case value of 1 mm/year was applied to areas of outcrop. Other areas are described in the text and Table 2.8 of Appendix C of Ausenco-Norwest (2012), and appear appropriate.

The maximum evapotranspiration (ET) rate zone for the Modflow Evapotranspiration package was based on the difference between Potential ET and Actual ET gridded data from the Bureau of Meteorology. The values ranged from 0.0025 to 0.0033 m/d. The extinction depth was assigned to 10 m and is appropriate based on Canadell et al (1996) and is consistent with the assumed maximum plant rooting depth for the area for the assessment of GDEs.

The approach adopted in the Arrow Bowen Basin EIS groundwater model to assign parameters to formations is for primary formations to be assigned to a layer in the model. However areas are present in layers where other formations exist, and in those locations properties are assigned that represent the other formation. This method is widely used in groundwater modelling using block-centred discretisation, and consistent with the Australian Groundwater Modelling Guidelines (Barnett, et al, 2012).

5.2.1.2 Moranbah Gas Project Hydraulic Parameters

Slug tests were undertaken at a range of shallow monitoring wells installed in the vicinity of dams. The results are reported in Arrow (2013a). The tested locations are within the area of Arrow Bowen Basin EIS groundwater model, and the data is useful for comparative purposes.

Four lithologies were intersected by the monitoring wells, including:

- Basalt (weathered);
- Alluvium (Quaternary);
- Fort Cooper Coal Measures (FCCM) (weathered); and
- Sediment (Tertiary).

The test data were analysed for hydraulic conductivity using the Bouwer and Rice (1976) method which is appropriate for unconfined aquifer conditions. The results are presented in Table 5.1 and compared with URS (2012) and the calibrated model values.

Table 5.1: Moranbah Gas Project Slug Test Hydraulic Conductivity Results (m/day)

Lithology (main formation present)	Slug test range	Average K[1]	URS reported value range	Calibrated model value range
Basalt (weathered)	0.0061 to 0.62	0.21	0.1 to 10	0.05
Alluvium (Quaternary)	0.010 to 1.4	0.31	0.2 to 20	1 to 40
FCCM (weathered)	0.027 to 1.02	0.53	0.005 to 0.05	0.0001 to 0.0044
Tertiary Sediments	0.43	0.43	0.2 to 20	1 to 40
Note 1: average only considers wells in Table 3-1 of Arrow (2013a) that have single screened lithology. This includes 7 data points for basalt, 6 for Quaternary alluvium, 2 for FCCM, 1 for Tertiary sediments.				

In summary, the results show the following:

- Basalt: the calibrated model range falls within the slug test range.
- Alluvium: the calibrated model range is higher than the slug test range, but there is some overlap.
- FCCM: the calibrated model range is lower than the slug test range.
- Tertiary: the calibrated model range is higher than the single slug test result. The result is however within the lower end of the URS (2012) range.

Overall the results provide a satisfactory level of consistency with the modelled values. It is considered that the Fort Cooper Coal Measures are likely to exhibit decreasing hydraulic conductivity with increasing depth, and hence a better correlation with the calibrated model results would be expected when taking this factor into account. On a regional scale hydraulic conductivity will vary. As slug test data is representative only of the conditions at the specific bore location, and averaging of field data is required for the modelling process, there will be variation from this field data in the adopted modelling parameters.

5.2.2 Stratigraphic Controls

The presence or absence of the Rewan Formation, which is considered to be a regional aquitard (URS, 2012) will influence the degree of potential for connectivity between the target coal seam gas formations and the overlying Quaternary and Tertiary aquifers. As presented in Appendix L of the EIS the Rewan Formation is present across the majority of the study area, however is noted to be absent in the following general areas:

- Western parts of ATP742, ATP1103 and ATP1031;
- Most of ATP749 and ATP759;
- Northern parts of ATP1031; and
- Small parts of ATP1025 to the north and north west.

As described in Section 5.1.1 the presence or absence of the Rewan Formation is considered in the geological model used to construct the Arrow Bowen Basin EIS groundwater model, and the influence on the modelling results with respect to drawdown propagation is incorporated.

Whilst limited site-specific information is available regarding permeability of the FCCM, it is also considered to be a regional confining unit over the MCM due to the inferred low permeability of interburden which includes mudstone and carbonaceous shale. The available slug test data, which represents horizontal hydraulic conductivity in the weathered formation near the surface, is likely to be two orders of magnitude higher than the vertical hydraulic conductivity. As noted in Section 5.2.1.2 hydraulic conductivity will be expected to decrease further with increasing depth.

5.2.3 Structural Controls

Additional consideration has been made with regard to the structural controls on migration pathways as described below, supporting the hypothesis that pathways for migration across faults are limited or non-existent.

5.2.3.1 Faults

Kinnon (2010) completed a detailed assessment of data obtained from an existing coal seam gas project in the northern Bowen Basin to assess well pathways, production performance and water and gas origins. The study area encompasses a region of coal seam gas development where the seams are gently folded along strike into a series of synclines and anticlines, with normal faults present across the central anticline. The faults strike ENE with throws of between 2 to 10 m. The largest of the normal faults bisects the coal seam gas production field.

Stable isotope and water quality analysis was used to assess zones of potential recharge, water mixing and flow pathways. The results of the study, which are considered to be directly relevant to the study area for the Project, showed that compartmentalisation of gas reservoirs was evident and that this was due to the structural geology of the gas field. The study findings indicate that compartmentalisation is evident due to regions of higher and lower gas production rates on either side of a major fault.

Also, the study shows differences in isotopic compositions of produced water for wells north and south of the major fault line at similar depths, implying little communication across the fault boundary, and that the fault acts as a permeability barrier to water and gas flow (Kinnon, 2010). This relationship between groundwater compartmentalisation and structural geology was conceptualised in Figures 4-22 and 4-23 of Appendix L in the EIS.

5.2.3.2 Arrow Field Observations

Figure 5.2 shows Arrow pilot production wells together with mapped major faults, showing the proximity of existing pilot production wells to the major faults. In some cases minor faults have been encountered during drilling; however no significant loss or gain of water has been observed during drilling through these structures. This provides field evidence which supports a hypothesis of limited connectivity along faults.

In addition it is considered that the presence of faults, if permeable across formations, may over time lead to the loss of gas from coal seams due to migration. Therefore, the presence of gas within the target seams (as observed in the field) provides supporting evidence that pathways for migration are not present or limited.

Additional discussion regarding the permeability of faults within the Bowen Basin, and further evidence of limited migration pathways caused by faults, is presented in Section 5.1.2.3.

5.3 Groundwater Dependent Ecosystems

As detailed in Section 4, there are a number of available information sources that provide an understanding of the type and likelihood of GDEs in the Bowen Basin. Detailed desktop assessment, site surveys, remote sensing and risk assessment have been completed for the southern extent of the Bowen Basin with particular regard to springs, and state and national datasets are also available that provide information on potential non-spring GDEs.

The following sections outline the types of GDEs that have been identified within the Bowen Basin and presents the findings of the detailed desktop assessment with respect to GDEs in and immediately surrounding the Project area. A 50 km buffer zone surrounding the Project area has been adopted as a "study area" for the assessment of GDEs.

5.3.1 Types of Groundwater Dependent Ecosystems in the Bowen Basin

Based on the information sources reviewed in Section 4, and as described in detail below, the following types of GDEs (as described in the GDE Toolbox) have been identified within the Bowen Basin:

- Ecosystems dependent on the surface expression of groundwater including:
    - Springs, spring wetlands, spring fed watercourses.
    - Groundwater discharge to rivers and wetlands.
- Ecosystems dependent on the subsurface presence of groundwater, including plant roots accessing shallow groundwater. These are termed vegetation GDEs.

Known springs, spring wetlands and spring fed watercourses identified in the study area (i.e. within the 50 km buffer zone of the Project area) have typically been investigated through detailed field studies to validate their presence and likely groundwater dependence. These field studies have typically been completed as part of assessments for the development of the Surat CMA UWIR and associated Surat basin projects.

The GDE Atlas has identified many potential GDE landscapes, including potential areas where groundwater discharges to rivers and wetlands, or where plants may access groundwater. These have not been verified as being actual GDEs, and further discussion on the likelihood of the landscapes actually being groundwater dependent is provided below.

5.3.2 Spring vents and watercourse springs

A spring vent is a point where there is a surface expression of groundwater, and may be mounded or flat. A watercourse spring occurs where the natural land surface has been eroded sufficiently to intersect the watertable. The surface expression of groundwater may occur periodically or all year round. The Queensland Herbarium also defines a spring wetland as being where an area of ground is maintained in a damp condition by one or multiple spring vents (Queensland Herbarium, 2012).

DEHP maintains an inventory of identified springs in the Queensland Springs Dataset. Many of these sites have been studied in detail through the completion of field surveys including those completed in 2011 by KCB and the Queensland Herbarium (KCB, 2012 and Queensland Herbarium, 2012).

5.3.2.1 Spring conservation ranking

A conservation ranking relating to the biological importance of a spring vent has been developed by the Queensland Herbarium for the majority of spring vents contained in the DEHP database based on the site-specific information. The conservation ranking assigns a value to each spring vent and complex according to the following criteria:

- Category 1a: Contains at least one GAB endemic species not known from any other location beyond this spring complex;
- Category 1b: Contains endemic species known from more than one spring complex; or has populations of threatened species listed under State or Commonwealth legislation that do not conform to Category 1a;
- Category 2: Provides habitat for populations of plant and/or animal species not known from habitat other than spring wetlands within 250km;
- Category 3: Spring wetland vegetation without isolated populations (Category 2) with at least one native plant species that is not a widespread coloniser of disturbed areas;
- Category 4a: Spring wetland vegetation comprised of exotic and/or only native species that are wide spread colonisers of disturbed areas;
- Category 4b: The original spring wetland is destroyed by impoundment or excavation. The probability of important biological values being identified in the future is very low;
- Category 5: all springs inactive; and
- NA: not applicable (spring not included in ranking classification work).

No known springs are located within the Project area. Spring complexes and vents identified in proximity (within 50 km) of the Project area are presented in Figure 5.3 and Table 5.2, all of which are located to the south of the Blackwater tenure (ATP1025), within the Surat CMA. EPBC or NCA listed species or communities have not been identified at these spring locations. They represent recharge springs (a spring supplied by groundwater from an aquifer or aquifers that are in the vicinity of the spring and are not confined) which reflect interaction of the watertable or a perched aquifer with the ground surface. This spring type typically represents the surface expression of groundwater with a short groundwater flow path associated with local to intermediate flow systems. For these reasons, the outcropping formation present at the location of each spring complex or vent is interpreted to represent the source aquifer. The conservation ranking is also presented in Figure 5.3 and Table 5.2, and shows that the springs are either Category 2 or 3 or have not been classified.

Table 5.2: Summary of Known Springs within 50 km of the Project Area

Spring Complex Name	Spring Complex Number	# Vents in Complex	Site Name	Spring Conservation Ranking	Outcrop Geology (inferred source aquifer)	Discharge and recharge mechanisms
16	16	1	Numma	3	Rewan Formation (sandstone)	Springs are located in highlands south of Blackwater in the Blackdown Tableland, typically along ridgelines where either a change in geology or break-of-slope are expected to result in the surface expression of the watertable. Groundwater flow (discharge) to the springs considered to be from local groundwater systems associated with the Blackdown Tableland, and is disconnected to the groundwater systems associated with the underlying target coal measures. Recharge to these springs is considered to occur locally through direct rainfall recharge to the watertable aquifer.
35	35	2	Springton	NA	Clematis Sandstone	
			Rusty's	NA	Clematis Sandstone	
78	78	2	Middle	3	Tertiary Sandstone	
			Mud	3	Clematis Sandstone	
Cleanskins	510	1	Cleanskin paddock	NA	Clematis Sandstone	
Rainbow Spring	1	11	Rainbow Falls	2	Precipice Sandstone	
			Two-mile	2	Precipice Sandstone	
			Balamoo East	NA	Clematis Sandstone	
			North Escarp	NA	Cainozoic gravels	
			Ardurad	NA	Rewan Formation (sandstone)	

Table 5.2: Summary of Known Springs within 50 km of the Project Area (cont'd)

Spring Complex Name	Spring Complex Number	# Vents in Complex	Site Name	Spring Conservation Ranking	Outcrop Geology (inferred source aquifer)	Discharge and recharge mechanisms
Rainbow Spring (cont'd)			Rockland	NA	Rewan Formation (sandstone)	
			Balamoo West	NA	Precipice Sandstone	
			Balamoo Central	NA	Rewan Formation (sandstone)	
			Miiosa CRk2	NA	Rewan Formation (sandstone)	
			Miiosa CRk3	NA	Rewan Formation (sandstone)	
			Blackdawn	NA	Precipice Sandstone	
SF212	68	2	Cooinda	2	Rewan Formation (sandstone)	
			SF212	NA	Clematis Sandstone	

In addition to the springs presented in Table 5.2, a further two potential spring sites within 50 km of the Project area in proximity to the springs listed in Table 5.2 have been identified through remote sensing, thematic mapping and aerial validation studies (Halcrow, 2012 and 2013). The two potential spring sites (refer Figure 5.3) have been earmarked for ground validation by Halcrow as part of the detailed study commissioned by Santos Ltd.

No known watercourse springs are located within the Project area. The following watercourse springs are located within 50 km of the Project area, as presented in Figure 5.3:

- Site W114: Mimosa Creek Tributary;
- Site W113: Mimosa Creek;
- Upper reaches of the Connors River, Funnel Creek, Denison Creek and Lotus Creek;
- Mid-reaches of the Connors River and Funnel Creek; and
- Lower reaches of the Isaac River.

5.3.3 Nationally important wetlands

A search of the EPBC Act 'Protected Matters: Nationally Important Wetlands' directory found that there are no Nationally Important Wetlands within the Project area. The search identified five wetlands within 50 km of the Project area as presented in Table 5.3 and Figure 5.4. It is noted that Lake Elphinstone has also been classified as a Category C Environmentally Sensitive Area (a referrable wetland) in the EIS.

Table 5.3: Nationally Important Wetlands within 50 km of the Project Area

Wetland Name	Wetland Category	Wetland Type	Likely groundwater dependence
Lake Elphinstone	Inland wetland	B6 - Seasonal/intermittent freshwater lakes B10 - Seasonal/intermittent freshwater ponds B14 - Freshwater swamp forest	Potential for dependence on groundwater. Lake water supply is noted to be sourced from runoff and stream flow from the local catchment. However it is also possible that it has some groundwater dependence. Maximum lake depth is not known but most of the lake is less than 2m. Lake levels fluctuate seasonally and water is semi-permanent.
Why Not Aggregation	Human-made wetlands	C2 - Ponds, including farm ponds, stock ponds, small tanks	Not groundwater dependent as it is an artificial impoundment located on a drainage depression rather than a stream. The feature is filled by local runoff.

Table 5.3: Nationally Important Wetlands within 50 km of the Project Area (cont'd)

Wetland Name	Wetland Category	Wetland Type	Likely groundwater dependence
Eungella Dam	Inland wetland and Human-made wetlands	B1 – Permanent rivers and streams B4 – Riverine floodplains C1 - Water storage areas; reservoirs, barrages, hydro-electric dams, impoundments	Not groundwater dependent. The wetland has been created by damming a valley of the Broken River. Water supply is listed as being stream flow and runoff from the catchment.
Bowen River: Birralee – Pelican Creek	Inland wetland	B2 - Seasonal and irregular rivers and streams B4 – Riverine floodplains B5 - Permanent freshwater lakes B6 - Seasonal/intermittent freshwater lakes	Potential for stream reaches to receive groundwater baseflow. The central part of the feature is described as a large permanent clear water hole with rapids, sand, rock or rubble bars, terraces and small waterholes at the upstream and downstream ends. Most of this section of the river has cut into volcanic rocks and has a bedrock bed, which has been partially covered by sheets and banks of sand, gravel and pebbles.
Broken River, Urannah Creek and Massey Creek Aggregation	Inland wetland	B1 – Permanent rivers and streams B2 - Seasonal and irregular rivers and streams B4 – Riverine floodplains B9 - Permanent freshwater ponds B10 - Seasonal/intermittent freshwater ponds B14 - Freshwater swamp forest	Not considered to be groundwater dependent. The system is described as an upper perennial and intermittent riverine wetland. Water is transported from the high rainfall upper catchment to the lower rainfall western side of the site providing a reliable source of water and refuge in times of drought.

Source: Environment Australia (2001) and DoE (2013)

5.3.4 GDE Atlas mapping layers – surface expression of groundwater

The GDE Atlas (BoM, 2013) presents a wide range of landscapes that may potentially contain ecosystems dependent on groundwater for some or all of their water requirements. GDEs that potentially access the surface expression of groundwater mapped in the GDE Atlas (wetlands and baseflow fed watercourses) are presented in Figure 5.5, and represent a subset of the GDEs presented in the GDE Atlas based on the following criteria:

- Exclusion of GDEs classified as having a low potential for interaction with groundwater that are unlikely to represent actual GDEs. This exclusion also removed any instance of GDEs attributed as being 'disconnected, losing' with respect to groundwater-surface water connectivity, that are not considered to represent true GDEs;
- Exclusion of wetlands classified as 'artificial/highly modified wetlands (dams, ring tanks, irrigation channels, drains, canals); and
- Exclusion of GDEs classified as springs, as the locations of known springs, verified by field surveys, are presented in Figure 5.3.

After application of the exclusions identified above, the location of remaining potential GDEs accessing the surface expression of groundwater are presented in Figure 5.5 and represent regions where groundwater potentially discharges to watercourses and wetlands. These areas of potential interaction are typically distributed across the study area along watercourses, where the watertable is expected to be at its shallowest. Within and in the vicinity of the Project area they are classified as watercourse or riverine systems along floodplains and swamps. Many of these creeks are considered to be ephemeral (URS, 2012). Detailed studies have not been completed to determine whether these features are truly groundwater dependent, however where a degree of groundwater dependence exists it is expected this will be episodic rather than permanent.

A number of stream reaches presented in Figure 5.5 to the east of the Project area that are mapped as being identified in a previous study were described in the EIS as likely GDEs. These were identified as part of a detailed study of the Isaac-Connors catchment (SKM, 2009a), and include reaches of the Connors and Isaac Rivers, and Funnel and Lotus Creeks.

There is limited spatial coverage of groundwater (watertable) elevation to assess the likelihood of actual groundwater interaction with surface features. SKM (2009a) states that in the Isaac-Connors catchment the watertable elevation varies spatially and temporally however is typically 5-20 metres below ground surface (mbgs). JBT Consulting (2010) outline that the ephemeral nature of the Isaac River indicates that groundwater baseflow is not significant, and this is supported by SKM (2009) who also indicate that creeks and rivers in the study area are typically losing (loss of surface water to underlying strata).

Based on the available data the extent of baseflow contribution to streams and rivers in the Project area is likely to be limited in extent, and vary seasonally. In some areas however it is expected that rivers and streams within the Project and study area receive baseflow contribution where depth to groundwater is shallower (i.e. around 5 m below ground) and where the watercourse is sufficiently incised into the land.

Based on the information presented above, the potential GDE landscapes identified within the Project area in Figure 5.5 that have been assigned a high potential for groundwater interaction includes:

- Reaches of Kangaroo, Suttor, Anna, Hail, Bee, Phillips and Cherwell Creeks;
- Isaac River (Upper and Mid); and
- Burton Gorge Dam.

There are further unnamed surface features, including tributaries of the creeks and river listed above, that are mapped as having a high potential for interaction with groundwater, particularly in the north of the Project area. In addition, Lake Elphinstone is located immediately outside of the Project area and mapped as having a high potential for interaction with the surface expression of groundwater.

GDEs mapped as being potentially dependent on the surface expression of groundwater also coincide with areas of National and Conservation Parks in the proximity of the Project area, including Homevale National and Conservation Park in the north east, and the Blackdown Tableland National Park in the south.

5.3.5 GDE Atlas mapping layers – subsurface presence of groundwater

As described in Section 5.3.1, GDEs reliant on the subsurface presence of groundwater relates to vegetation that is accessing the watertable and/or capillary fringe. This may occur where depth to groundwater is near surface or where the vegetation has sufficient rooting depth to access deeper groundwater.

The GDE Atlas maps these ecosystems that potentially rely on the subsurface presence of groundwater. A sub-set of the GDE Atlas mapping is provided in Figure 5.6 and represents GDEs that are classified as having either a high or moderate potential for interaction with groundwater. GDEs classified as having a low potential for interaction have been excluded as they are unlikely to represent actual GDEs. A single area of vegetation within the study area has been identified as potentially groundwater dependent through previous study. Details of the study where this is identified are not available through the GDE atlas.

Regions where extensive areas are mapped as containing potential GDE landscapes are typically constrained to the north west and north east of the Project area south of Collinsville, south of Glenden to the top of ATP759, to the east of the Project area around Nebo, to the west of the Project area around Dysart and to the south of the Project area near Blackwater.

The majority of these areas are defined as having moderate potential for the interaction with the subsurface presence of groundwater.

Within the Project area there are regions mapped with a high potential for interaction with the subsurface presence of groundwater. These areas are primarily represented as riparian vegetation along the Isaac and Mackenzie Rivers, and Stephens, Phillips, Harrow and Kangaroo Creeks, as well as other minor creeks throughout the northern parts of the Project area.

As per GDEs mapped as being potentially dependent on the surface expression of groundwater outlined in Section 5.3.4, areas of potential GDE interaction with the subsurface presence of groundwater also coincide with areas of National and Conservation Parks in the proximity of the Project area, including Homevale National and Conservation Park in the north east, and the Blackdown Tableland National Park in the south.

There is insufficient spatial coverage of groundwater monitoring bores across the study area to reliably map the depth to watertable, however registered groundwater bores in the area that have available groundwater elevation data support the SKM (2009) study for the Isaac-Connors catchment that indicated that the watertable is typically between 5 and 20 mbgs. These depths to watertable are expected to potentially be within plant rooting depths particularly along watercourses.

5.3.6 EHP Groundwater Dependent Ecosystem dataset

The EHP GDE dataset does not extend into the Project area or immediate surrounds therefore has not been considered further in this assessment.

5.4 Groundwater Quality

The groundwater quality information presented in the EIS was sourced primarily from studies completed by Raymond and McNeil (2011) and Pearce and Hansen (2006). Since the release of the EIS, water quality data for the northern Bowen Basin has been collated and assessed in Ausenco-Norwest (2013). This study was based on 211 samples collected from 110 Arrow production wells and 1,239 samples collected from 547 individual bores contained within the DNRM database.

In addition, Worley Parsons (2012) completed a study that collated basin-wide groundwater quality data and provides additional information to supplement data specific to the Project area.

Water quality data in both studies (Ausenco-Norwest, 2013 and Worley Parsons, 2012) is representative of the target coal seam gas formations (Blackwater Group), as well as overlying alluvium, basalt, Tertiary sediments, Triassic sediments and underlying Permian formations (Back Creek Group).

The spatial distribution of bores with available groundwater quality information is focused to the east (primarily in the alluvium) and south west of the Project area and the majority of the Arrow-sourced data is associated with the Moranbah Gas Project. Most of these bores are located outside of the Project area, however there is sufficient spatial distribution to provide a regional overview of water quality across the geological formations present within the study area, as demonstrated in Ausenco-Norwest (2013).

The assessment of groundwater quality presented in the EIS, as well as that documented in Ausenco-Norwest (2013) highlight that groundwater quality across the study area, within each aquifer assessed, is moderately to highly variable. There is no apparent correlation between salinity with respect to depth or location within the basin within a geological formation or between formations (Ausenco-Norwest, 2013). Likewise there appears to be no trend in spatial distribution of major ion data and major ion data cannot be used to definitively characterise an aquifer.

5.4.1 Groundwater Chemistry

A summary of the groundwater chemistry for major formations within the Bowen Basin is presented in Table 5.4. Water type based on major ion composition, total dissolved solids (TDS) and pH are provided, with the 10^{th} and 90^{th} percentiles presented for TDS and pH as well as the median value. The number of samples (n) used in the assessment is also shown for each formation. The water quality information presented is sourced from Worley Parsons (2012) and Ausenco-Norwest (2013), and it is noted that both studies removed data outliers from their assessments.

The data presented in Table 5.4 indicates that groundwater quality is typically slightly alkaline, and good quality (i.e. TDS < 1,000 mg/L) groundwater is present in areas within the Quaternary alluvium, Tertiary basalt and Clematis Sandstone aquifers. Water quality is expected to be highly variable (Ausenco-Norwest, 2013 and Worley Parsons, 2012) and good quality groundwater is likely to be limited in spatial extent.

Table 5.4: Summary of Groundwater Quality by Aquifer

		Dominant Water Type	TDS (mg/L)			pH (units)		
			10th	90th	Median	10th	90th	Median
Quaternary Alluvium (n=216)[1]		Na^+ - Cl^- and Na^+ - HCO_3^-	263	3042	520	6.9	8.2	7.7
Tertiary Basalt (n=132)[1]		Na^+ - Cl^- to Na^+ - HCO_3^- and Mg^+- HCO_3^-	432	3244	896	7.5	8.4	8.1
Tertiary Sediments (n=28)[1]		Na^+ - Cl^-	368	7230	1940	7.1	8.2	8
Triassic Sediments	Triassic Sediments (n=14)[1]	Na^+ - Cl^-	1431	4316	1931	7.4	8.2	8.0
	Clematis Sandstone (n=266)[2]	Na^+ - HCO_3^- to Na^+ - HCO_3^- - Cl^-	156	571	387	7.1	8.3	7.9
	Rewan Formation (n=63)[2]	Na^+ - Cl^- to Na^+ - Cl^-- HCO_3^-	325	8023	1490	7.3	8.3	7.8
RCM, FCCM and MCM over- and interburden (excluding coal measures) (n=160)[2] (Upper Permian Sandstone)		Na^+ - HCO_3^- and Na^+ - Cl^-	574	8598	1767	7.4	8.4	7.9
Blackwater Group (n=186)[1] (Upper Permian Coals)		Na^+ - Cl^- to Na^+ - HCO_3^-	1204	8786	4256	7.4	8.5	7.9
Back Creek Group (n=81)[1] (Lower Permian Sandstone)		Na^+ - HCO_3^- to Na^+ - HCO_3^- - Cl^-	725	6767	1925	7.4	8.4	7.9
Permian Volcanics (n=59)[2]		Na^+ - HCO_3^-	655	4988	1384	7.3	8.4	7.9

Source: 1: Ausenco-Norwest (2013)
2: Worley Parsons (2012)

5.5 Cultural and Spiritual Sites of Significance

The Indigenous Cultural and Heritage study presented in Appendix W of the EIS identified uncommon and culturally important places listed in the Queensland Indigenous Cultural Heritage Register and Database. Four of these sites are potentially reliant on groundwater based on their description in the database as wells. The sites, located in the north of the Project area are presented in Figure 5.7, and are described as:

- A contact place / well located within ATP1103 along the Isaac River approximately 28 km north of Moranbah immediately east of the Goonyella and Riverside Opencut Mines and North Goonyella Underground Mine;
- Two stone artefact scatter / well sites located within ATP1103 approximately 15 km southwest of Glenden; and
- A well located within ATP749 approximately 32 km south east of Glenden.

No further detail on these sites is available for the SREIS assessment, including the current status of these features or well depth.

5.6 Subsidence

In 2010 Geoscience Australia (GA) completed a review of available information from coal seam gas proponents (Origin Energy, QGC and Santos) to provide expert advice to SEWPaC (now DoE) in relation to the likely groundwater impacts of proposed coal seam gas activities in the Surat and Bowen Basins. It was identified that there was potential for subsidence to occur. Williams et al (2012) also identified the potential for land subsidence as a result of coal seam gas extraction, and identified this as a natural resource management issue that requires attention. However based on an assessment of coal seam gas activities in similar environments, Geoscience Australia and Habermehl (2010) concluded that the risk of impacts to shallow groundwater systems was low.

In recognition of the identified potential for subsidence, albeit low, Altamira Information Ltd (Altamira) was engaged to complete a ground motion study on behalf of Arrow Energy for their existing Moranbah Gas Project in the Bowen Basin (Altamira, 2013). The study involved analysing ground motion using satellite interferometry across the Moranbah Gas Project area. The study enabled an evaluation of ground surface motion across the Moranbah Gas Project area during a known period of coal seam gas production.

The ground motion study used data obtained from the advanced land observation satellite (ALOS) launched by the Japan Aerospace Exploration Agency in January 2006, and was similar to previous assessments undertaken in the Surat and southern Bowen Basins. Data was obtained from two satellite tracks covering Petroleum Leases 191, 196, 223 and 224 for the period December 2006 to January 2011. Data sets were available for 22 traverses for one of the satellite tracks and 18 traverses for the other track. These data sets provided a reasonably even surface coverage over the period of interpretation.

Altamira processed the satellite data using the same method applied to baseline subsidence monitoring for the Surat and southern Bowen Basin. The processing involved identification of phase difference between points within the areas scanned for each data set and applying various corrections to account for the elevation of the points, the velocity of the satellite and atmospheric effects.

Points on the ground suitable for measurement were identified based on amplitude stability of the detected radar response and coherence of the interferograms. Medium resolution interferograms were generated by combining the results of blocks of high resolution points to generate a processing resolution of 35 m by 35 m. This process reduces noise in the interpreted results but reduces the spatial resolution (Altamira, 2013).

5.6.1 Altamira Assessment

The Altamira (2013) study determined the amount of settlement over the period from December 2006 to January 2011, during which coal seam gas water was extracted by Arrow from Petroleum Leases 191, 196, 223 and 224 located to the east of Moranbah, in an area traversed by the Isaac River.

Coal seam gas has been extracted since 2003 from a network of production wells within these petroleum leases. Over the time period of the Altamira ground motion study (December 2006 to January 2011), gas was extracted mainly from the Moranbah Coal Measures, with a minor component from the Fort Cooper Coal Measures. Co-produced water associated with coal seam gas production from the leases is described in Table 1 of Appendix B.

The study found considerable variability across the Project area identifying areas of both uplift and subsidence. The uplift arises from seasonal factors (swelling of soils) and subsidence occurs primarily as a result of settling of manmade structures such as railway embankments. The results showed the bulk of the area monitored was subject to a rate of movement of less than 8 mm/year over the monitoring period which Altamira defined as “stable” (i.e. below the measurement threshold; see also Figure 5.8 and Figure 4 of Appendix B). Isolated locations with a greater rate of movement (both upward and downward) were identified, however. Each of these was analysed; details are presented in the Altamira report and discussed in Appendix B. These instances included:

- Areas of interpreted upward movement attributed to seasonal rainfall over the time period and changes in soil moisture associated with swelling of reactive clay soils;
- Localised settlement areas associated with areas of bare earth possibly associated with erosion;
- Settlement at an isolated location at a production well site over the period January 2007 to December 2010;
- Localised upward movement interpreted at a location which appears to be a gas processing site over the period January 2007 to December 2010, possibly related to swelling of reactive clay soils in a vegetation cleared area;
- Settlement interpreted on a circular embankment apparently constructed for a rail loop; and
- Settlement interpreted at the embankment for a water storage pond associated with a racecourse.

Further interpretation of ground motion study

Further analysis of Altamira data was carried out by Coffey to assess whether any widely distributed low magnitude subsidence effects were present (Appendix B).

The Altamira results database was re-processed to provide average ground movement over 500 m by 500 m blocks for the period 2007 to 2011. The results of this processing are presented in Figure 5.8. It was apparent that over most of the area interpreted ground movement was less than 10 mm (subsidence or uplift) over the four year period. Figure 5.8 shows where interpreted ground movement exceeded 10 mm over that four year period, as described below.

A diagonal zone of upward movement was interpreted over the four year monitoring period in the north of Petroleum Lease 191, along the alignment of Teviot Brook. This was considered likely to be associated with swelling of reactive clay soils caused by above average rainfall (Appendix B). Minor subsidence (between 10 mm and 20 mm) was interpreted to have occurred at a number of dispersed locations within the area studied.

Within Petroleum Lease 223, areas with subsidence interpreted to be in the range 10 to 20 mm over the monitoring period were identified. Given that the coal seam gas extraction activity over the period is limited in this area (only 3 ML of co-produced), it is unlikely that this ground movement is caused by coal seam gas production. It is possible that the interpreted minor subsidence could be related to minor works such as soil desiccation at cleared areas. Review of aerial imagery reveals the presence of open cut mining operations and potential heavy vehicle movement in this area which is considered a more likely cause of the minor subsidence interpreted.

Within Petroleum Lease 191, areas with average downward vertical movement in the range 10 mm to 20 mm were observed along the western margin that approximately correlates with the gas pipeline network and coal seam gas extraction in this area. However, less correlation is seen in the southern and eastern parts of Petroleum Lease 191, where the small downward movements may be more clearly associated with open-cut mining.

5.6.2 Calculated estimates of subsidence potential

Estimations of potential subsidence for the Moranbah Coal Measures due to coal seam gas development associated with the Moranbah Gas Project were undertaken as presented in Appendix B and summarised below.

Subsidence associated with Moranbah Gas Project coal seam gas extraction occurs due to the combined effects of the following processes:

1. Shrinkage of the coal seam due to removal of gas; and
2. Compression of the coal seam and overlying formations due to reduced groundwater pressure.

These processes are considered separately below, and then combined to provide an estimate of gross subsidence potential.

Shrinkage of coal seams

The mechanical properties of the Moranbah Coal Measures, that govern the contraction of coal due to gas extraction from its seams, are not known. However an indication of potential shrinkage due to reduction in gas content based on reasoned assumptions is made in Appendix B, indicating the following:

Estimated vertical shrinkage:	10 mm
Estimated range (to include uncertainty):	5 mm to 15 mm.

Compression of coal seams and overburden

An estimate of the compression of the coal seam and overlying formations is also made in Appendix B, and is based on conservative assumptions of rock compression modulus (a measure of the compressive stiffness of the rock) for the coal and overburden. The estimate assumes an average drawdown of 100 m in the Moranbah Coal Measures and an indicative formation thickness of 250 m sandstone with 15 m aggregate thickness of coal seam. The following compression was estimated (also refer Appendix B):

Estimated formation compression:	30 mm
Estimated range (to include uncertainty):	10 mm to 60 mm.

This assessment contains uncertainty in relation to the rock mechanical properties of both the coal and overlying formations. However it is noted that conservative values were adopted and the formations may have greater compressive stiffness. Consequently the assessment should be considered indicative only. The range provided above recognises this uncertainty.

Estimated gross subsidence potential

A gross estimate of aggregate subsidence potential and range can be made by combining the shrinkage and compression components presented above. Based on this, the following gross subsidence estimate is made (refer Appendix B):

Estimated gross subsidence:	40 mm
Estimated range (to include uncertainty):	15 mm to 75 mm.

Comparison with Moranbah Gas Project observed subsidence

Assuming the 10 mm to 20 mm downward vertical movement identified along the western margin of Petroleum Lease 191 presented in Section 5.6.1 is a result of subsidence due to coal seam gas production (Appendix B), then the observed ground movement is within the lower end of the calculated range based on coal shrinkage and compression calculations. This supports the assumption that conservative selection of coal and rock stiffness properties for the subsidence assessment was made.

In addition, the calculated range based on coal shrinkage and compression is less than localised rates of ground movement due to natural swelling in reactive clays reported in the ground motion study (Altamira, 2013).

Comparison with Coal Mining and other Gas Provinces

The above assessment of subsidence potential and observed effects based on the Moranbah Gas Project show that the magnitude of potential subsidence resulting from coal seam gas development in the Bowen Basin is low, and substantially less than that arising from underground longwall coal mining, where subsidence is typically greater than 1 m. For example, the vertical subsidence predicted for an underground coal mine in the Bowen Basin is anticipated to be 2.7 m (Hansen Bailey, 2011).

Grigg (2012) reports that subsidence associated with the Powder River Basin coal-bed methane project located in Wyoming USA has also been assessed using satellite interferometry. In that basin high production rates of approximately 356 ML/day have resulted in a maximum subsidence of 40 mm to 60 mm associated with large clusters of gas wells. It is noted that this is within the range based on calculation presented above (15 mm to 75 mm).

Conclusion

The subsidence interpreted from satellite interferometry indicates that the magnitude of the surface ground movement associated with coal seam gas extraction in the Moranbah Gas Project is:

- Small;
- Within the lower range of calculations used to estimate subsidence; and
- Significantly less than expected for longwall coal mining.

It is concluded that these outcomes will also apply to the BGP because the Moranbah Gas Project area and the activities undertaken are considered to be a reasonable analogue of the Project area and the BGP activities. In addition it is noted that any subsidence resulting from coal seam gas development would be broadly distributed and that differential subsidence would not occur, further reducing the risks of surface impacts arising.

5.7 Seismicity

Additional review of seismicity within the Bowen Basin has been undertaken since completion of the EIS. As discussed in the following sub-sections, the review found that:

- The Bowen Basin is relatively aseismic;
- The risks of induced seismicity that can result from hydraulic stimulation are low compared to natural earthquakes; and
- The likelihood of hydraulic stimulation induced events causing any damage is low.

5.7.1 Natural Seismicity

Natural seismicity in the Bowen Basin was considered as part of a technical review (Appendix A) that considered published data including Geoscience Australia (2013). Figure 5.9 presents the recorded earthquakes for a 1 million km^2 window centred on the northern Bowen Basin with earthquake intensity proportional to the symbol size.

In addition, the figure shows the April 2011 Bowen earthquake and aftershocks (located approximately 100 km north of the project area) as interpreted by Mathews et al (2011). The Bowen earthquake was identified as a magnitude 5.7 event, with five small aftershocks of magnitude 3.2 to 4.1 in the following few days.

Notwithstanding the 2011 event, the Bowen Basin is relatively aseismic (Hillis et al, 1999) and this is consistent with the observed lack of neotectonic features (Clark et al, 2011). Clark et al describe much of Queensland as "…*devoid of significant concentrations of historic seismicity*".

In comparing basins, the western boundary of the Sydney Basin shares some similarities with the northern Bowen Basin (transition from extra-basin media to intra-basin Permian units, stress orientation, and strike of the boundary). However the Sydney Basin is one of Australia's most active seismic regions. In the Sydney Basin, lineaments of strike 50°/230° have been successfully targeted for enhanced water supply (for example, water supply wells at Wolgan Valley near Lithgow, where the targeted lineament, associated with a major drainage course, exhibited significantly enhanced hydraulic conductivity along its plane, compared to hydraulic conductivity measurements made in piezometers off the lineament). This is in contrast to the lack of field evidence for significant permeability associated with faulting and lineaments in the Bowen Basin.

5.7.2 Induced Seismicity

Seismicity that has resulted from human activities is known as induced seismicity. Induced earthquakes are associated with changes to the mass loading of the earth (for example by large open cut mining, or by filling of reservoirs), by underground mining, or by injection of fluids into the sub-surface.

Experience in Australia and elsewhere in the world indicates that the risks of induced seismicity that can result from hydraulic stimulation are low compared to natural earthquakes (Geoscience Australia, 2013). Hydraulic stimulation is commonly associated with shale gas developments, conventional oil and gas reservoir stimulation, and geothermal exploration. In some provinces, including the Bowen Basin, hydraulic stimulation may be necessary to increase the permeability of coal seams to enable access to the gas reserves.

Hydraulic stimulation releases energy in the sub-surface when the target formation is fractured, and this process releases energy in the form of seismic events of low intensity that are only detectable by sensitive seismological instruments (Geoscience Australia, 2013). The magnitude of these events is usually less than 2.0 (Kansas Geological Survey, 2013). In general, events below magnitude 3 are usually not felt at the surface.

Induced seismicity can also occur when rocks under elastic strain release energy through movement along existing faults. It is feasible that this can occur during hydraulic stimulation when high pressure fluid lubricates an already stressed fracture plane. Two incidences of low magnitude seismic events at depths of 2 km and 3.6 km below the surface occurred near Blackpool (in the UK). These events, magnitude 1.5 and 2.3, have been attributed to hydraulic stimulation (British Geological Survey, 2012). The second of these events (in May 2011) is reported to have been felt at the surface by at least one person.

However despite this, the British Geological Society report that the likelihood of hydraulic stimulation induced events causing any damage is low. An independent study found that the seismic events were two orders of magnitude higher than normal for hydraulic stimulation, and probably occurred as a result of direct injection of fluids into a fault (Pater and Baisch, 2011).

Preliminary research on hydraulic stimulation induced seismicity in Australia indicates that induced seismic events release less energy than naturally occurring seismic events of similar size (Geoscience Australia, 2013).

Arrow Microseismic Field Data

Microseismic fracture mapping is a technique that provides an image of fractures by detecting micro-earthquakes triggered by hydraulic stimulation. The location of the microseismic events is obtained using a receiver array positioned nearby, and the results from microseismic fracture mapping can be used to "calibrate" fracture growth models.

Microseismic mapping was undertaken in November and December 2012 during the hydraulic fracture stimulation of three vertical coal seam gas wells located 38 km north of Moranbah. The project wells (Red Hill - RH060F, RH050F, and RH052F) were drilled in the Moranbah Coal Measures. A total of 11 hydraulic stimulation treatment stages were stimulated for production and mapped (Pinnacle, 2013).

The objectives of the fracture microseismic mapping service were to:

- Measure the fracture geometry (height, length, width, and azimuth);
- Characterise the relationship between total volume pumped and generated fracture half-length and height;
- Determine the relative degree of induced fracture complexity;
- Characterise the relationship between treatment fluid viscosity and generated fracture geometry;
- Monitor the project in real time to prevent significant out-of-zone height growth into known area water aquifers; and
- Provide information that can be used for future well placement and infill drilling strategies.

The network of individual fractures generated at the RH060F well were contained within an extent of approximately 29 m width in formations below the Goonyella Middle seam, while those generated at the RH052F and RH050F wells (above the Goonyella Middle seam) were contained within an extent of approximately 53 m width.

Fluids of different viscosity were used, and differences in treatment fluid viscosity and pump rate between stages had varying effects on the generated fracture geometry. The average fracture half-length for stages that pumped water is approximately 65 m. Most of the fracture geometry of the RH050F was generated during the water portion of the treatments, and only a limited amount of additional length was generated while the cross-linked gel was pumped.

Most fractures appear to be contained within their target interval, and there does not appear to be a relationship between pump rate and generated fracture height. Fractures typically reached their maximum height early during treatment stages. However it was found that the generated degree of fracture complexity may increase as treatment fluid viscosity decreases.

The moment magnitude of microseismic events for this project was moderate on all stages except the Goonyella Middle seams. The average magnitude in the Goonyella Middle seam for the RH060F (excluding the very high-magnitude events) was approximately -3.07 Mw and for RH050F and RH052F was -3.91 Mw (or less than magnitude 1 on the Richter scale for both wells). Microseismic events of average magnitude were imaged up to 242 m away from the toolstring during treatments on the RH060F and 253 m away from the toolstring during treatments on the RH050F and RH052F.

In summary, it is concluded that the risk of induced seismicity in the Bowen Basin due to hydraulic stimulation is low.

6 GROUNDWATER MODELLING UPDATE

This section presents the results of peer review and modelling undertaken in addition to that presented in the EIS, including modelling of the likely impacts associated with permeable faults, uncertainty analysis, and a conceptual basin-wide water balance model.

6.1 Background

Numerical groundwater modelling was conducted for the EIS (referred to as the Arrow Bowen Basin EIS groundwater model) to predict groundwater drawdown in response to the Project including cumulative drawdown (Ausenco-Norwest, 2012).

The Arrow Bowen Basin EIS groundwater model incorporates an active model domain of approximately 42,000 square kilometres (Ausenco-Norwest, 2012) and was designed:

- For the purpose of predicting groundwater drawdown on a large scale reflective of the regional nature of the Project; and
- With the objective to delineate the areas within aquifers affected by drawdown from Arrow's coal seam gas operations exceeding the threshold criteria set forth by the DEHP.

Model parameterisation included hydraulic conductivity data based on parameter ranges compiled by URS (Appendix E tables of the EIS Appendix L - Groundwater and Geology Technical Report) and based on the available data, literature sources, and estimates, to provide initial bounding values. A final set of parameters was chosen to provide a conservative representation based on steady-state calibration, model verification, production data from the Moranbah Gas Project and data provided by Arrow reservoir engineers (Ausenco-Norwest, 2012).

The Project production was assessed with respect to the pre-1980 steady-state calibrated head distribution, making use of the steady-state head distribution as the initial heads for transient Project production. The groundwater model simulates production beginning in 2017 and ending in 2072 (55 years) followed by modelled recovery over a further 50 years. The total groundwater production (55 years) volume simulated in the model is approximately 274 GL. However it should be noted that since the EIS publication the planned production volume has been reduced to 153 GL over 36 years. Hence the impact assessment which is based on a higher production than now planned, is increased in conservatism.

The detailed groundwater model report is provided in Appendix M of the EIS, and is summarised in Chapter 7 of the EIS Groundwater and Geology Technical Report (Appendix L of the EIS).

Since the submission of the Bowen Gas Project EIS in December 2012, additional small-scale modelling has been undertaken to address specific aspects, such as faults, at a local scale (refer Section 6.4.2 and Appendix C).

6.2 Peer Review of the Arrow Bowen Basin EIS groundwater model

NTEC Environmental Technology (NTEC) was engaged by Arrow to independently review the Arrow Bowen Basin EIS groundwater model in 2012 with respect to the Australian Groundwater Modelling Guidelines (Barnett et al, 2012). Arrow subsequently engaged CDM Smith Australia Pty Ltd (CDM Smith) in 2013 to prepare a report summarising the previous NTEC review stages (CDM Smith acquired NTEC in early 2013).

CDM Smith undertook a peer review of the Arrow Bowen Basin EIS groundwater model providing commentary under a more general framework (CDM Smith, 2013). The results of this review, which considered the Australian Groundwater Modelling Guidelines (Barnett et al, 2012) are summarised below. The report detailing the review is provided in Appendix D.

The review covered a range of documents that included reports in the EIS as follows:

- Arrow Energy Bowen Gas Project EIS, Chapter 14 – Groundwater;
- Arrow Energy Bowen Gas Project EIS, Appendix L – Groundwater and Geology Technical Report (Sections 4.10, 7 and 8); and
- Arrow Energy Bowen Gas Project EIS, Appendix M – Groundwater Model Technical Report (selected parts).

Section 3 of the peer review report provides a checklist of the suitability of the Arrow Bowen Basin EIS groundwater model against the checklist provided in Table 9.1 of the Australian Groundwater Modelling Guidelines. The model was deemed to be fit for the purpose of estimating groundwater impacts created by coal seam gas extraction.

Key findings of the review were that:

- The model was well-designed and executed;
- The conceptualisation of the groundwater flow regime was complete;
- The model employs good software to represent structural geometry, discretisation and parameterisation appropriate for a regional scale model;
- Calibration to steady state groundwater measurements from before 1980 is well-considered and the model achieves a good fit;
- Limited availability of regional groundwater measurements affected by coal seam gas production causes the model to have a confidence level classification of Class 1, whereas otherwise the model contains many features of a higher confidence level;
- Model predictions are appropriately designed, and presented to meet the model and project objectives; and
- The sensitivity analysis undertaken considers the most uncertain parameters and generally indicates that the base case simulation was conservative in predicting the largest likely impacts.

The model conforms to best industry practice, is fit for purpose, and fulfils the appropriate criteria of the Australian Groundwater Modelling Guidelines.

6.3 Arrow Bowen Basin EIS groundwater model – Uncertainty Analysis

Following the completion of initial model predictions for the EIS, an assessment of model parameter predictive error/uncertainty, including NSMC and Pareto front analyses, was conducted in order to better understand the model limitations and to identify data gaps (Ausenco-Norwest, 2013a). These are modelling methods that utilise statistical methods to generate parameter sets to help calibrate a model.

A parameter estimation software package (PEST – Doherty, 2002) was used to undertake the analysis using existing defined parameter zones and reaches in the model. The results classified groups of parameters which could be predicted based on existing observations, and identified areas where future monitoring can better inform ongoing modelling and reduce predictive error. A report was prepared to present the initial assessment findings and results, and is provided in Appendix E.

The initial findings indicated that the model parameters associated with alluvium and Tertiary basin infill in the upper two model layers were associated with the least amount of predictive error/uncertainty (Ausenco-Norwest, 2013a). The parameters identified as having the greatest predictive error/uncertainty were the majority of the vertical hydraulic conductivities and horizontal hydraulic conductivities in the deeper model layers representing Permian formations, and hence these were identified as areas of focus for future data collection.

The results of the NSMC and Pareto front uncertainty analysis indicates that the estimates of groundwater drawdown associated with BGP production are conservative. This indicates the parameter set used for the modelling process is reasonable. For example, the calibrated conductivity values are considered reasonable when compared to estimates derived from field data (refer Section 5.2.1.2 and Appendix C of Appendix L of the EIS) and compared to parameters adopted for the OGIA Surat CMA groundwater model, where similar values are seen for comparable lithologies and comparison indicates that the calibrated anisotropy ranges are appropriate (refer Section 5.2.1.1).

The uncertainty analysis considered other parameter combinations including higher hydraulic conductivity and lower evapotranspiration. The aerial extent of drawdown arising from these simulations was not greater than the BGP base case in the majority of cases. The aerial extent of drawdown in the BGP base case was at the higher end of predictions compared to the majority of the simulations undertaken in the uncertainty analysis (Ausenco-Norwest, 2013a).

It is therefore concluded that the simulation used for the impact assessment represents a plausible, conservative assessment of groundwater drawdown arising from BGP production.

6.4 Arrow Bowen Basin EIS groundwater model Predictions - Bowen Gas Project Only

The model predictions for 50 years post-production indicate that the impacted area will grow by an additional 0 to 4 km approximately, depending on location. Hence the overall prediction is that 5 m drawdown in the deep aquifers will expand no more than 1 to 10 km from the coal seam gas wells after 110 years (i.e. 50 years post-production). The model predicted drawdown contours for the Bowen Gas Project case suggest that shallow aquifers will not be significantly impacted at the cessation of operations, nor 50 years post-operations.

6.5 Fault Permeability Modelling

Since publication of the EIS, additional groundwater model scenarios have been undertaken to simulate the potential for faults to provide preferential pathways for flow between aquifers, and to consider how the effect of such changes to aquifer interconnectivity would influence the potential drawdown impacts caused by the Project.

6.5.1 Fault Representation in the Bowen Basin EIS Groundwater Model

Stress within the Bowen Basin is predominantly compressive and as a result thrust and reverse faulting is predominant. Major thrust faults occur within both the northern and southern domains of the Bowen Basin with throws ranging from 30 m to >500 m (Sliwa, 2011).

The Arrow Bowen Basin EIS groundwater model fault representation simulation was based on a conceptual model of faults as closed, low permeability discontinuities consistent with anticipated faulting expression under a compressive tectonic setting. This conceptual model is further supported by several lines of evidence as described in Section 5.1, and such faulting would be expected to result in compartmentalisation of hydro-stratigraphic units within the system.

Sources of data referenced by Ausenco-Norwest (2012) for the fault modelling incorporated into the Petrel geological model included:

- Petrochina FCCM Model;
- Arrow Work Package Models;
- Bowen Basin Structural Geology map (CSIRO, 2008); and
- Sliwa (2011) and Velseis (2011) Faults – interpretation of 2D seismic data across the basin.

There are 14 major faults sourced from the Petrel geological model that was used to generate the layer files for the Arrow Bowen Basin EIS groundwater model (Ausenco-Norwest, 2012). Section 3.2.2 of Ausenco-Norwest (2012) describes the methodology adopted for representation of the faults in the groundwater model using the MODFLOW Horizontal Flow Barrier (HFB) package. HFBs were assigned a thickness of 1 m, and a hydraulic conductivity of $1x10^{-9}$ m/day. This approach simulates low-permeability 'sealing' faults as effective barriers to groundwater flow in the consolidate layers, by reducing conductance between cells on each side of the fault.

The 2 m drawdown and 5 m drawdown contours are provided for the coal production layers in Ausenco-Norwest (2012) for the end of coal seam gas production, and for 50 years after. The results show little difference between scenarios with sealing faults, when compared with the results from the model scenarios without faults.

6.5.2 TMR Arrow SREIS Groundwater Model - Simulation of Permeable Faults

6.5.2.1 Methodology and Simulations

Major faulting within the model domain has been simulated in the Arrow Bowen Basin EIS groundwater model via the Modflow HFB package, consistent with the adopted conceptualisation (refer Section 6.5.1 above). For completeness a separate study has been undertaken to consider a scenario where faults or other conduits such as weathered dykes behave as pathways to groundwater flow. If these features were sufficiently permeable, it might be assumed that they could influence the movement of groundwater in response to coal seam gas production.

These additional model simulations, conducted since the submission of the EIS, have been undertaken to determine the model sensitivity to permeable faults using Telescopic Mesh Refinement (TMR) to create a more refined model within the subregion of the Arrow Bowen Basin EIS groundwater model (Appendix C). Figure 2-1 in Appendix C identifies the area within which the TMR model has been exported (referred to herein as the TMR groundwater model). The aim of the study was to test two hypotheses:

- Hypothesis 1 - Closed faults or conduits act as barriers to groundwater flow along and across faults near a coal seam gas well.

- Hypothesis 2 - Coal seam gas production from a well in close proximity to an open fault or conduit will increase flow along the fault plane or conduit towards the pumping zone, resulting in aquifer connectivity.

The code employed for the TMR groundwater model remains the same as the Arrow Bowen Basin EIS groundwater model - MODFLOW SURFACT within the Groundwater Vistas user interface. The TMR data was imported into a new model with a 10 km x 10 km domain and refined from 1.5 km grid cells in the regional groundwater model, to 100 m grid cells in order to better represent the faults. Vertical flow along the fault was simulated in cells of 100 m width. This was represented in the model using hydraulic conductivity zones by varying the hydraulic conductivity values as per the scenarios presented in Table 2-1 of Appendix C. A hypothetical conduit for flow feature (possible weathered intrusion such as a dyke) was also simulated in the TMR groundwater model. This was also represented using hydraulic conductivity zones by varying the vertical hydraulic conductivity values as per the scenarios presented in Table 2-1 of Appendix C.

Whilst the placement of wells is yet to be finalised for the Project, the outcomes of this study nevertheless provided a synthetic scenario to provide an assessment of the significance of flow along permeable features in the model.

Fault zone modelling conclusions

The results of the study were found to be in support of Hypothesis 1 – that faults or conduits will act as barriers to groundwater flow along and across faults near a coal seam gas production well. This was supported by the following key findings:

- Drawdown impacts are constrained to the target aquifer and do not propagate into the overlying or underlying aquifers.
- Flow direction on each side of the closed fault suggests compartmentalisation of the groundwater, due to the fault acting as a barrier to groundwater flow.
- Groundwater flux for the modelled fault is low, ranging from ~0.01 to 0.015 m3/day, in comparison to modelled well production rates of 57 m3/day.

An assessment of the opposite scenario where faults or other conduits behave as pathways to groundwater flow showed that:

- Drawdown and flow direction on each side of the fault indicated that the fault can act as a preferential vertical pathway for flow, however groundwater flux for the fault remains low, ranging from 0.09 to 0.05 m3/day.

This result partially supports Hypothesis 2. However the study showed that the fault only played a minor role in the propagation of drawdown impacts, which remain low as demonstrated by the small change in total flux along the fault zone between a production case and no-production case of only 0.003 m^3/day.

Based on the findings, the study concluded that:

- Faults in the Bowen Basin behave as barriers to groundwater flow along and across fault planes near coal seam gas wells.
- In the event that a fault zone or weathered dyke represents an existing preferential pathway for flow, the fault or dyke will only play a minor role in propagation of drawdown impacts across formations.

6.5.3 Conceptual Water Balance Modelling

A conceptual water balance model is presented for the Bowen Basin to quantify major inflows and outflows of the regional groundwater system for the 36 years of water production for the Project, based on Arrow's updates to the project description (refer to Section 2).

The conceptual water balance model deals with bulk averaged volumes and enables gross water flows and potential impacts to be understood in a regional context.

The area included in the conceptual water balance model was based on the Arrow Bowen Basin EIS groundwater model and comprises the active model domain (Figure 7-1 of Appendix M of the EIS). The area of the active model domain is 44,129 km^2 in size and includes the outer geological and hydrogeological boundary of the Northern Bowen Basin.

6.5.4 Conceptual Water Balance Model Parameters

Data inputs for the conceptual water balance model are derived from the Arrow Bowen Basin EIS groundwater model (Ausenco-Norwest, 2012) and from other sources.

The following components have been incorporated into the conceptual water balance model and are discussed in the sections below:

- Gross recharge;
- Evapotranspiration;
- River baseflow;
- Groundwater extraction (Bowen Gas Project and Moranbah Gas Project);
- Groundwater extraction (other groundwater users); and
- Changes in groundwater storage.

6.5.5 Inflows - Recharge

Rainfall varies spatially across the modelled area and is interpreted from rainfall measurement stations at discrete locations. In addition, rainfall is subject to seasonal variation, with increased rainfall occurring in the summer months (Appendix L of the EIS). Recharge to groundwater occurs through the deep percolation of infiltrated rainwater, and actual infiltration and hence recharge rates are dependent on many factors including surficial geology, vegetation and slope.

Because recharge over a large model region cannot be measured directly, it is often established through the model calibration process.

The contribution of irrigation recharge to total recharge has not been quantified or included in this conceptual water balance model, which assumes the majority of irrigation water is utilised by crops and does not infiltrate to underlying aquifers. Water extracted for irrigation purposes is accounted for as an outflow from the conceptual water balance model.

Gross recharge adopted for the conceptual water balance model was based on the Arrow Bowen Basin EIS groundwater model base case transient summary mass balance (Ausenco-Norwest, 2012). The average recharge inflow rate was 453,752 m^3/day (Ausenco-Norwest, 2012). The volume of gross recharge for the 36 years of the project life is approximately 5,962 GL or 165.6 GL/yr.

6.5.5.1 Evapotranspiration

Evapotranspiration data sourced from the Bureau of Meteorology was incorporated into the numerical groundwater model using the Modflow EVT package. Evapotranspiration rates were calculated for model cells, resulting in values ranging from 0.0025 to 0.0033 m/day (Ausenco-Norwest, 2012). Based on this, the average evapotranspiration rate derived from the numerical groundwater model was 409,651 m^3/day. For the 36 years modelled by the conceptual water balance, the volume of water lost from the system to evapotranspiration is approximately 5,382.8 GL or 149.5 GL/yr.

6.5.5.2 Rivers

Surface water studies have indicated a number of baseflow stream reaches in the region, including reaches of the Mackenzie River, Murray Creek, Funnel Creek and Connors River. The numerical groundwater model did not identify any perennial losing river reaches in the model domain, however areas of river alluvium in ephemeral river reaches were assigned a higher rate of recharge to account for the potential for losing rivers to provide recharge (Appendix L of the EIS).

The Arrow Bowen Basin EIS groundwater model incorporated the MODFLOW Rivers package to account for baseflow to the Bowen River and Isaac Connors River system, based on SKM (2009) and the Australian Hydrological Geospatial Fabric (AGHF) Network Streams (BOM).

Accordingly, in the Arrow Bowen Basin EIS groundwater model, river inputs are partly accounted for as recharge, and partly through the MODFLOW River boundary package.

6.5.5.3 Groundwater Extraction

<u>Non-Coal Seam Gas Groundwater Extraction</u>

Groundwater in the region is extracted for non-coal seam gas uses, such as irrigation, stock watering, domestic/town supply, commercial, industrial and mining use (Appendix L of the EIS). Groundwater extracted by those industries incorporated into the model is represented in the conceptual water balance model outflows. The mining use component is likely to predominantly comprise groundwater extracted from bores, and dewatering of groundwater inflow to pits may not be included.

Data from DNRMs Water Management System Database (formerly the Water Entitlements Registration Database (WERD)) was incorporated into the numerical groundwater model, with an annual volume of 13 GL of groundwater assumed to be extracted. For the project life this totals 468 GL over 36 years. The conceptual water balance model assumes that all entitlements were active and in full use for the entire model simulation. It is noted that the actual amount extracted may be lower than the allocation, and allocations are likely to vary over the modelling period (Ausenco-Norwest, 2012).

<u>Coal Seam Gas Groundwater Extraction</u>

Groundwater extraction comprising co-produced water from coal seam gas extraction is represented as outflow from the conceptual water balance model.

The estimated extraction volume of water for the Project was calculated to be 274 GL (or an average of 18.6 ML/day) over a 40 year project life (Chapter 4 of the EIS). This figure was later revised in the updated project description (Section 2) and the volume estimate was reduced to 153 GL over a 36 year project life. Based on the revised project description water will be extracted over 36 years, equivalent to 4.25 GL/yr.

The Moranbah Gas Project has an estimated extraction volume of 11.4 GL over a 37 year project life (2012 – 2049) (Ausenco-Norwest, 2012). An output of 0.31 GL/yr has been adopted for the conceptual water balance model, equating to 11.16 GL over the 36 year water balance period.

6.5.6 Conceptual Water Balance Model Results

Values for model inflows based on average annual rates are summarised in Table 6.1 and presented in Chart 6.1. The results of the conceptual water balance model should be considered an approximation only, but indicative of gross processes within the 44,129 km^2 model domain.

Table 6.1: Average Annual Water Balance Model Outputs

Input (GL/yr)		**Output (GL/yr)**	
Recharge (including focussed recharge from losing streams)	165.62	Evapotranspiration	149.52
		River baseflow to gaining streams	14.43
		Bowen Gas Project co-produced water	4.25
		Moranbah Gas Project co-produced water	0.31
		Groundwater extraction allocations (Water Management System Database Production)	13
TOTAL	**165.62 GL/yr**	**TOTAL**	**181.51 GL/yr**

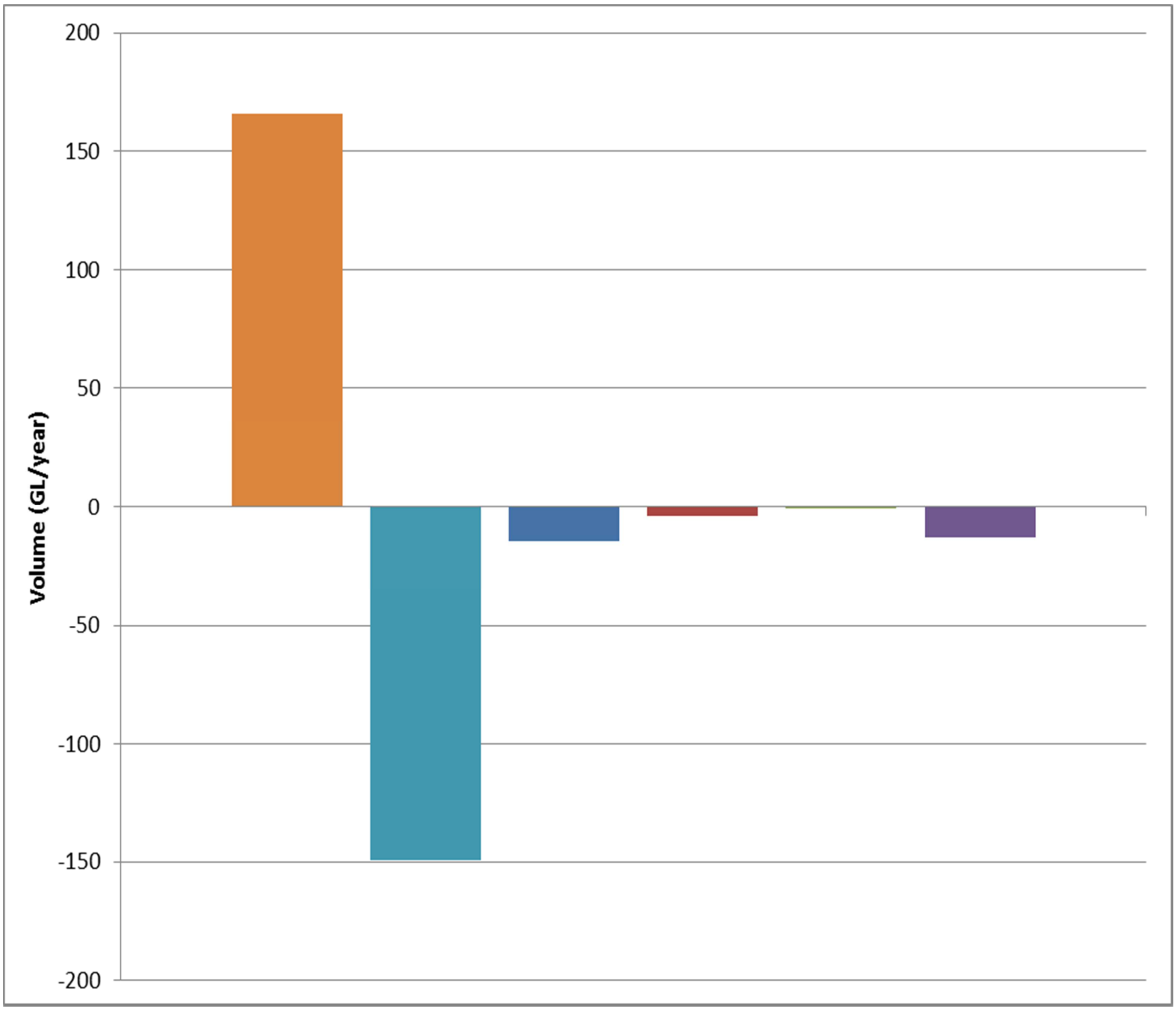
The conceptual water balance notional deficit is estimated as:

Inputs (165.62 GL/yr) – **Outputs** (181.51 GL/yr) = **Deficit** (-15.89 GL/yr)

The notional deficit is interpreted as a general decline in storage. However it is considered that this decline will be partly offset by changes to throughflow from adjacent terrains (if such occurs) or by enhanced recharge.

Enhanced recharge can occur in a basin setting due to the increased hydraulic gradients that result from groundwater extraction. An undeveloped groundwater basin exists in a state of approximate equilibrium that balances groundwater recharge and discharge processes, and the flows between formations are in steady-state. Groundwater development necessarily alters basin equilibrium, and recharge boundary conditions are changed. This process can lead to increased groundwater recharge rates because of the increased hydraulic gradients resulting from drawdown. However these effects are not accounted for in groundwater models, and cannot be represented in the conceptual water balance model.

Chart 6.1: Annual Groundwater Balance



Legend:

7 ENVIRONMENTAL VALUES

This section provides a review of the groundwater environmental values of the Project area and their characteristics. As presented in the EPP Water, the groundwater environmental values to be protected in the study area include:

- Biological integrity of aquatic ecosystems;
- Consumptive or productive uses (drinking water, aquaculture, agriculture and industrial purposes);
- Recreational (primary, secondary and visual) or aesthetic use; and
- Cultural and spiritual purposes, which includes aesthetic, historical, scientific, social or other significance to the present generation or past or future generations.

There are broadly similar geological and hydrological characteristics for each aquifer system, and the environmental values to be protected have been categorised under the systems defined below.

An assessment of the environmental values relevant to the Project are summarised in Table 7.1. The environmental values are based on the discussion provided in Section 5 of Appendix L of the EIS and reflect the following relevant updates to the understanding of the existing environment for each groundwater system.

An initial outcome of the review of the environmental values resulted in a minor refinement to the groundwater systems. In the EIS, the target coal seams of the Blackwater Group and the underlying aquifers of the Back Creek Group were combined into the coal seam gas groundwater system. To separate direct impacts on the target coal seams from indirect impacts to the underlying aquifers, the Back Creek Group has been separated into a discrete deep groundwater system.

7.1 Shallow Groundwater System

The shallow groundwater system incorporates unconfined or watertable aquifers of Quaternary alluvium (river and floodplain), Tertiary basalts and Tertiary sediments (including Suttor and Duaringa Formations).

Biological Values

Riverine wetlands, palustrine wetlands, and riparian vegetation potentially reliant on groundwater from the shallow groundwater system exist within the Project area. These ecosystems are considered to be slightly to moderately disturbed due to anthropogenic processes caused by grazing, cropping, mining and urbanisation.

Springs associated with Cainozoic gravels and Tertiary sandstone are present to the south of Blackwater. The springs are classified as GAB recharge springs, and source water from local flow systems. The springs have high ecological importance.

The Homevale National Park, which is present in the north east of the Project area where Tertiary basalt outcrop is considered to represent an area of pristine biological integrity.

Lake Elphinstone may be supported by the shallow alluvial groundwater system. The lake bed is described as consisting of unconsolidated Quaternary alluvial fan and lacustrine sediments, is the largest natural freshwater body in Central Queensland and provides drought refuge and likely breeding sites for a range of fauna (Environment Australia, 2001).

Consumptive and Productive Use Values

Groundwater salinity varies spatially. Lenses of fresher groundwater (low salinity) exist where sand and gravel dominate the alluvium, and these areas have a wide range of productive and consumptive uses however are considered to be limited in spatial extent. This occurs primarily to the east of the Project area associated with Nebo, Bee and Cooper Rivers. More common is moderately saline groundwater that is suitable for stock watering, mining and industrial purposes.

Anthropomorphic Values

Three of the four sites listed as being wells of Indigenous cultural significance identified in the Project area are assumed to be associated with the shallow groundwater system based on outcrop geology mapping. In the absence of additional information on these features the outcropping geological formation present at their respective locations is interpreted to be the source of any groundwater supply to these features. At three of these locations, the outcropping geology includes river alluvials and colluvium, and therefore anthropomorphic values of the shallow groundwater system are considered to be present in isolated areas.

7.2 Intermediate Groundwater System

The intermediate groundwater system represents typically confined aquifers located above the coal seam gas formations. This includes the Triassic Clematis Sandstone and Rewan Formation. It is noted that whilst the Rewan Formation is considered to be a regional aquitard, there is the potential for groundwater use from the Rewan Formation, particularly where it is highly weathered at outcrop or shallow subcrop, therefore it has been defined to have environmental value. Where the formations within the groundwater system outcrop or shallow subcrop, they may represent the watertable aquifer.

Biological Values

Springs associated with outcropping Clematis Sandstone and Rewan Formation are present to the south of Blackwater. The springs are classified as GAB recharge springs, and source water from local flow systems. The springs have high ecological importance.

Where present in the north of the Project area the aquifers of the intermediate groundwater system are generally considered to be moderately disturbed due to anthropogenic processes caused by agriculture and grazing. Where present in the south they are generally considered to be near pristine or slightly disturbed due to conservation as a national park.

Lake Elphinstone rests on outcropping Rewan Formation. While the lake bed itself consists of Quaternary alluvials (as identified above) and therefore the shallow groundwater system is identified as a potential groundwater supply to the lake, it may also be supported by the intermediate groundwater system. Lake Elphinstone also represents an area of high ecological value for the intermediate groundwater system.

Consumptive and Productive Use Values

There is limited information available on the Clematis Sandstone in the Project area however based on available water quality data for the Clematis Sandstone across the Bowen Basin it is expected that where present, it has the potential to have consumptive and productive value.

Based on available water quality data, the Rewan Formation also has productive value however the spatial extent of the Rewan Formation being utilised for productive purposes will be limited due to the unit typically acting as a regional aquitard.

Anthropomorphic Values

No known sites within study area.

7.3 Coal Seam Groundwater System

The coal seam groundwater system includes the RCM, FCCM and MCM within the Permian Blackwater Group.

Biological Values

There is the potential for some interaction with GDEs where the formations outcrop and form the watertable aquifer, and some pockets of fresher groundwater may occur in the outcrop or shallow subcrop areas where direct rainfall recharge occurs.

Consumptive and Productive Use Values

Limited yields of poor quality water (typically brackish, with average salinity of 5,300 mg/L TDS) result in limited potential for productive and consumptive uses. There is the potential for small scale primary industry use in some areas.

Anthropomorphic Values

A single well with Indigenous cultural significance in the north east of the Project area has been identified (Appendix W of the EIS). It is assumed to be associated with the outcrop geology which correlates to the Fair Hill Formation / FCCM. Therefore anthropomorphic values of the coal seam groundwater system are considered to be present in isolated areas.

7.4 Deep Groundwater System

The deep groundwater system includes the Permian Back Creek Group, which acts as the hydraulic basement below the coal seam groundwater system.

Biological Values

The Back Creek Group outcrop extensively in the west of the study area and there is the potential for interaction with GDEs where the watertable is sufficiently shallow. Some potential for GDEs also exist in the vicinity of Homevale National Park and Conservation Park.

Consumptive and Productive Use Values

Limited yields of typically poorer quality water (average salinity of 3,200 mg/L) result in limited potential for productive and consumptive uses however some areas of lower salinity may provide for small scale primary industry use.

Anthropomorphic Values

No known sites within study area.

Table 7.1: Summary of Groundwater Environmental Values

Groundwater System / Aquifer	Environmental Values										
	Biological areas[1]				Suitability for consumptive and productive uses						Anthropomorphic
	Ecological Importance[2]	Groundwater supports biological integrity of pristine biological systems	Groundwater supports biological integrity of slightly to moderately disturbed biological systems	Groundwater can support biological integrity of slightly to highly disturbed biological systems	Domestic & Town Supply[3]	Irrigation[4]	Stock Watering[5]	Mining	Other (amenities, aquaculture, education, roadwork, and testing)[5]	Industrial[6]	Cultural & Spiritual Values of the Water
Shallow Groundwater System (unconfined or watertable aquifers)											
Quaternary Alluvium	High	Not expected	Some areas	Some areas	Some areas	Some areas	Some areas	Some areas	Some areas	Some areas	Isolated areas
Tertiary Basalt	Moderate to high	Isolated areas	Isolated areas	Some areas	Some areas	Some areas	Some areas	Some areas	Some areas	Some areas	Not identified in Project area
Tertiary sediments	High	Not expected	Isolated areas	Some areas	Not expected	Isolated areas	Isolated areas	Isolated areas	Some areas	Some areas	Not identified in Project area
Intermediate Groundwater System (typically confined aquifers located above coal seam gas formations)											
Clematis Sandstone	High	Isolated areas	Some areas	Some areas	Some areas	Some areas	Some areas	Some areas	Some areas	Some areas	Not identified in Project area
Rewan Formation	High	Isolated areas	Isolated areas	Isolated areas	Not expected	Isolated areas	Some areas	Some areas	Some areas	Some areas	Not identified in Project area

Table 7.1: Summary of Groundwater Environmental Values (cont'd)

Groundwater System / Aquifer	Environmental Values											
	Biological areas[1]				Suitability for consumptive and productive uses						Anthropomorphic
	Ecological Importance[2]	Groundwater supports biological integrity of pristine biological systems	Groundwater supports biological integrity of slightly to moderately disturbed biological systems	Groundwater can support biological integrity of slightly to highly disturbed biological systems	Domestic & Town Supply[3]	Irrigation[4]	Stock Watering[5]	Mining	Other (amenities, aquaculture, education, roadwork, and testing)[5]	Industrial[6]	Cultural & Spiritual Values of the Water
Coal Seam Groundwater System											
RCM, FCCM and MCM	Low to moderate	Not expected	Some areas	Some areas	Not expected	Isolated areas	Some areas	Some areas	Some areas	Some areas	Isolated areas.
Deep Groundwater System (Back Creek Group)											
Back Creek Group	Low to moderate	Isolated areas	Some areas	Some areas	Not expected	Isolated areas	Some areas	Some areas	Some areas	Some areas	Not identified in Project area

1. The biological environmental values of water to be protected under the EPP Water include:

- For high ecological value waters –The biological integrity of an aquatic ecosystem that is effectively unmodified or highly valued;
- 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;
- For highly disturbed waters – The biological integrity of an aquatic ecosystem that is measurably degraded and of lower ecological value than waters mentioned above; and
- Spring complexes are considered under biological values.

2. 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

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

3. Australian Drinking Water Guidelines 2004 (NHMRC and NRMMC 2004).
4. ANZECC 2000 - Australian Water Quality Guidelines for Irrigation Water Quality.
5. ANZECC 2000 - Australian Water Quality Guidelines for Fresh and Marine Waters – Guidelines for Livestock Watering.
6. Groundwater quality criteria are specific to application.

8 POTENTIAL GROUNDWATER IMPACTS

The Project has the potential to impact groundwater systems as a result of project activities carried out through the development, operation and decommissioning phases. As presented in the EIS, potential groundwater related impacts may fall within the following categories:

- Direct impacts caused by coal seam depressurisation;
- Indirect impacts caused by coal seam depressurisation;
- Impacts caused by field and infrastructure development, operation and decommissioning; and
- Cumulative impacts caused by this and other projects requiring the dewatering and depressurisation of the Permian coal measures.

This section provides a review of the potential impacts to the environmental values of groundwater systems identified in the EIS and identifies any new potential impacts identified during the course of the SREIS assessment, or impacts that are no longer relevant.

Assessment of the impact magnitude is also provided below and proposed mitigation and management measures are presented in Section 9.3.

8.1 Impact Magnitude Assessment Assumptions

An assessment of the magnitude of impact resulting from project activities was made in the EIS based on the predictions made by the Arrow Bowen Basin EIS Groundwater Model described in Section 6. The modelling predictions remain unchanged from the EIS, and as presented in Section 6 the modelling is considered to conservatively represent the potential drawdown resulting from the depressurisation of the RCM and MCM. In addition it is noted that the modelling takes into account the areas where the Rewan Formation is present or absent, therefore the influence of this formation on the propagation of drawdown impacts to overlying aquifers is represented in the modelling outputs.

The potential impacts of the BGP are assessed on their own for the base case. The sensitivity of model prediction to the potential sealing properties of the faults was evaluated for the base case with discrete fault representation. A cumulative impacts case was also simulated which included production from the MGP and the Water Management System Database bores in addition to the BGP. The impacts of scenario results for the BGP only are presented relative to steady state conditions, while the cumulative case results are relative to the modelled head distribution at the end of 2011 resulting from the initial MGP and Water Management System Database production prior to BGP production.

The assessment of impact magnitude for this supplementary groundwater assessment uses the results of groundwater modelling for the BGP only base case scenario at the end of coal seam gas production as well as 50 years after the cessation of coal seam gas production. The assessment of impact magnitude takes into consideration the predicted severity, duration and geographical extent of the potential impact.

As described in Section 3, the Water Act (2000) sets out trigger thresholds for the classification of immediately affected areas, long-term affected areas and potentially impacted springs. These thresholds have been used in the assessment of impact magnitude to define “acceptable” drawdown limits for relevant environmental values.

Where groundwater drawdown in an aquifer is predicted to exceed the bore trigger threshold (2 m for unconsolidated aquifers and 5 m for consolidated aquifers) existing groundwater users may have productive and/or consumptive uses impaired, where a groundwater bore can no longer provide a reasonable quantity or quality of water for its authorised purpose.

For the purpose of assessment of potential impact magnitude on springs, other GDEs and cultural and spiritual sites the spring trigger threshold of 0.2 m predicted groundwater drawdown was adopted with an additional 10 km buffer zone applied beyond the extent of the predicted 0.2 m drawdown. This approach has been adopted to provide additional conservatism in the modelling predictions and is consistent with the approach adopted by OGIA in the Surat CMA UWIR for the assessment of potentially affected springs (QWC, 2012).

Consistent with the approach adopted for the assessment of potential impacts in the EIS, modelled drawdown results for Layer 3 have been adopted for the assessment of potential impacts to aquifers in the shallow groundwater system. This will conservatively assess the propagation of drawdown impacts from the target coal seams, through the overlying intermediate groundwater system to the aquifers in the shallow groundwater system.

8.2 Potential Groundwater-related Impacts and Pre-mitigation Impact Magnitude

Depressurisation of the RCM and MCM required for coal seam gas extraction may result in direct and indirect impacts:

- Direct impacts will result in potentiometric surface drawdown in the target coal seams.
- Indirect impacts to aquifers above and below the target seams from depressurisation of the coal seam groundwater system.

Table 8.1 identifies the potential impacts that may arise from depressurisation of the RCM and MCM.

Field development activities that have the potential to impact on environmental values include both wellfield and infrastructure development. The potential impacts associated with field development and operations are presented in Table 8.2 and potential impacts resulting from the management of coal seam gas water are presented in Table 8.3.

The magnitude of the potential impact prior to the implementation of mitigation measures is also provided in these tables.

Table 8.1: Potential Impacts from Depressurisation of the RCM and MCM

Activity / impact	Potentially affected groundwater system	Change to potential impact since EIS	Pre-mitigation Impact Magnitude
Direct Impacts			
Potentiometric surface drawdown in the coal measures resulting in reduced supply to existing or future groundwater users.	Coal Seam groundwater system	No change.	Modelling predicts >5 m drawdown at the end of coal seam gas production in the target formations covering extensive parts of the Project area. In some regions drawdown >5 m extends beyond the Project area, primarily associated with the Leichhardt and Vermont seams. Limited recovery is observed in the 50 years after the cessation of coal seam gas production. Impact magnitude is therefore considered to remain **high** prior to the implementation of mitigation measures.
Potentiometric surface drawdown in the coal measures resulting in reduced groundwater availability to GDEs.		New potential impact identified based on additional information on GDEs.	A single spring vent (site name North Escarp, refer Figure 8.1) is located within the 10 km buffer beyond the 0.2 m drawdown contour for the Leichhardt seam therefore, under the Water Act, is classified as being potentially affected by the depressurisation of the RCM and MCM. However, as this is a recharge spring the source aquifer is considered to be associated with the outcrop geology (Cainozoic sandy gravel). No drawdown impact is predicted at this location in the aquifers overlying the Leichardt seam therefore this spring is not considered to be directly impacted by depressurisation of the RCM and MCM. The coal measures outcrop within the extent of 0.2 m predicted drawdown and 10 km buffer zone, and in some limited areas this coincides with mapped potential GDEs. In these areas the coal measures form the watertable aquifer and may support GDEs where groundwater is sufficiently shallow. Based on available water level information groundwater in the coal measures, where they outcrop, is typically >10 m below ground, and is generally considered to be beyond the rooting depth of vegetation. There may however be some isolated areas, in particular where surface drainage channels coincide with outcropping coal measures, that groundwater may support GDEs reliant on the subsurface presence or surface expression of groundwater. In addition the coal measures are not expected to support large areas of GDEs due to poor quality groundwater and limited yield.

Table 8.1: Potential Impacts from Depressurisation of the RCM and MCM (cont'd)

Activity / impact	Potentially affected groundwater system	Change to potential impact since EIS	Pre-mitigation Impact Magnitude
Direct Impacts (cont'd)			
Potentiometric surface drawdown in the coal measures resulting in reduced groundwater availability to GDEs. (cont'd)			The extent of potential impact extends beyond the Project area, and limited or no recovery is observed in the 50 year period after cessation of coal seam gas production. Impact magnitude is therefore considered to be **moderate** prior to the implementation of mitigation measures.
Potentiometric surface drawdown in the coal measures resulting in reduced supply to sites of cultural/spiritual value.		Additional information on cultural/spiritual sites available for SREIS impact assessment.	A site of cultural significance associated with the FCCM is located within the 10 km buffer zone of the 0.2 m drawdown contour for the FCCM (groundwater model Layers 8, 9 and 10 in the Arrow Bowen Basin EIS groundwater model, refer Figure 8.1). Potential impact remains 50 years after cessation of gas production. Impact magnitude is therefore considered to be **moderate** prior to the implementation of mitigation measures.
Indirect Impacts			
Groundwater flux between adjacent aquifers above and below the coal measures causing groundwater quality impacts.	Shallow, Intermediate and Deep groundwater systems.	No change.	Depressurisation of the target coal seams will reduce flux to aquifers above the target formations and increase flux into the coal measures from underlying aquifers. This will reduce the potential for contamination of overlying or underlying aquifers from poorer quality water of the coal measures. Therefore impact magnitude will be **very low** as any inter-aquifer flows caused by depressurisation of the coal measures, which contain poorer quality water than surrounding aquifers, will not involve flow of poor quality water into higher quality aquifers.

Table 8.1: Potential Impacts from Depressurisation of the RCM and MCM (cont'd)

Activity / impact	Potentially affected groundwater system	Change to potential impact since EIS	Pre-mitigation Impact Magnitude
Indirect Impacts (cont'd)			
Potentiometric surface drawdown in adjacent aquifers causing reduced supply to existing or future groundwater users		No change.	Modelling predicts >2 m drawdown in isolated areas for the shallow groundwater system, including isolated instances outside of the Project area (refer Figure 8.2a). This drawdown coincides with some areas of alluvial outcrop and represents areas of potential impairment for existing groundwater users. Figure 8.2a shows where predicted shallow groundwater system drawdown >2 m coincides with existing registered groundwater bores screening the shallow groundwater system. This indicates the potential for a limited number of existing, Department of Environment and Resource Management (DERM) registered bores to be impacted (confined to the north of the Project area). The alluvial aquifer system is dynamic with several recharge mechanisms. It is expected to recover over time when groundwater extraction associated with coal seam gas activities is removed, due to the close connection between surface recharge processes and the shallow groundwater system. The potential for hydraulic stimulation activities to result in fractures that propagate to overlying aquifers, resulting in induced flow and reduced availability of groundwater to existing users is considered unlikely. As discussed in Section 5.7.2, fracture mapping completed indicates most fractures resulting from hydraulic stimulation were contained within their target interval, and the maximum vertical extent measured was 32 m. Hence, vertical hydraulic conductivity in the overlying and underlying formations is not likely to be affected by the hydraulic stimulation. The duration and extent of impact is minor, however impact severity exceeds the bore trigger threshold in isolated instances. Therefore impact magnitude for the shallow groundwater system is considered to be **moderate** prior to the implementation of mitigation measures. Modelling predicts >5 m drawdown in isolated areas in aquifers associated with the intermediate groundwater system (refer Figure 8.2b). Modelling predicts that 50 years after the cessation of gas production the extent of drawdown in the intermediate groundwater system will have increased in comparison to the drawdown extent at the cessation of gas production. While this indicates continued propagation of depressurisation impacts from the coal seam groundwater system into the overlying intermediate groundwater system, the areas of drawdown in excess of 5 m remains in isolated areas.

Table 8.1: Potential Impacts from Depressurisation of the RCM and MCM (cont'd)

Activity / impact	Potentially affected groundwater system	Change to potential impact since EIS	Pre-mitigation Impact Magnitude
Indirect Impacts (cont'd)			
Potentiometric surface drawdown in adjacent aquifers causing reduced supply to existing or future groundwater users (cont'd)			Figure 8.2b shows that there are no existing DERM registered bores screening the intermediate groundwater system in the area of predicted impact (>5 m). Therefore impact magnitude for the intermediate groundwater system is considered to be **very low** prior to the implementation of mitigation measures. No drawdown >5 m is predicted in the deep groundwater system as a result of the depressurisation of the RCM and MCM therefore impact magnitude is considered to be **very low**.
Potentiometric surface drawdown in adjacent aquifers causing reduced groundwater availability for GDEs		Additional information on GDEs available for SREIS impact assessment.	Springs located in proximity to the Project area (south of ATP1025 near Blackwater, refer Figure 8.1) have assumed source aquifers from the shallow and intermediate groundwater systems. The majority (17 out of 19) are associated with the aquifers that form the intermediate groundwater system. Modelling predicts the springs are located beyond the 10 km buffer zone of the 0.2 m drawdown for shallow and intermediate aquifers (Arrow Bowen Basin EIS groundwater model Layer 3 and 4 respectively, refer Figure 8.1). All springs either overlie areas where the Rewan Formation is present, or are situated where the Rewan Formation outcrops. The Rewan Formation is considered to be a regional aquitard and will act to limit the potential for the effects of RCM and MCM depressurisation to propagate to the spring source aquifer. Lake Elphinstone is a MNES potentially supported by both the shallow and intermediate groundwater systems. The Lake is situated immediately outside the Project area, and is within the 10 km buffer zone of the 0.2 m drawdown contour for Layer 3 of the Arrow Bowen Basin EIS groundwater model (refer Figure 8.1), which also generally reflects the drawdown predicted in Layer 4. Modelling predicts some reduction in drawdown 50 years after the cessation of gas production. The Bowen River: Birralee – Pelican Creek reach is a MNES (nationally important wetland) associated with the shallow groundwater system. It is located approximately 44 km north of the Project area and is not predicted to be impacted by any groundwater drawdown associated with Project activities. Modelling predicts all other known spring fed watercourses within the study area, as described in Section 5.3.2, are

Table 8.1: Potential Impacts from Depressurisation of the RCM and MCM (cont'd)

Activity / impact	Potentially affected groundwater system	Change to potential impact since EIS	Pre-mitigation Impact Magnitude
Indirect Impacts (cont'd)			
Potentiometric surface drawdown in adjacent aquifers causing reduced groundwater availability for GDEs (cont'd)			located beyond the 10 km buffer zone of drawdown for all aquifers therefore are not predicted to be impacted. GDEs potentially reliant on the surface expression and subsurface presence of groundwater are mapped as being present throughout the study area, including areas of predicted drawdown in the shallow, intermediate and deep groundwater systems. The shallow groundwater system forms the watertable aquifer across most of the study area and may support GDEs in some areas. The extent of where this may occur is considered to be restricted to watercourse and drainage lines where the watertable is sufficiently shallow. Available water level information indicates that depth to groundwater is typically beyond the rooting depth of plants, however along the mid-reaches of the Isaac River there may be some potential for groundwater interaction. Appendix L of the EIS indicates that the main channels of the Isaac and Mackenzie Rivers are incised around 3-5 m below the floodplain, and tributaries to the Mackenzie, Suttor and Bowen Rivers have channels incised 3 to 5 m. This reduces the potential for groundwater baseflow to occur as depth to groundwater is typically >10 m. Further south there are fewer mapped potential GDEs, and depth to groundwater remains in the order of 10-20 m below ground which is typically beyond the rooting depth of plants. There is limited groundwater level information available to inform the assessment of the potential for the intermediate groundwater system to support GDEs potentially reliant on the surface expression or subsurface presence of groundwater. In the absence of this it is assumed that, where it outcrops and potential GDEs are mapped, the intermediate groundwater system may support GDEs in some areas. In the north of the study area mapped potential GDEs coincide with areas of intermediate groundwater system outcrop, primarily along watercourses, and some of these fall within the 0.2 m drawdown contour or the 10 km buffer zone beyond this. In the south of the study area, where there is impact predicted in the intermediate groundwater system either the intermediate groundwater system does not outcrop or there are no mapped potential GDEs.

Table 8.1: Potential Impacts from Depressurisation of the RCM and MCM (cont'd)

Activity / impact	Potentially affected groundwater system	Change to potential impact since EIS	Pre-mitigation Impact Magnitude
Indirect Impacts (cont'd)			
Potentiometric surface drawdown in adjacent aquifers causing reduced groundwater availability for GDEs (cont'd)			The deep groundwater system outcrops in isolated areas and where this occurs groundwater is expected to be too deep to support GDEs. Based on this information the magnitude of impact prior to the implementation of mitigation measures is classified as follows: • Shallow and intermediate groundwater system impact magnitude is **moderate.** • Deep groundwater system impact magnitude is **very low**.
Potentiometric surface drawdown in adjacent aquifers causing impacts to cultural/spiritual values		Additional information on cultural/spiritual sites available for SREIS impact assessment.	Three sites of cultural significance located within the Project area are associated with the shallow groundwater system. One of the three sites is located within the 10 km buffer of the 0.2 m drawdown contour therefore is considered to be potentially impacted by drawdown related Project activities. Impact severity reduces 50 years after the cessation of gas production however the site is still within the 10 km buffer zone. Impact magnitude for the shallow groundwater system is therefore considered to be **moderate** prior to the implementation of mitigation measures. Impact magnitude for the intermediate and deep groundwater systems is considered to be **very low** due to the absence of known culturally significant sites associated with these systems.
Potentiometric surface drawdown in adjacent aquifers due to leakage through coal seam gas wells (well failure) causing groundwater quality impacts from inter-aquifer flows.		No change.	The potential inter-aquifer well fluxes that would be caused by the failure rate of a small percentage of wells is not hydrologically significant compared to inter-aquifer fluxes through confining layers over large regional areas. Inter-aquifer fluxes that occur locally due to failed wells are expected to decline rapidly, as local pressure equilibrium is approached between the formations in the vicinity of the well.

Table 8.1: Potential Impacts from Depressurisation of the RCM and MCM (cont'd)

Activity / impact	Potentially affected groundwater system	Change to potential impact since EIS	Pre-mitigation Impact Magnitude
Indirect Impacts (cont'd)			
Potentiometric surface drawdown in adjacent aquifers due to leakage through coal seam gas wells (well failure) causing groundwater quality impacts from inter-aquifer flows. (cont'd)			In the longer term as aquifer pressures recover after the cessation of impacting activity, modelling shows that differential pressure is observed to reduce between formations, further reducing the potential for adverse impact. Based on the above, the magnitude of impact is considered to be **low** prior to the implementation of mitigation measures.
Induced flow (leakage) between adjacent aquifers above and below the coal measures causing physical changes to aquifer structure leading to subsidence.	Loss of structural integrity may affect all groundwater systems where significant pressure reduction occurs.	Additional information is available on baseline conditions and the mechanisms for coal seam gas extraction to result in subsidence.	To result in adverse differential movement of rock formations, the subsidence would need to be significant and occur on a localised scale, at differing rates. As subsidence is not expected to be significant (refer Section 5.6 and GA and Habermehl, 2010) and is expected to be widespread, differential movement is not expected. The magnitude of impact of depressurised formations which might cause adverse physical effects due to subsidence is therefore considered to be **very low**. Potential for subsidence impact on surface water values are discussed in the Surface Water and Hydrology technical studies of the SREIS (Appendix F and Appendix G respectively) and associated chapters (Section 8, Surface Water and Section 9, Hydrology and Geomorphology).

Table 8.2: Potential Impacts from Coal Seam Gas Field Development

Activity / impact	Potentially affected groundwater systems	Change to potential impact since EIS	Pre-mitigation Impact Magnitude
Wellfield Development and Sub-surface Impacts			
Production well installation – cross-contamination of aquifers.	Shallow, Intermediate and Coal Seam groundwater systems (Deep groundwater system is excluded based on depth and that this groundwater system will not be intersected by coal seam gas production wells).	No change.	Potential impact is contained within the Project area or localised around each production well. Impact severity is minor when considering regional hydrogeological inter-aquifer fluxes and impact duration is limited to the period of well drilling and installation. If a well is incorrectly installed and allows on-going cross-contamination, impact duration will be for the life of the production well, ceasing when the well is decommissioned. Impact magnitude is therefore considered to be **low** prior to the implementation of mitigation measures.
Production well installation – contamination by drilling process.		No change.	Potential impact is contained within the Project area or localised around each production well. Impact severity is minor when considering regional hydrogeological processes and the materials used by Arrow during drilling of production wells (water and salt-based drilling muds). Impact duration limited to the period of well drilling and installation. Impact magnitude is therefore considered to be **low** prior to the implementation of mitigation measures.
Production well installation – contamination by surface process.		No change.	There is the potential for impact to occur due to surface process associated with drilling activities including drilling fluid storage and the operation of the drilling rig and ancillary equipment. Potential impact is contained within the Project area or localised around each production well. Impact severity is minor due to the materials used by Arrow during installation of production wells (water and salt-based drilling muds) and implementation of standard procedures to reduce the potential for impact and impact duration is limited to the period of well drilling and installation. Impact magnitude is therefore considered to be **low** prior to the implementation of mitigation measures.

Table 8.2: Potential Impacts from Coal Seam Gas Field Development (cont'd)

Activity / impact	Potentially affected groundwater systems	Change to potential impact since EIS	Pre-mitigation Impact Magnitude
Wellfield Development and Sub-surface Impacts (cont'd)			
Hydraulic stimulation – contamination by surface process.	All groundwater systems.	No change.	There is the potential for impact to occur due to surface process associated with hydraulic stimulation activities including fluid storage and the operation of pumping systems and ancillary equipment, and management of flowback water. Potential impact is contained within the Project area and localised around each production well. Impact severity is minor due to the predominantly water based fluids used and the containment systems adopted. Hydraulic stimulation fluids and flowback fluids will be stored in a HDPE lined dam or tank. Bunding will be used to contain fluid leaks and will be installed around equipment where practicable. Impact duration is limited to the period of well drilling and installation. Impact magnitude is therefore considered to be **low** prior to the implementation of mitigation measures.
Hydraulic stimulation – cross-contamination of aquifers.		No change.	The aquitard formations (mudstones and siltstones) of the Rewan Formation, coal measure interburden and the Back Creek Group that predominantly separate the target coal seam from the developed aquifer formations typically behave elastically, and are therefore expected to respond to applied stresses through ductile deformation rather than brittle fracturing. Therefore these confining layers are expected to resist fracture propagation beyond the target coal seam, with any fractures truncating along a low shear strength plane such as the top or bottom of a coal seam. Impact magnitude is considered to be **low** prior to the implementation of mitigation measures.
Hydraulic stimulation - induced seismicity.		No change.	Research on hydraulic stimulation induced seismicity in Australia indicates that induced earthquakes release less energy than naturally occurring earthquakes of similar size (Geoscience Australia, 2013). Field evidence demonstrates that microseismic events due to fracturing are low, and not perceptible at the surface other than with sensitive seismology equipment. Impact magnitude is considered to be **low** prior to the implementation of mitigation measures.

Table 8.2: Potential Impacts from Coal Seam Gas Field Development (cont'd)

Activity / impact	Potentially affected groundwater systems	Change to potential impact since EIS	Pre-mitigation Impact Magnitude
Wellfield Development and Sub-surface Impacts (cont'd)			
Monitoring bore installation – cross-contamination of aquifers.	All groundwater systems. Monitoring wells will potentially intersect all groundwater systems.	No change.	Potential impact is localised around each monitoring bore. Impact severity is minor when considering regional hydrogeological inter-aquifer fluxes and impact duration is limited to the period of bore drilling and installation. If a monitoring bore is incorrectly installed and allows on going cross-contamination, impact duration will be for the life of the monitoring bore, ceasing when the bore is decommissioned. Impact magnitude is therefore considered to be **low** prior to the implementation of mitigation measures.
Monitoring bore installation – contamination by drilling process.		No change.	Potential impact is localised around monitoring well. Impact severity is minor when considering regional hydrogeological processes and the materials used by Arrow during installation of monitoring wells (water and salt-based drilling muds). Impact duration is limited to the period of well drilling and installation. Impact magnitude is therefore considered to be **low** prior to the implementation of mitigation measures.
Monitoring bore installation – contamination by surface process.		No change.	There is the potential for impact to occur due to surface process associated with drilling activities including drilling fluid storage and the operation of the drilling rig. The potential area of impact is localised around monitoring well. Impact severity is minor due to the materials used by Arrow during installation of monitoring wells (water and salt-based drilling muds) and impact duration is limited to the period of well drilling and installation. Impact magnitude is therefore considered to be **low** prior to the implementation of mitigation measures.

Table 8.2: Potential Impacts from Coal Seam Gas Field Development (cont'd)

Activity / impact	Potentially affected groundwater systems	Change to potential impact since EIS	Pre-mitigation Impact Magnitude
Wellfield Development and Sub-surface Impacts (cont'd)			
Installation of other sub-surface infrastructure (e.g. gathering lines and underground storage tanks) – contamination from leaks and spills.	All groundwater systems.	No change.	Potential impact is localised around sub-surface infrastructure. Impact severity is minor due to the methods of fuel and chemical storage, handing and disposal used by Arrow. If a piece of sub-surface infrastructure is incorrectly installed or on-going leaks and spills occur, this would extend over the operational life of the infrastructure, ceasing when the gathering line or tank is decommissioned or removed. Based on the potential area for impact to occur (i.e. area of groundwater system outcrop) impact magnitude is considered to be **moderate** for the shallow groundwater system and **low** for the intermediate, coal seam gas and deep groundwater systems prior to the implementation of mitigation measures.
Surface storage of chemicals, fuels, oils – contamination of groundwater systems.	All groundwater systems. (all groundwater systems outcrop within the Project area)	No change.	Spills or leaks of stored chemicals, fuels and oils may enter the groundwater systems that form the watertable aquifer and migrate to other groundwater systems, impacting water quality, impairing consumptive and productive uses and GDEs. Based on the potential area for impact to occur (i.e. area of groundwater system outcrop) impact magnitude is considered to be **moderate** for the shallow groundwater system and **low** for the intermediate, coal seam gas and deep groundwater systems prior to the implementation of mitigation measures.
Waste generation and storage – contamination of groundwater systems.	All groundwater systems. (all groundwater systems outcrop within the Project area)	No change.	Leakage of stored waste may enter the groundwater systems that form the watertable aquifer and migrate to other groundwater systems, impacting water quality, impairing consumptive and productive uses and GDEs. Based on the potential area for impact to occur (i.e. area of groundwater system outcrop) impact magnitude is considered to be **moderate** for the shallow groundwater system and **low** for the intermediate, coal seam gas and deep groundwater systems prior to the implementation of mitigation measures.

Table 8.2: Potential Impacts from Coal Seam Gas Field Development (cont'd)

Activity / impact	Potentially affected groundwater systems	Change to potential impact since EIS	Pre-mitigation Impact Magnitude
Wellfield Development and Sub-surface Impacts (cont'd)			
Waste water and sanitation (effluent) – contamination of groundwater systems.		No change.	Leakage of effluent may enter the groundwater systems that form the watertable aquifer and migrate to other groundwater systems, impacting water quality, impairing consumptive and productive uses and GDEs. Based on the potential area for impact to occur (i.e. area of groundwater system outcrop) impact magnitude is considered to be **moderate** for the shallow groundwater system and **low** for the intermediate, coal seam gas and deep groundwater systems prior to the implementation of mitigation measures.
Infrastructure Footprint Impacts			
Reduced aquifer recharge due to placement of impervious surface coverings.	All groundwater systems. (all groundwater systems outcrop within the Project area)	No change.	Direct rainfall recharge to the watertable aquifer may be reduced in the areas where impervious surfaces are placed. Under the current project description the total area of Project tenements is 8,000 km^2 and the total footprint of project components (assumed to represent the area of impervious surfaces) is <100 km^2. Taking into consideration the overall area for potential aquifer recharge across the region in comparison to the expected reduction in area due to impervious surface placement the impact magnitude is considered to be **low** in the shallow groundwater system and **very low** for the intermediate, coal seam gas and deep groundwater systems prior to the implementation of mitigation measures.
General impacts associated with installation of FCFs and CGPFs		No change.	Based on the potential area for impact to occur (i.e. area of groundwater system outcrop) impact magnitude is considered to be **moderate** for the shallow groundwater system and **low** for the intermediate, coal seam gas and deep groundwater systems prior to the implementation of mitigation measures.

Table 8.3: Potential Impacts from Coal Seam Gas Water

Activity / impact	Potentially affected groundwater systems	Change to potential impact since EIS	Pre-mitigation Impact Magnitude
Impact caused by seepage of untreated coal seam gas water from storage facilities.	All groundwater systems. (all groundwater systems outcrop within the Project area)	No change.	Seepage of untreated coal seam gas water from storage facilities to the watertable may alter groundwater quality and impair consumptive and productive uses and GDEs. Proposed storage facilities are associated with DA2, DA34 and DA40 (refer Figure 2.1). In these areas, the outcrop geology is either the Rewan Formation (DA34) or Rewan Formation and Blackwater Group (DA2 and DA40). Depending on the placement of the storage facilities within the DAs, the impact may extend beyond the area of activity or project footprint, and may persist beyond the cessation of brine storage. Therefore impact magnitude is considered to be **moderate** in the intermediate and coal seam groundwater systems, and **very low** in the shallow and deep groundwater systems prior to the implementation of mitigation measures.
Altered groundwater flow direction caused by seepage from coal seam gas water storage facilities.		No change.	Seepage from coal seam gas water storage facilities may result in localised groundwater mounding and radial flow. The impact is minor, localised and will experience rapid recovery at the cessation of coal seam gas water storage. Proposed storage facilities are associated with DA2, DA34 and DA40 (refer Figure 2.1). In these areas, the outcrop geology is either the Rewan Formation (DA34) or Rewan Formation and Blackwater Group (DA2 and DA40). Depending on the placement of the storage facilities within the DAs, the impact may extend beyond the area of activity or project footprint, and may persist beyond the cessation of brine storage. Impact magnitude is therefore considered to be **low** in the intermediate and coal seam groundwater systems, and **very low** in the shallow and deep groundwater systems prior to the implementation of mitigation measures.
Impact caused by seepage of brine from storage facilities.		No change.	Brine seepage from storage facilities may alter groundwater quality and impair consumptive and productive uses and GDEs. Proposed storage facilities are associated with DA2, DA34 and DA40 (refer Figure 2.1). In these areas, the outcrop geology is either the Rewan Formation (DA34) or Rewan Formation and Blackwater Group (DA2 and DA40). Depending on the placement of the storage facilities within the DAs, the impact may extend beyond the area of activity or project footprint, and may persist beyond the cessation of brine storage.

Table 8.3: Potential Impacts from Coal Seam Gas Water (cont'd)

Activity / impact	Potentially affected groundwater systems	Change to potential impact since EIS	Pre-mitigation Impact Magnitude
Impact caused by seepage of brine from storage facilities. (cont'd)			Therefore impact magnitude is considered to be **moderate** in the intermediate and coal seam groundwater systems, and **very low** in the shallow and deep groundwater systems prior to the implementation of mitigation measures.
Unplanned discharge of untreated coal seam gas water to the land surface, including from infrastructure for distribution of produced water		No change.	Unplanned discharge of untreated coal seam gas water to ground may enter the watertable aquifer, alter groundwater quality and impair consumptive and productive uses and GDEs. The impact may extend beyond the area of activity or project footprint, and may persist beyond the cessation of production. Impact magnitude is therefore considered to be **moderate** in the shallow and intermediate groundwater systems and **low** in the coal seam and deep groundwater systems prior to the implementation of mitigation measures.
Unplanned discharge of untreated water or brine to the land surface.		No change.	Unplanned discharge of untreated water to ground may enter the watertable aquifer, alter groundwater quality and impair consumptive and productive uses and GDEs. The impact may extend beyond the area of activity or project footprint, and may persist beyond the cessation of production. Impact magnitude is therefore considered to be **moderate** in the shallow and intermediate groundwater systems and **low** in the coal seam and deep groundwater systems prior to the implementation of mitigation measures.

8.3 Cumulative Impacts

Cumulative impacts are the successive, incremental and combined impacts of an activity on society, the economy and the environment. Cumulative impacts are most often raised in the context of multiple resource operations in the same basin or geological province. The groundwater related cumulative impacts in the Bowen Basin have been assessed.

8.3.1 Cumulative Groundwater Impacts Presented in the EIS

The cumulative impact assessment presented in the EIS comprised two parts, firstly, a quantitative assessment of cumulative groundwater drawdown represented in the Arrow Bowen Basin EIS groundwater model, and a qualitative assessment based on literature from existing and operating mines in the project vicinity.

8.3.1.1 Quantitative Assessment

The groundwater impact assessment completed for the EIS considered the results of two modelling scenarios, one including the Project only (identified as the BGP only scenario in the Arrow Bowen Basin EIS groundwater model) and the second incorporating the Project and other identified large scale impacts on Bowen Basin groundwater systems (identified as the cumulative scenario in the Arrow Bowen Basin EIS groundwater model). The cumulative scenario also included water use based on entitlements, as determined by the DNRM Water Management System Database, and production from the MGP. The EIS assumed that these combined impacts in conjunction with the potential impacts from the Project will have cumulative impacts on groundwater systems.

The Water Management System Database entitlement production included all groundwater entitlements being in full continuous use from 2003 to the end of the model simulation in 2122. The actual usage, in fact, may be as little as 20% of annual entitlement (SKM, 2009) and may change due to policy changes and entitlements expiring. The resulting volume of Water Management System Database groundwater production in the model is significant. It totals 108,700 ML between 2000 and end of 2011. Based on the Water Management System Database database, the predictive model has an annual volume of 13,000 ML totalling 715,000 ML between 2017 and 2072. This is 2.6 times more groundwater than projected for the Project for the same period based on the conceptual development plan presented in the EIS. The total simulated groundwater production for the Project (55 years) is approximately 274,000 ML. The MGP adds a relatively small volume to the projected production volume for the Project within the same target coal measures. The historical production from 2003 to 2011 is 3,300 ML of water. The future predictions into 2049 indicate an additional 11,400 ML of groundwater production for a total groundwater production of 14,700 ML over the life of the MGP.

The Arrow Bowen Basin EIS groundwater model prepared for the EIS assumed that groundwater drawdown impacts related to other mines would occur on a local scale (i.e. within 10 km of the mine site). This assumption, coupled with a lack of detailed publically available information meant that groundwater extractions from operating coal mines in the model domain were not incorporated into the cumulative impacts representation.

The prediction for the BGP only scenario indicates that drawdown of >2 m will primarily remain within the boundaries of the Arrow tenements, closely following the spatial distribution of coal seam gas wells, and within the target coal measure formations. However some small areas of drawdown of > 2m are indicated by the model as occurring in the Rewan Formation, which is combined with the interburden of the RCM in the geological model. The areas of drawdown in excess of 2 m are located mainly along the subcrop of the Vermont coal seam of the RCM and where the Rewan Formation is very thin and begins to pinch out. The model predicted drawdown contours for the BGP only scenario suggest that the shallow alluvium/colluvium aquifers will not be significantly impacted at the cessation of operations, or 50 years post-production, and only isolated areas are affected (Figure 7-2 and 7-10 Ausenco-Norwest, 2012).

The model results for the target coal seams show predicted drawdown tightly linked to well placement with only slightly increased areas of drawdown 50 years later. The model results show that the anticipated drawdowns are expected to propagate a limited horizontal distance from the coal seam gas producing areas. This is consistent with the comparatively low horizontal permeability of the target coals. The model predictions for 50 years post-operation (i.e. in 2122) suggest that the impacted area will grow laterally by approximately 0 to 4 km, depending on the location. Hence the overall prediction is that 5 m drawdown in the coal seam gas aquifers will spread no more than 1 to 10 km from the coal seam gas wells after 110 years (i.e. in 2122, 50 years after production ceases).

The cumulative impacts modelling conducted for the EIS indicates that drawdown is significant throughout the model domain including several areas outside of the Project area primarily within the aquifers of the shallow groundwater system, which are linked to the Water Management System Database production, not coal seam gas water production related to the Project. Figures presented in Appendix F show the modelled drawdowns in selected target aquifers for the cumulative scenario at the cessation of operations and 50 years post-production.

It is considered likely that post-production recovery would be relatively slow, and the baseline conditions were unlikely to be re-established within a time frame of less than a thousand years (approximately). This interpretation was confirmed by numerical groundwater modelling which showed that significant recovery occurred over a time-frame measured in millennia (Ausenco-Norwest, 2012). Further to this, the rate of groundwater recovery may be slowed even more by the existing and future mining operations in proximity to the Project.

Table 8.4 highlights the aquifer and the maximum drawdown in that aquifer for the relevant model layers under the BGP only and cumulative case scenarios. The spatial extent of drawdown for the two scenarios is displayed in Ausenco-Norwest (2012) and Appendix F. The results clearly show that the cumulative case has a significantly greater spatial impact on the study area than the BGP.

Table 8.4: Arrow Bowen Basin EIS Groundwater Model –Modelled Drawdowns

Model Layer	Primary Formation in Layer	End of Coal Seam Gas Production				50 Years after Coal Seam Gas Production			
		Bowen Gas Project Only		Cumulative Case		Bowen Gas Project Only		Cumulative Case	
		Maximum Drawdown (m)	Aquifer with Maximum Drawdown	Maximum Drawdown (m)	Aquifer with Maximum Drawdown	Maximum Drawdown (m)	Aquifer with Maximum Drawdown	Maximum Drawdown (m)	Aquifer with Maximum Drawdown
1	Multiple Formations represented Quaternary Alluvium	>2	Tertiary Duaringa Formation	>50	Blackwater and Clematis Formation	>2	Tertiary Duaringa Formation	>100	Alluvium/Colluvium
2	Multiple Formations represented Tertiary sediments	>5	Rewan Formation	>50	Blackwater Formation	>5	Rewan Formation	>50	Blackwater Formation
3	Multiple Formations represented Clematis Sandstone	>5	Rewan Formation	>50	FCCM	>5	Rewan Formation	>100	FCCM
5	Rangal Coal Measures (Leichhardt seam)	>5	RCM (Leichhardt seam)	>100	RCM (Leichhardt seam)	>5	RCM (Leichhardt seam)	>100	RCM (Leichhardt seam)
7	Rangal Coal Measures (Vermont seam)	>5	RCM (Vermont seam)	>100	RCM (Vermont seam), FCCM	>5	RCM (Vermont seam)	>100	RCM (Vermont seam), FCCM

Table 8.4: Arrow Bowen Basin EIS Groundwater Model –Modelled Drawdowns (cont'd)

Model Layer	Primary Formation in Layer	End of Coal Seam Gas Production				50 Years after Coal Seam Gas Production			
		Bowen Gas Project Only		Cumulative Case		Bowen Gas Project Only		Cumulative Case	
		Maximum Drawdown (m)	Aquifer with Maximum Drawdown	Maximum Drawdown (m)	Aquifer with Maximum Drawdown	Maximum Drawdown (m)	Aquifer with Maximum Drawdown	Maximum Drawdown (m)	Aquifer with Maximum Drawdown
11	Moranbah Coal Measures (Q GMU seam)	>5	MCM (Q seam)	>50	MCM (Q seam), Back Creek Group	>5	MCM (Q seam)	>100	MCM (Q seam), Back Creek Group
15	Moranbah Coal Measures (GM seam)	>5	MCM (GM seam)	>50	MCM (GM seam), Back Creek	>5	MCM (GM seam)	>100	MCM (GM seam), Back Creek Group
17	Moranbah Coal Measures (GML seam)	>5	MCM (GML seam)	>50	MCM (GML seam), Back Creek Group	>5	MCM (GML seam)	>100	MCM (GML seam), Back Creek Group

8.3.1.2 Qualitative Assessment

The second portion of the cumulative impacts assessment conducted for the EIS consisted of a qualitative assessment of cumulative impacts on groundwater resources, from the Project in conjunction with the following proposed projects:

- Caval Ridge Mine;
- Codrilla Coal Project;
- Daunia Mine;
- Eagle Downs Coal Project;
- Eaglefield Expansion Project;
- Grosvenor Longwall Expansion Project;
- Middlemount Coal Project (Stage 2);
- North Goonyella Longwall Expansion Project; and
- Washpool Coal Project.

The EIS acknowledged that all of the future coal mines identified as part of the assessment are likely to have groundwater impacts. Of these, Eagle Downs is the only underground mine development. During operations, and either as a result of the post mining open cut voids or the underground goafed (mined void) areas, all of the coal mining projects are likely to result in localised depressurisation of the groundwater systems around the sites. Review of the available EIS documentation found the zones of depressurisation to be generally limited to a 5 to 10 km radius with varying durations. Those projects where EIS documents were not available were also considered to contribute to the cumulative groundwater impacts however, this was difficult to assess in the absence of technical data available in the public domain.

8.3.2 Supplementary Cumulative Impact Assessment

Mining operations are relatively dispersed across the Bowen Basin due to its size and the distribution of coal resources across the area. Most existing coal mine projects in the Bowen Basin are located on the western limb of the basin, targeting the Permian coal seams. There are 13 operational coal mines within the Project area with a further 28 coal mines operating beyond the Project area, but within the regional numerical groundwater model domain (refer Figure 8.3, Table 8.5 and Table 8.6). There are approximately a further 13 projects under development in the Bowen Basin, as at December 2013 (refer Figure 8.4, Table 8.7 and Table 8.8). Expansion of coal mining in the Bowen Basin has contributed to the generation of a number of cumulative impacts, including groundwater resources.

There is no standard methodology in Queensland for the assessment of cumulative impacts as part of an EIS process and there are no specific requirements in the legislation as to how cumulative impacts should be addressed. For the purposes of the EIS and SREIS, cumulative impacts were defined as changes to the environment that are caused by an action in combination with other past, present and future human actions (Hegmann et al., 1999). The Queensland Coordinator Generals' generic Terms of Reference (ToR) provides guidance on the cumulative impact assessment for an EIS.

For this cumulative impacts assessment, the combined effects of different developments within a similar spatial and temporal scope are considered. Cumulative impacts occur when impacts from individual developments combine to result in an impact which is greater than the individual residual impact of each development, when considered in isolation. This impact may be positive or negative. The severity and duration of the cumulative impact will depend on the timing and duration of operational activities. It should be noted that many new mines will not require dewatering as existing mines may have already lowered the watertable to sufficient depths to allow for mining.

The potential groundwater related impacts, resulting from the Project, considered in the supplementary groundwater assessment, include:

- Direct impacts caused by coal seam depressurisation.
- Indirect impacts caused by coal seam depressurisation (i.e. subsidence).
- Impacts caused by field and infrastructure development, operation and decommissioning.
- Induced seismicity.

This section provides a review of the projects considered for the cumulative impacts assessment undertaken to inform the SREIS, and considers any new information that has become available since preparation and submission of the EIS.

Table 8.5: Operational Mines within the Project Area

Mine Name	Deposit Name	Owner	Operator	Target Coal Seam(s)	Mine Type	Mining Start Date
Broadlea North O/C	Broadlea North	AMCI ConsMin (Cayman) L.P. and Vale SA	AMCI Australia Pty Ltd	Leichhardt Seam, Rangal Coal Measures	Open-cut	Care and Maintenance
Burton Mine	Burton	Peabody Energy	Thiess	Rangal Coal Measures	Open-cut	1996
Coppabella	Coppabella	Peabody Energy	Australian Premium Coals Pty Ltd	Fort Cooper and Rangal Coal Measures	Open-cut	1998
Hail Creek Open cut	Hail Creek	Joint Venture (JV) - Rio Tinto Coal Australia (92%), Marubeni Coal (5.33%) & Sumisho Coal Development (2.67%).	Rio Tinto Coal Australia Pty Ltd	Fort Cooper and Rangal Coal	Open-cut	2003
Jellinbah East	Jellinbah East	Jellinbah Mining Pty Ltd	Jellinbah Resources	Rangal Coal Measures	Open-cut	1989
Millenium	Millennium	Peabody Energy	Peabody Energy	Rangal Coal Measures	Open-cut	2006
Moorvale	Moorvale	Peabody Energy	Australian Premium Coals Pty Ltd	Rangal Coal Measures	Open-cut	2003
Newlands	Eastern Creek	NCA Joint Venture	Newlands Coal Pty Ltd	Rangal Coal Measures Upper Newlands seam - Extends to depth of 400 m	Open-cut	1983

Table 8.5: Operational Mines within the Project Area (cont'd)

Mine Name	Deposit Name	Owner	Operator	Target Coal Seam(s)	Mine Type	Mining Start Date
Newlands	Newlands	NCA Joint Venture	Newlands Coal Pty Ltd	Rangal Coal Measures (late Permian) Upper Newlands seam - Extends to depth of 400 m	Open-cut	1983
North Goonyella Underground	North Goonyella	Peabody Energy	North Goonyella Coal Mines	Moranbah Coal Measures (late Permian)	Underground Coal Mine	1994
Norwich Park	Norwich Park	BHP Billiton (50%) Mitsubishi Corporation (50%)	BHP Billiton Mitsubishi Coal Alliance (BMA)	German Creek Formation (late Permian)	Open-cut	1979
Poitrel	Poitrel	BHP Billiton (80%), Mitsui Coal Australia (20%)	BHP Billiton Mitsui Coal	Rangal Coal Measures (late Permian)	Open-cut	2006
Suttor Creek	Suttor Creek	NCA Joint Venture	Newlands Coal Pty Ltd	Rangal, Fort Cooper and Moranbah Coal Measures (late Permian)	Open-cut	2004

Table 8.6: Operational Mines Outside the Project Area (within the groundwater model domain)

Mine Name	Deposit Name	Owner	Operator	Target Coal Seam(s)	Mine Type	Mining Start Date
Blackwater	Blackwater	BHP Billiton Mitsubishi Alliance	B.M. Alliance Coal Operations Pty Ltd	Rangal Coal Measures (late Permian)	Open-cut	1967
Blackwater South	South Blackwater	BHP Billiton Mitsubishi Alliance	B.M. Alliance Coal Operations Pty Ltd	Rangal Coal Measures (late Permian)	Open-cut	1967
Blair Athol	Blair Athol	New Emerald Coal Ltd	New Emerald Coal Ltd	Blair Athol Coal Measures (early Permian)	Open-cut	1984. Mine temporarily closed in November 2012. Expected to reopen in mid-2014.
Carborough Downs	Carborough Downs	Vale S.A (80%) Nippon Steel Corporation (5%) POSCO (5%) Tata Steel (5%) JFE Steel Corporation (2.50%) JFE Shoji Trade Corporation (2.50%)	Vale	Leichhardt Seam, Rangal Coal Measures (late Permian)	Underground Coal Mine	2004
Clermont Coal Project	Clermont	JV - Rio Tinto (50.1%) Mitsubishi Development (31.4%) J-Power Australia (15%) J.C.D Australia (3.5%)	Rio Tinto Coal Australia Pty Ltd	Wolfang seam (Permian)	Open-cut	2010 (17 years mine life)
Collinsville Open Cut	Collinsville	NCA JV	Xstrata	Collinsville Coal Measures (early Permian)	Open-cut	1954
Cook Underground	Cook	Caledon Resources	Caledon Resources	Rangal Coal Measures (late Permian)	Underground Coal Mine	2001
Curragh	Curragh	Wesfarmers Curragh Pty Ltd	Wesfarmers Curragh Pty Ltd	Rangal Coal Measures (late Permian)	Open-cut	2003

Table 8.6: Operational Mines Outside the Project Area (within the groundwater model domain) (cont'd)

Mine Name	Deposit Name	Owner	Operator	Target Coal Seam(s)	Mine Type	Mining Start Date
Curragh North	Curragh North (Formerly Pisces)	Wesfarmers Curragh Pty Ltd	Wesfarmers Curragh Pty Ltd	Rangal Coal Measures (late Permian)	Open-cut	2004 (40 years mine life)
Ensham	Ensham	Ensham Resources	Ensham Resources	Rangal Coal Measures (late Permian)	Open-cut	1993
Foxleigh Mine	Foxleigh	Anglo American Plc (70%) POSCO (20%) Itochu Corporation (10%)	Foxleigh Mining Pty Ltd	Rangal Coal Measures (late Permian)	Open-cut	1999
German Creek (includes Grasstree, Central and Southern Colliery)	German Creek	Anglo Coal Australia Pty Ltd (70%) and Mitsui Coal Holdings (30%)	Anglo Coal (Capcoal Management) Pty Ltd	German Creek Formation (late Permian)	U/G and O/C	O/C at German Creek: 1981 U/G at Southern Colliery: 1988
German Creek East	German Creek East	German Creek East JV (Anglo Coal/Marubeni Coal)	Capricorn Coal Management Pty Ltd	Rangal Coal Measures (late Permian)	Open-cut	1979
Goonyella Riverside Broadmeadow Underground	Goonyella Riverside Broadmeadow	BHP Billiton Mitsubishi Alliance (BMA)	B.M. Alliance Coal Operations Pty Ltd	Moranbah - German Creek Coal Measures (late Permian)	Underground Coal Mine?	1971 (25 years mine life)
Gregory Crinum	Gregory Crinum	BHP Billiton Mitsubishi Alliance	B.M. Alliance Coal Operations Pty Ltd	German Creek Formation (late Permian)	Gregory - O/C and Crinum - U/G	1979/1997

Table 8.6: Operational Mines Outside the Project Area (within the groundwater model domain) (cont'd)

Mine Name	Deposit Name	Owner	Operator	Target Coal Seam(s)	Mine Type	Mining Start Date
Isaac Plains Open Cut Coal	Isaac Plains	Isacc Plains Coal Management	AMCI Australia Pty Ltd	Rangal Coal Measures (late Permian)	Open-cut	2006 (15 years mine life)
Kestrel	Kestrel	JV - Rio Tinto Coal Australia Pty Ltd (80%) and Mitsui Kestrel Coal Investment Pty Ltd (20%)	Rio Tinto Coal Australia Pty Ltd	German Creek Formation (late Permian)	Underground Coal Mine	1992
Lake Lindsay	Lake Lindsay	Anglo American Plc (70%) Mitsui and Company (30%)	Anglo Coal (Capcoal Management) Pty Ltd	Rangal Coal Measures (late Permian)	Open-cut	1981
Minerva	Minerva	Sojitz Corporation (96%) Korea Mining Promotion Corporation (4.00%)	Sojitz Corporation	Reids Dome beds (early Permian)	Open-cut	1994
Moranbah North	Moranbah North	Principal beneficial owner is Anglo Coal Australia Pty Ltd	Anglo Coal (Moranbah North) Pty Ltd	Moranbah Coal Measures (late Permian)	Underground Metallurgical Coal	1998 (20 years mine life)
Oaky Creek	Oaky Creek	Xstrata Coal Queensland (55%), Sumisho Coal Australia (25%), Itochu Coal Resources Australia (15%) ICRA OC (10%)	Oaky Creek Coal Pty Ltd	German Creek, Moranbah Formation (late Permian)	Open-cut and underground	2001
Peak Downs	Peak Downs	BMA	B.M. Alliance Coal Operations Pty Ltd	Moranbah Coal Measures (late Permian)	Open-cut	1972

Table 8.6: Operational Mines Outside the Project Area (within the groundwater model domain) (cont'd)

Mine Name	Deposit Name	Owner	Operator	Target Coal Seam(s)	Mine Type	Mining Start Date
Riverside	Riverside (Gonyella North)	BHP Billiton Mitsubishi Alliance (BMA)	B.M. Alliance Coal Operations Pty Ltd	Goonyella Lower seam, Moranbah Coal Measures (late Permian)	Open-cut	1969
Saraji	Saraji	BHP Billiton Mitsubishi Alliance	B.M. Alliance Coal Operations Pty Ltd	Moranbah Coal Measures (late Permian)	Open-cut	1972
Sonoma	Sonoma	Sonoma Mine (Indirect), Cliffs Natural Resources (45%), QCoal Sonoma (45%), JFE Shoji Trade Corporation (5.00%), China Steel Corporation (5.00%)	Leighton Contractors	Moranbah Coal and Fort Cooper Coal Measures (late Permian)	Open-cut	2007
South Walker Creek	South Walker Creek	BHP Mitsui Coal	B.M. Alliance Coal Operations Pty Ltd	Rangal Coal Measures (late Permian)	Open-cut	1996
Wards Well	Wards Well	BHP Billiton Mitsubishi Alliance	BHP Coal	Rangal Coal Measures (late Permian)	Underground Coal Mine	Unknown
Yarrabee	Yarrabee	Felix Resources Limited/Yarrabee Coal	Yarrabee Coal Company Pty Ltd	Rangal Coal Measures (late Permian)	Open-cut	1982

Table 8.7: Proposed Projects Located within the Project Area

Project and Proponent	Description	Location	Project Status	Relationship to BGP
Byerwen Coal Project – Byerwen Coal Pty Ltd	The project involves the construction and operation of an open-cut coal mine. The project is expected to produce a peak of approximately 15 Mtpa of ROM coal	~20 km west of Glenden	EIS is available and in progress	Located within ATP742
Codrilla Coal Mine Project - Macarthur Coal	Development of an open-cut coal mine producing an average of 4 Mtpa of ROM coal; Construction phase: 2012 - 2013	~45 km south/south west of Nebo	EIS is complete. IAS and SEIS available	Located within ATP759
Daunia Mine - BMA	New open-cut coal mine to produce 4.5 Mtpa of coal; Construction period: 2011 - 2013; and Estimated capital cost $1.6 billion	~30 km south east of Moranbah	Project approved. EIS and Coordinator General's Report available	Located within ATP1103
Eagle Downs Coal Project - Bowen Central Coal Joint Venture (Bowen Central Coal and Aquila Coal)	Development of a greenfield underground coal mine producing up to 8 Mtpa of coking and thermal coal for export; Construction period: 2012-2014; Estimated capital of $1.26 billion	~20 km south east of Moranbah	EIS approved. EIS available	Located within ATP1103
Eaglefield Expansion Project - Peabody	Open-cut expansion and associated infrastructure upgrades to increase production from 5 Mtpa to 10.2 Mtpa ROM coal; Construction period: 2012 - 2013	~36 km north of Moranbah and 32 km south west of Glenden	EIS is complete. EIS available	Located on the south-western boundary of ATP742
Ellensfield Project – Ellensfield Coal Management Pty Ltd	The project involves the development of a greenfield underground coal mine producing up to 3 Mtpa of semi-soft coking coal and thermal coal for export	~ 35 km north east of Moranbah and ~ 175 km south west of Mackay	EIS is complete	Located within ATP1103
Minyango Project – Blackwater Coal Pty Ltd	The project involves the construction and operation of a dual seam underground coal mine on a greenfield site in Central Queensland. The project is expected to have a peak production rate of 9 Mtpa of ROM coal	Immediately south of Blackwater township, approximately 170 km west of Rockhampton	EIS is available and in progress	Located within ATP1025

Table 8.8: Proposed Projects Outside the Project Area (within the groundwater model domain)

Project and Proponent	Description	Location	Project Status	Relationship to Arrow Bowen Gas Project
Caval Ridge Mine - BMA	New open-cut mine to produce 5.5 Mtpa of coking coal for export; Construction period: 2012 - 2014; Estimated capital cost $4 billion	6 km south west of Moranbah	Project approved. EIS and Coordinator-General's Report available	Located ~20 km west of the Project area tenement boundary at ATP 1103
Grosvenor Coal Project - Anglo Coal	Development of a greenfield underground coal mine to produce 5 Mtpa of product coal; Construction period: 2012 - 2014; Estimated capital $1.115 billion	Immediately north of Moranbah	EIS is complete	Located ~12 km north/north west of the Project area tenement boundary at ATP 1103.
Middlemount Coal Project (Stage 2) - Middlemount Coal	Stage 2 is an expansion of the current open cut mine to produce up to 5.4 Mtpa of ROM coal; Stage 2 forms the basis of the project as Stage 1 is approved for production of 1.8 Mtpa of ROM coal; Construction period: 2011 - 2014	~6 km south west of Middlemount	EIS is complete	Located ~3 km west of the Project area tenement boundary at ATP 1031
Moranbah South – Anglo American Metallurgical Coal Pty Ltd	The project involves the construction and operation of a greenfield underground coal mine. The project is expected to have a peak production rate of 18 Mtpa of ROM coal	150 km south west of Mackay	EIS is available and in progress	Located ~ 2 km west of the Project area tenement boundary at ATP 1103
Red Hill Mine – BM Alliance Coal Operations Pty Ltd	A new underground coking coal mine (Red Hill Mine) with a yield of 14 million tonnes per annum; and expansion of two existing coking coal mines (Broadmeadow and Goonyella Riverside)	20 km north of Moranbah	EIS is complete	Located ~ 2km west of the Project area tenement boundary at ATP 1103
Washpool Coal Mine Project - Washpool Coal subsidiary of Aquila Resources Limited	Development of a greenfield open-cut coal mine producing up to 2.6 mtpa of product hard coking coal; Construction period: 2012 - 2013; Workforce: 307 (construction) and 378 (operation); and Estimated capital of $396 million	~24 km north west of Blackwater	EIS available	Located ~18 km west of the Project area tenement boundary at ATP 1103

8.3.3 Direct impacts caused by coal seam depressurisation

Predictive groundwater modelling from coal mines in the Moranbah area indicate that groundwater drawdown within the confined target coal seams, as a result of mine dewatering and associated depressurisation, could potentially extend 5 to 30 km. The drawdown extent varies across mine sites as the depth to the target coal formations vary across the Bowen Basin. For the existing Newlands coal mine, groundwater modelling shows that drawdown in the coal seams is generally limited to within 1 km of the mining footprint. This is supported by groundwater modelling conducted for the proposed Byerwen coal project (not undertaken as part of the BGP assessment) where induced drawdown is expected to be within 2 km in the target coal seams.

Groundwater drawdown has also occurred in the coal seams within the Grosvenor mining lease area which is also located within Arrow's MGP area. Existing groundwater extraction undertaken at the MGP and drainage to the Moranbah North Mine underground workings contribute to cumulative groundwater drawdown in this area. This also has implications for coal handling for the affected coal mining operations due to greater dust production and more friable coal. The predictive groundwater modelling undertaken for the Moranbah South Project further supports that cumulative impacts from coal mining and coal seam gas activities occur in this area.

Groundwater modelling was also undertaken as part of the proposed Eaglefield Expansion Project (EEP). The estimated cumulative dewatering drawdown impact associated with the EEP and surrounding existing mines (North Goonyella, Eaglefield and Goonyella-Riverside) is approximately 4 km in the FCCM and MCM. The RCM overlie and are separated from the MCM by the FCCM. The low vertical permeability of the MCM and RCM and the separation of the FCCM is expected to limit vertical flow between these formations such that the cumulative impact of drawdown is considered to be limited in these areas. In addition, as discussed in Section 5, it is concluded that fault permeability in the region is predominantly low and unlikely to provide a mechanism for significant vertical flow.

The cumulative case considered by the Arrow Bowen Basin EIS groundwater model was based on a proposed production of 274 GL over the project life, as well as the cumulative effects of the non-coal seam gas users from the Water Management System Database database. Given that the revised production case is significantly reduced (153 GL) and the actual non-coal seam gas usage is estimated at <20% of the Water Management System Database entitlements, it is considered likely that the modelling has overstated the cumulative impact case as modelled. Hence it is concluded that the actual cumulative impacts are not under-represented.

In considering the observations made at the MGP area, and the cumulative modelling scenarios undertaken for other coal mining projects in the area, Arrow's activities may impact on other coal mines if they are located within the predicted area of drawdown. However given that coal mines already dewater to access the coal, any potential impacts associated with coal seam gas depressurisation are likely to be low.

8.3.4 Indirect impacts caused by coal seam depressurisation

Identified indirect impacts caused by coal seam gas depressurisation include:

- Groundwater quality impacts caused by aquifer flux inter-connectivity;
- Reduced groundwater supply to existing or future groundwater users;
- Reduced groundwater availability for GDEs and cultural and spiritual values; and

- Subsidence.

As described in Section 8.3.3, the low vertical permeability of the MCM and RCM and the separation of the FCCM would limit vertical flow between these formations such that the cumulative impact of drawdown is considered to be limited in those areas, and further that fault permeability in the region is low and unlikely to provide a mechanism for significant vertical groundwater flow. Therefore groundwater quality impacts caused by aquifer flux inter-connectivity are not indicated, nor are impacts to groundwater supply.

The ground movement interpreted from Altamira satellite interferometry indicated that the magnitude of any subsidence associated with coal seam gas extraction in the petroleum leases is:

- Small (comparable in scale to ground motion occurring due to natural processes);
- Within the lower range of calculations used to estimate subsidence potential; and
- Significantly less than expected for longwall coal mining.

In addition it is noted that any subsidence resulting from coal seam gas development would be broadly distributed and that differential subsidence would not occur, further reducing the risk of any surface impacts occurring.

Consequently, the cumulative impacts caused by subsidence associated with the coal seam gas development are low.

8.3.5 Impacts caused by field and infrastructure development, operation and decommissioning

Contamination of groundwater systems is a potential cumulative impact that could result where there are significant leaks or spills from a variety of coal seam gas construction and operation surface activities (e.g., storage and handling of hazardous materials) and subsurface activities (e.g., drilling and installation of production and monitoring wells) combined with mining activities.

Other projects (existing and future) with the potential to contribute to cumulative impacts from field and infrastructure development, operation and decommissioning will be limited spatially to those located within the Project area (identified in Tables 8.5 and 8.8).

Potentially contaminating surface activities are more likely to impact on shallow groundwater systems. However given the depth to water in the shallow aquifer, a large instantaneous source mass and/or long-term diffuse source (i.e. from a dam) would be required for contamination to migrate to the watertable.

Aquifers of deeper systems are isolated by depth, and are less likely to be adversely impacted by leaks and spills of hazardous materials or coal seam gas water from surface storage infrastructure. Also, in the event of a leak or spill, the contaminants would more likely migrate laterally away from the source, and in the direction of local groundwater flow and at a rate comparable with the groundwater flow velocity. The shallow groundwater systems are often localised systems that are less likely to be accessed by multiple proponents. The mitigation measures developed to address this potential impact require that dams and surface storage infrastructure be installed to relevant standards, together with impact detection systems (e.g., shallow groundwater monitoring bores) in the vicinity of the infrastructure. Therefore, the potential for cumulative contamination of shallow groundwater systems from surface activities is considered to be the same as the residual impact of the Project in isolation.

A variety of surface activities (e.g. hazardous materials storage) and subsurface activities (e.g. well installation, production and testing) have the potential to create cumulative impacts within one or multiple coal seam gas fields. 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. Regular maintenance and well testing will further limit potential impacts.

Given the cumulative impact is considered to be the same as the residual impact of the Project in isolation, no additional mitigation and management measures are proposed to manage Arrow's potential contribution to cumulative impact. Monitoring programs conducted by existing and future proponents will ensure that groundwater quality indicators are used to implement appropriate response actions in the unlikely event of leaks, spills, or inadequate well installations.

8.3.6 Induced seismicity

Induced seismicity associated with the hydraulic stimulation of rocks results in seismic events of very low magnitude (microseismic events), with no demonstrated potential to result in damage to buildings or infrastructure. Based on data from Pinnacle (2013) the magnitude of these microseisms is demonstrated to be very low, and measured as negative magnitudes.

Preliminary research on hydraulic stimulation induced seismicity in Australia indicates that induced earthquakes release less energy than naturally occurring earthquakes of similar size (Geoscience Australia, 2013) and are generally less than magnitude 1. It is feasible for hydraulic stimulation to induce movement on existing fault planes, however this requires that the extent of stimulation is sufficient to intersect nearby potentially active faults, and also that such faults would be active.

In the Bowen Basin, existing faults are comparatively well mapped, and often avoided when locating coal seam gas wells. Hence, risks are reduced, and confined to intersection of unknown small faults. Together with the low seismic activity in the basin, risks of induced earthquakes are small, and any such events would be of low magnitude.

Induced seismicity comprises events associated with hydraulic stimulation operations that are constrained in time and place. Therefore the magnitude of these events is non-cumulative. However it is reasonable to assume that other extractive industries, such as coal seam gas developers or miners, could also trigger induced seismic events. This would increase the overall number of potential events in the Project area, but not the magnitude of events.

In summary, the demonstrated evidence is that induced seismic events are of very low magnitude that can only be measured with sensitive seismology equipment. They are inherently non-cumulative in magnitude terms, and it is concluded that the risk associated with induced seismicity in the Bowen Basin due to hydraulic stimulation is very low.

9 SIGNIFICANCE ASSESSMENT AND IMPACT MITIGATION

Section 8 presents the potential impacts to groundwater environmental values caused by Project activities, including unmitigated impact magnitude. The following sections present the approach adopted for and result of the assessment of impact significance.

9.1 Impact Significance Assessment Approach

The impact assessment method adopted for the groundwater technical study prepared for the EIS has been applied to the SREIS. The approach considers the sensitivity of an environmental value (Section 9.2) and the magnitude of potential impacts on that value (Section 8.2) to determine the significance of the impact.

The following approach was adopted for the assessment of impact significance:

- Assess magnitude of impacts (Section 8);
- Classify environmental value sensitivity based on all available information;
- Review the mitigation measures presented in the EIS to identify new mitigation measures required or remove existing mitigation measures that are no longer relevant or appropriate
- Assess the significance of potential impacts on groundwater environmental values, prior to the application of mitigation and management measures; and
- Assess the residual impact significance following application of the mitigation and management measures.

9.2 Environmental Values – Classification of Sensitivity

The sensitivity of the environmental values to impacts resulting from project activities was determined by assessing their intrinsic characteristics, or susceptibility to threatening processes, based on the classification scheme presented in Table 9.1 of Appendix L of the EIS.

The following constraints and assumptions have been made with regard to the classification of groundwater environmental value sensitivity:

- The sensitivity criteria are assessed based on the potential area of impact of the Project, which can extend beyond the boundary of the Project area;
- Biological values are assessed with consideration for typical groundwater quality available to support ecosystems as well as the physical likelihood of groundwater supporting ecosystems;
- Recharge springs and other GDEs are located within the area that may be affected by drawdown of groundwater. For the assessment of springs, other GDEs and sites of cultural and spiritual importance the potential area of impact is defined by adopting a 10 km buffer zone around the 0.2 m drawdown contour of relevant aquifer(s) (should they extend to that area). This is considered to be a conservative approach to the identification of potentially affected springs and other GDEs for sensitivity classification;
- Sites of cultural and spiritual importance that may have groundwater dependence have been identified within the Project area and have been taken into consideration in the impact assessment.

As limited information is available regarding the site characteristics a conservative assumption has been made that the wells identified are present and that they intersect the watertable aquifer;

- Consumptive and productive uses consider the general groundwater quality available;
- 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; and
- Rehabilitation potential is considered with respect to impacts from depressurisation.

A sensitivity ranking has been assigned to each groundwater system and represents an overall ranking for all aquifers associated with the particular system, as presented in Table 9.1. The process for assigning an overall sensitivity ranking to groundwater systems involved an assessment of the intrinsic properties and hydrogeological processes that contributed to the value of each system against defined criteria for conservation status (biological value, consumptive and productive use, cultural and spiritual value), rarity, resilience, dynamics and rehabilitation potential.

The overall sensitivity rankings assigned to the shallow and intermediate groundwater systems remain unchanged from those presented in the EIS. While individual scores assigned to the components that make up the overall sensitivity score were reviewed and in some cases revised, the new overall score did not result in a material change to the ranking.

The overall sensitivity of the coal seam groundwater system has increased from low to moderate based primarily on the potential for the system to support a site of Indigenous cultural and spiritual importance and the limited recharge potential post depressurisation. Also, the coal seam groundwater system may support small scale industrial uses in some areas.

The newly defined deep groundwater system has a low overall sensitivity due to poor groundwater quality and limited potential for the system to support consumptive or productive uses or areas of biological importance.

Table 9.1: Classification of Environmental Value Sensitivity

Groundwater System	Conservation Status			Rarity of Occurrence	Resilience To Change	Dynamism of Existing Environment	Rehabilitation Potential	Sensitivity Score	Sensitivity Rating
	Biological Values	Consumptive and Productive Values	Cultural and Spiritual (Anthropomorphic) Values						
SHALLOW GROUNDWATER SYSTEM (watertable or unconfined aquifers of Quaternary and Tertiary sediments and Tertiary basalt)	3	3	2	3	3	3	2	19	Moderate
INTERMEDIATE GROUNDWATER SYSTEM (confined aquifers overlying coal seam gas formations, including Clematis Sandstone and Rewan Formation, unconfined where aquifers outcrop)	3	2	1	2	3	3	3	17	Moderate

Table 9.1: Classification of Environmental Value Sensitivity (cont'd)

Groundwater System	Conservation Status			Rarity of Occurrence	Resilience To Change	Dynamism of Existing Environment	Rehabilitation Potential	Sensitivity Score	Sensitivity Rating
	Biological Values	Consumptive and Productive Values	Cultural and Spiritual (Anthropomorphic) Values						
COAL SEAM GROUNDWATER SYSTEM (confined aquifers associated with coal seam gas formations including Blackwater Group, unconfined where aquifers outcrop)	1	2	2	2	3	4	4	18	Moderate
DEEP GROUNDWATER SYSTEM (confined aquifers underlying coal seam gas formations including the Back Creek Group, unconfined where aquifers outcrop)	2	2	1	2	2	4	1	14	Low

Groundwater environmental 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 Mitigation, Management and Monitoring Measures

Section 8 identified the potential impacts to groundwater associated with Project activities. To ensure impacts are addressed and impact to environmental values is avoided or minimised, mitigation and management measures are required.

In addition to mitigation measures and commitments outlined in the EIS (Section 9 and Section 10 of Appendix L Groundwater and Geology Technical Report in the EIS (URS, 2012)), Arrow is committed to the implementation of additional mitigation and management measures and monitoring programs required to minimise potential impacts identified as part of the supplementary assessment process.

9.3.1 Review of Measures Presented in the EIS

The mitigation measures identified in the EIS were reviewed to assess whether they remain relevant to this supplementary groundwater assessment. Review of Arrow's refined project description (including coal seam gas water and salt management options) together with the outcomes of the supplementary groundwater assessment has resulted in the removal of mitigation measures associated with:

- Consideration of injection of suitably treated coal seam gas water as part of the management hierarchy to enhance shallow and deep aquifer recovery. Injection of coal seam gas water is no longer considered a viable management option for the project;
- Verification of the preferred water management strategy by modelling the effectiveness of substitution and injection on the minimisation of groundwater drawdown. These coal seam gas water management options are no longer considered viable for the project;
- Groundwater modelling simulations to predict impacts on groundwater resources in overlying and underlying aquifers to evaluate the suitability of these resources in make good measures. This measure does not align with the revised coal seam gas water management strategy for the project and is no longer relevant;
- Monitoring associated with coal seam and land subsidence. The results of the supplementary groundwater assessment, specifically the findings of the Altamira Information ground movement study, justify removal of monitoring measures associated with subsidence presented in the EIS.

All other mitigation and monitoring measures presented in the groundwater impact assessment prepared for the EIS remain relevant.

A revised set of commitments associated with management of potential impacts related to the project are presented in Appendix O of the SREIS. All commitments related to the protection of groundwater values have been revisited as part of the supplementary assessment process. Appendix O of the SREIS details those commitments that are no longer relevant and also shows that some commitments have been combined to clarify their intent. The new commitments resulting from the supplementary groundwater assessment are also presented in Appendix O of the SREIS.

9.3.2 Statutory Reporting Frameworks

Regulatory requirements set out a number of mitigation and management measures regarding the protection of groundwater values. Under Queensland legislation the Water Act specifies underground water obligations including baseline assessments, the establishment of a UWIR and make good obligations, and the EP Act requires an application for an Environmental Authority (EA). The two legislative processes have different reporting requirements with respect to the mitigation, management and monitoring of potential impacts to groundwater.

A UWIR sets out report obligations that require the establishment of a Water Monitoring Strategy (WMS) and Springs Impact Management Strategy (SIMS), and an EA requires a Groundwater Monitoring Program (GMP). Details of these regulatory processes are provided below to further support the information provided in the EIS and the findings of the supplementary groundwater assessment.

9.3.3 Additional Mitigation, Monitoring and Management Measures

Based on the findings of the supplementary groundwater assessment additional mitigation and management measures were identified, including:

- Underground water obligations including:
    - Report obligations associated with a UWIR.
    - Make good obligations.
- Preparation of an EA application including development of management practices to protect identified environmental values;
- Implementation of the Code of Practice for Construction and Abandoning Coal Seam Gas Wells in Queensland; and
- Arrow's procedure for hydraulic stimulation.

These additional mitigation, management and monitoring measures are discussed below.

9.3.4 Report obligations associated with a UWIR

ATP1025 is located within the Surat CMA therefore within this area any potential groundwater related impacts arising from Project activities require management under the Surat CMA UWIR (QWC, 2012).

Arrow will establish a UWIR for all tenements:

1) within which production testing or production of coal seam gas occurs, and
2) that are not covered under the Surat CMA UWIR.

A UWIR sets out report obligations that a tenure holder must comply under an approved UWIR or final report. This may include:

- Water monitoring activities: These obligations involve constructing monitoring bore installations, carrying out baseline assessments and reporting data on an ongoing basis; and
- Spring impact management activities: These obligations involve implementing a program for monitoring springs and a program to assess options for mitigating the impact of water extraction on springs.

9.3.4.1 Water Monitoring Strategy

Arrow will develop a WMS for the Project. The WMS will incorporate a number of the monitoring program components identified in the EIS, and the document will aim to:

- Monitor groundwater at sufficient density, in line with the development of the Project;
- Improve Arrow's understanding of the geology of units overlying and underlying the Blackwater Group;
- Collect data on water quality and pressures in aquifers and aquitards within the Project area;
- Establish background trends;
- Identify changes in aquifer conditions within areas of development;
- Identify changes in aquifer conditions near sensitive receptors and groundwater use;
- Improve future groundwater flow modelling; and
- Fulfil Arrow's obligations under the Water Act (2000).

The WMS will be developed and updated over time to consider current gas production operations, planned future expansion operation and other external groundwater extraction operations (e.g. coal seam gas or mining companies). The WMS will be reviewed in line with the obligation to review UWIRs and where applicable updated as Arrow's operations expand or outside influences change and potentially interfere with groundwater in the vicinity of Arrow's operations. The annual WMS review allows Arrow to incorporate relevant regulatory changes and the sampling program as necessary.

Details of the components that will make up the WMS are provided below.

Regional Groundwater Monitoring Program

The GMP to be established under the WMS is based on establishing a targeted network of groundwater monitoring bores, and a water quality and water level assessment regime that reflects field development.

The scope for establishing an appropriate GMP for the Project includes:

- Identify existing bores that may provide data suitable for inclusion to the monitoring program;
- Identify where additional groundwater monitoring bores are required. The selection of target aquifers and locations will be influenced by the areas of predicted groundwater level decline in excess of the bore trigger thresholds; and
- Review and report results of monitoring annually.

Groundwater Monitoring Network

The locations of monitoring bores that will be incorporated in the GMP will target suitable locations within the Project gas DAs. This will be a staged process in line with the scheduled development of the coal seam gas field over time.

In addition to this, proposed monitoring bore locations will be selected to:

- Avoid overlapping mine tenures and the possibility of bores being destroyed by open cut or underground mining operations so that the bores provide long term monitoring records for groundwater level and quality; and
- Be located between existing or planned production and existing groundwater users or sensitive receptors.

The number of groundwater monitoring bores that make up the groundwater monitoring network will provide adequate spatial coverage of groundwater monitoring points consistent with the hydrogeological significance of the unit and the likelihood for the unit to be impacted by Project activities. The timing of monitoring bore installations will allow for sufficient baseline data to be collected prior to the commencement of gas production and the propagation of impact to the aquifer targeted by the monitoring bore.

All new groundwater bores will be installed as per the Minimum Construction Requirements for Water Bores in Australia (National Minimum Bore Specifications Committee, 2012), the Minimum Standards for the Construction and Reconditioning of Water Bores that intersect the sediments of artesian basins in Queensland (DNRM, 2013a) or the Code of Practice for Constructing and Abandoning Coal Seam Gas Wells and Associated Bore is Queensland (DNRM, 2013).

Target Aquifers

For the purpose of the WMS the strata of interest across the regional monitoring area are grouped into hydrogeological units. The units include:

- Quaternary and Tertiary Aquifers. Includes Quaternary alluvium, Tertiary basalt and Tertiary sediments. The formations represent important local aquifers and are potentially directly connected to the underlying coal measures in areas where the underlying Rewan Formation is absent.
- Triassic Sediments. Includes the Moolayember Formation, Clematis Sandstone and Rewan Formation. The Clematis Sandstone represents a local to regionally important aquifer and the Rewan and Moolayember Formations are generally considered to be regional aquitards. The Clematis Sandstone is largely separated from the underlying target coal seams by the Rewan Formation.
- Permian Coal Measures. Includes the RCM, FCCM and MCM of the Blackwater Group. The RCM and MCM represent the Project targets and will undergo significant depressurisation during the course of the Project.
- Permian Basement. Includes the Back Creek Group which is the deepest formation of interest within the Project area and is generally considered to be a regional scale confining unit for the overlying Blackwater Group. Shallow unconfined groundwater can occur in outcrops and subcrops along the east and west margins of the Bowen Basin.

The results of the investigative drilling program completed to establish the regional groundwater monitoring network will be used to update the conceptual hydrogeological understanding of the Project area. The significance of risks will be re-evaluated on a local or site specific basis as the conceptual model is updated. This will provide further basis for monitoring predicted impacts to groundwater level and quality.

Groundwater Monitoring Frequency and Chemical Parameters

Groundwater level and pressure monitoring will be undertaken on a regular basis for a period of 12 months, while groundwater quality monitoring will be undertaken once within the first 12 months following bore installation.

Following the first 12 months of monitoring the data will be reviewed to assess temporal and spatial variations in groundwater level and quality and define a baseline groundwater data set.

Following the establishment of a baseline groundwater data set, the frequency of monitoring and sampling may be modified in response to interpretation of the results and establishment of trends. The chemical parameters included in the sampling events may also be modified. The proposed field parameters and laboratory analytical suite for groundwater samples are listed in Table 9.2.

Groundwater monitoring will be conducted in accordance with Arrow's Water Quality Sampling Manual.

Table 9.2: Summary of Regional Groundwater Pressure and Quality Monitoring

Monitoring Requirement	Parameters to monitor
Groundwater level / pressure	Depth below ground level (mbgl) and conversion into relative level (mAHD) Temperature (℃)
Groundwater Quality	**Field Parameters** Electrical Conductivity (µS/cm @ 25℃), pH, Redox Potential (Eh), Temperature (° C), Free gas at wellhead (Methane). **Laboratory Parameters** • Major cations and anions (calcium, magnesium, potassium, sodium, bicarbonate, carbonate, chloride, sulfate, total alkalinity), • Dissolved metals (arsenic, barium, boron, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, nickel, selenium, strontium, zinc), • Fluoride, • TDS, • Gas (dissolved Methane)

9.3.4.2 Spring Impact Management Strategy

A SIMS was not developed as part of the EIS as no springs were identified within the Project area and no springs beyond the Project area were predicted to be impacted. Since the release of the EIS, the OGIA released the final Surat CMA UWIR (QWC, 2012). For the assessment of potential impact to springs in the SREIS, the methodology set out in the Surat CMA UWIR SIMS was adopted, and this resulted in the identification of a single potentially affected spring within the Surat CMA.

A statutory framework exists for the management of this spring under the Surat CMA UWIR, therefore a separate SIMS will not be developed and the potentially impacted spring will be managed under the Surat CMA UWIR SIMS framework. Should potentially affected springs not covered by the Surat CMA UWIR be identified in the potentially impacted area in the future and a separate SIMS is required, the SIMS will include:

- Details of the spring(s), including location;
- Establishment of baseline spring conditions (i.e. seasonal variation in presence or extent, physical characteristics and ecology) and an assessment of the connectivity between the spring and the aquifer over which the spring is located;
- The predicted risk to, and likely impact on, the ecosystem and cultural and spiritual values of the spring because of a decline in water level of the aquifer over which the spring is located;

- The options available to prevent or mitigate any impact;
- A strategy, including the actions to be taken, for preventing or mitigating the predicted impacts on the spring or, if a strategy for preventing or mitigating the predicted impacts on the spring is not included, the reason for not including the strategy.
- A timetable for implementing the strategy; and
- A program for reporting to the OGIA about the implementation of the strategy.

9.3.5 Make Good Obligations

Make good obligations require the petroleum tenure holder to complete Bore Assessments and enter into Make Good Agreements with the bore owner. If asked, the petroleum tenure holder may also be required to negotiate a variation of the Make Good Agreement.

9.3.5.1 Bore Assessments

Under the Water Act Arrow has statutory requirements to undertake Bore Assessments in IAAs (refer Section 3). These assessments are used to evaluate whether a bore has impaired capacity, or is likely to have impaired capacity in the future, as a result of groundwater extraction associated with coal seam gas activities.

A water bore has impaired capacity if there is a decline in the water level of the aquifer at the location of the water bore because of the exercise of underground water rights, and as a result of the decline the water bore can no longer provide a reasonable quantity or quality of water for its authorised use or purpose.

Bore Assessments must be undertaken in accordance with DEHPs Bore Assessment Guideline (DEHP, 2013a), and involve the following:

- Preliminary assessment;
- Field assessment of current bore condition;
- Determination of whether water levels have declined, or are predicted to decline;
- Determination of whether declining water levels are due to the exercise of underground water rights by the petroleum tenure holder; and
- Determination of whether the bore can or will continue to provide a reasonable quantity and quality of water for its authorised use or purpose. This includes determination of the current bore yield.

Depending on discussion with the landholder, as well as the findings of each assessment stage, not all steps may be required to complete the water bore assessment.

9.3.5.2 Make Good Agreements

Under the Water Act Arrow must enter into a make good agreement with the owner of the bore which documents the outcome of the bore assessment and defines make good measures for the bore to be undertaken by the tenure holder including any of the following:

- Ensuring the bore owner has access to a reasonable quantity and quality of water, which may require altering an existing pump set up or bore configuration or provision of an alternative water supply;
- Monitoring the bore; and/or
- Compensating the bore owner.

The terms of a make good agreement may be changed should the bore owner or tenure holder identify a material change in the circumstances, that one or more of the make good measures are not effective or that another effective and more efficient make good measure exists.

9.3.6 Preparation of an Environmental Authority Application

EHP provides guidance on the requirements of an application for Environmental Authority (EA) for petroleum activities to identify potential impacts on environmental values and propose environmental protection commitments. The following sections outline the groundwater related requirements of an EA relevant to the Project.

9.3.6.1 Development of a Groundwater Monitoring Program

The EIS presented an initial framework for the GMP and this will be refined at the EA application stage when site infrastructure locations are known.

9.3.6.2 Management of GDEs

For GDEs not covered by a SIMS in a UWIR (i.e. ecosystems potentially dependent on the surface expression of groundwater or those dependent on the subsurface presence of groundwater, including Lake Elphinstone), Arrow will manage these GDEs according to the following framework:

- Identification of potential GDE landscapes;
- Use of modelling to predict impacts;
- Undertaking a risk assessment to identify GDEs at risk of impact. Where GDEs are identified as being at risk of impact, further assessment is warranted, including field studies and monitoring to ascertain connectivity of GDEs to underlying aquifers; and
- Monitor and manage impacts as required.

9.3.6.3 Management of Cultural and Spiritual Sites of Significance

Where sites of cultural and spiritual significance within the Project area that may have dependence on groundwater will be potentially impacted by the Project activities Arrow will:

- Liaise with traditional owners of the land in accordance with any endorsed Cultural Heritage Management Plan where the features are situated to locate features and further understand feature significance;
- Undertake field surveys to confirm the status of potentially impacted features (i.e. whether feature still exists and/or is actively used) associated with groundwater; and
- Develop monitoring, management and mitigation measures to assess, manage, avoid or minimise impact to the feature(s).

9.3.6.4 Containment Facilities

In addition to specific groundwater management requirements DEHP issues EAs that include conditions relating to the storage and handling of contaminants involved in coal seam gas operations. A GMP has been developed and implemented for EAs in place for PLs 191, 196 and 224. The primary purpose of the GMP is to establish baseline groundwater quality and to monitor seepage to the sub-surface from any regulated dam to understand its effect on groundwater and sub-surface soils.

As infrastructure locations are determined for the wider Project area, beyond Arrow's current MGP, site impact monitoring programs will be developed. The recommendations of the initial site impact monitoring requirements are detailed in Section 10 of Appendix L of the EIS.

9.3.7 Code of Practice for Constructing and Abandoning Coal Seam Gas Wells in Queensland

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. This cannot be avoided, as wells are required to access the gas resource.

The EIS described that around 6,625 wells would be drilled across the Project area. The revised project description for the SREIS anticipates around 4,000 production wells will be established due to the use of MBL well design.

The EIS identified a range of potential impacts associated with well failure during construction, operation and decommissioning phases of the project, including the potential to cause aquifer interconnectivity. A range of mitigation measures were identified to ameliorate the potential impacts.

The 'Code of Practice for Constructing and Abandoning Coal Seam Gas Wells in Queensland' (Queensland Government, 2013) has been developed to address the need for specific requirements to ensure that concerns are addressed in present day and future coal seam gas development.

The Code of Practice was facilitated by the former DEEDI and aims to ensure that all coal seam gas wells are constructed and abandoned to a minimum acceptable standard. This ensures that these activities are completed in a consistent manner and the processes are effectively monitored to ensure that:

- The environment, in particular underground sources of water, is protected;
- Risk to public and coal seam gas workers is managed to a level as low as reasonably practicable;
- Regulatory and applicable Australian and International Standards, as well as the Operator's internal requirements, are complied with; and
- The life of a coal seam gas well is managed effectively through appropriate design and construction techniques, ongoing monitoring and end of life decommissioning.

The Code of Practice presents a benchmark standard to underpin coal seam gas well management that exceeds previous specifications and it is intended that this Code of Practice will have enforceable effect in Queensland by being called up under the Petroleum and Gas Regulations as a "safety requirement". However the provisions of the Petroleum and Gas Act and regulation will take precedence over the Code should any cases occur where conflict arises.

In summary, application of the Code of Practice, together with the mitigation measures provided in the EIS, are expected to reliably mitigate any potential impacts associated with well integrity.

9.3.8 Arrow's Procedure for Hydraulic Stimulation

Hydraulic stimulation, where required, is specifically designed for each coal seam gas-bearing target formation. Cost-effective coal seam gas production is achieved by precisely targeting coal seam formations, and where necessary undertaking stimulation activities that maximise depressurisation and gas production within the coals while minimising the connection and leakage of groundwater from overlying formations into the coal seams (thereby minimising groundwater pumping). On this basis, the optimal approach for gas production is aligned with environmental objectives of preventing impacts on other aquifer systems.

Due to the existing stress field properties prevalent within the gas fields, together with the generally horizontal nature of the bedding layers of the coal seams and their brittle nature, the fractures created by the hydraulic stimulation process are designed to be contained within the stimulation impact zone. The overlying and underlying aquitard formations that separate the target coal seams from the developed aquifer formations (if present) typically behave elastically, and are therefore expected to respond to applied stresses through ductile deformation rather than brittle fracturing. Therefore these formations are expected to resist fracture propagation beyond the target coal seam, with many fractures truncating along a low shear strength plane, such as the top or bottom of a coal seam. This helps to ensure that fractures do not extend into the overlying and underlying rock layers beyond the stimulation impact zone, and the probability of fractures intercepting resource aquifers is very low.

9.3.8.1 Site Selection Factors and Planning

Selection of sites where hydraulic stimulation may be considered takes into consideration a range of physical and geological aspects to determine the suitability of the site, including:

- General information relating to well location (collar coordinates, lease, field, overlapping tenure holders) and individual well objectives;
- Detailed geological prediction of all formations and coal seams to be intersected, as well as proposed target formation, seam thicknesses and expected depth of drilling. This includes formation prognosis information including depth uncertainty and formation competency, reactivity and pressure;
- Detail of offset wells to further inform the geological understanding and drilling expectations;
- Expected reservoir conditions to assist with well engineering planning;
- Well evaluation details, including sampling and geophysical wireline logging; and
- An initial assessment considering:
    - Underground coal mining activity, potential underground mineable seams,
    - Geological structures including faults,
    - Potential for over-pressured formations,
    - Any anticipated geo-hazards;
    - Dewatered coal seam gas wells or formations in the area
    - Proximity to surface water bodies (dams, rivers, lakes, wetlands, watercourses etc)

Following successful completion of this process, a project-specific execution plan is developed for each hydraulic stimulation campaign, outlining the project structure, responsibilities, and procedures for information capture and storage.

9.3.8.2 Procedure for Hydraulic Stimulation

Hydraulic stimulation activities have well defined goals and design, and are required to be carried out under the requirements of the Petroleum and Gas (Production and Safety) Regulation 2004 and the Environmental Protection Act 1994 (EP Act).

Petroleum and Gas (Production and Safety) Regulation 2004

The Petroleum and Gas (Production and Safety) Regulation 2004 details the requirements for the holder of a petroleum tenure to provide a notice of intention to carry out hydraulic stimulation activities and a notice of completion of hydraulic stimulation activities. The holder of a petroleum tenure must also lodge a report at the completion of hydraulic stimulation activities. The report requirements are further detailed in Subdivision 6 Sections 46A of the Act, and generally include:

- A description of the hydraulic stimulation activities carried out, including intersected geological units;
- An assessment of the implications of the hydraulic stimulation activities for each petroleum well for the future management of the natural underground reservoir involved;
- Details of the equipment used to carry out and monitor the hydraulic stimulation activities;
- Details of any geological connection between a geological interval over which hydraulic stimulation activities were carried out and an aquifer;
- Description of the hydraulic stimulation fluids used; and
- Provision of details of each step taken to mitigate harm if a hydraulic stimulation event caused material environmental harm.

Environmental Protection Act 1994 (EP Act)

The EP Act 1994 describes the assessment process to be conducted for hydraulic stimulation for an environmental authority application. If well stimulation is planned as part of the petroleum activities, the application under the Act must include an assessment in order for the administering authority to assess and condition the activity. If the assessment is not supplied in the application, the environmental authority may condition that well stimulation activities cannot be undertaken. If hydraulic stimulation is not identified and assessed under the EA application and is subsequently required, a assessment must be completed and approved by EHP as part of an amendment to the granted EA prior to any hydraulic stimulation activities being carried out.

The application must include environmental protection commitments and objectives in relation to stimulation activities. This should include a commitment to take all reasonable and practical measures to ensure that stimulation activities do not negatively affect water quality, other than that within the stimulation impact zone of the target formation, and that stimulation activities will be carried out so as to not cause a connection of the target gas producing formation and another aquifer.

Under the EP Act, the assessment must address issues at a relevant geospatial scale, such that changes to features and attributes are adequately described. This generally includes:

- A description of the activities to be completed;
- A geological model of the field to be stimulated, and consideration for factors that may affect groundwater flow;
- Identification of relevant groundwater environmental values;
- Identification and assessment of chemicals to be used in the process, including hazard assessments; and
- Characterisation of potential environmental and human health risk and impacts associated with the activities.

Control strategies are required to include details of process control monitoring to be undertaken during stimulation activities to detect water quality impacts and interconnectivity. Based on the risk assessment, the administering authority will develop necessary and desirable environmental authority conditions, which will include baseline and impact monitoring conditions as part of the authorisation to undertake the activity.

Stimulation Impact Monitoring Program

If Arrow find there is a need to hydraulically stimulate any wells, Arrow will develop a stimulation impact monitoring program for each hydraulic stimulation campaign carried out in relation to the Project. The stimulation impact monitoring program will be developed in conjunction with the risk assessment required by conditions of an Environmental Authority.

The development of the stimulation impact monitoring program will consider all applicable environmental authority and legislative requirements as well as the findings from the EA assessment, which is aimed at identifying site specific conditions and management controls. The stimulation impact monitoring program will typically document the sampling requirements, sampling schedule and basis for assessment and comparison of the results. The stimulation impact monitoring program will be reviewed typically on an annual basis and updated as required.

9.3.9 Cumulative Impacts Management

A qualitative assessment of operating and proposed coal mines was completed as part of the supplementary assessment and identified that depressurisation impacts from mining activities are localised, and that contribution to subsidence and induced seismicity from mining projects are restricted in time and place. Therefore cumulative impacts from these aspects of surface activities are considered to be localised. In addition, it is noted that induced seismicity is inherently non-cumulative, due to the fact that such events, were they to occur, would be discrete in both time and place.

Due to data gaps, a quantitative assessment of cumulative impacts is not considered technically feasible until a future collective approach to the management of cumulative impacts is implemented and underpinned through statutory reporting obligations that provide adequate data, including mine dewatering, coal washing, and metered licensed use.

Interactions between coal seam gas production and coal mining operations will be managed with co-development agreements. These agreements will be established in areas of overlapping tenure and will be based on coordination of the activities of respective parties, and will provide the means to agree, monitor and communicate appropriate mechanisms to manage safety, commercial, operational and environmental matters.

9.4 Impact Significance Assessment

As presented in Section 9.1 the impact assessment method adopted for the groundwater technical study prepared for the EIS has been applied to the SREIS. The approach considers the sensitivity of an environmental value (Section 9.2) and the magnitude of potential impacts on that value (Section 8.2) to determine the significance of the impact.

Table 9.3, Table 9.4 and Table 9.5 present the assessment of impact significance of depressurisation, coal seam gas field development and coal seam gas water respectively, pre- and post-application of mitigation measures.

The mitigation measures presented in Tables 9.3 - 9.5 represent new mitigation measures not considered in the EIS, with the exception of where new impacts have been identified, in which case all relevant mitigation and management measures are presented.

Table 9.3: Assessment of Significance of Depressurisation Impacts

Impact	Groundwater system	Unmitigated Impact Significance			New Mitigation Measures	Residual (mitigated) impact significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Direct Impacts							
Potentiometric surface drawdown resulting in reduced supply to existing or future groundwater users.	Coal Seam Groundwater System	Moderate	High	High	• Underground water obligations (report obligations and make good obligations) • Arrow's procedure for hydraulic stimulation Refer Table 9-6 of Appendix L of the EIS for existing measures.	Very Low	Low
Potentiometric surface drawdown in the coal measures resulting in reduced groundwater availability to GDEs.	Coal Seam Groundwater System	Moderate	Moderate	Moderate	• Underground water obligations (report obligations) • EA application requirements (management of GDEs)	Very Low	Low
Potentiometric surface drawdown in the coal measures resulting in reduced supply to sites of cultural/spiritual value.	Coal Seam Groundwater System	Moderate	Moderate	Moderate	• EA application requirements (management of cultural and spiritual sites of significance)	Very Low	Low

Table 9.3: Assessment of Significance of Depressurisation Impacts (cont'd)

Impact	**Groundwater system**	**Unmitigated Impact Significance**			**New Mitigation Measures**	**Residual (mitigated) impact significance**	
		Sensitivity	**Magnitude**	**Significance Ranking**		**Magnitude**	**Significance Ranking**
Indirect Impacts							
Groundwater flux between adjacent aquifers above and below the coal measures causing groundwater quality impacts.	Shallow Groundwater System	Moderate	Very Low	Low	• Underground water obligations (report obligations and make good obligations) Refer Table 9-7 of Appendix L of the EIS for existing measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Very Low	Low		Very Low	Low
	Deep Groundwater System	Low	Very Low	Very Low		Very Low	Very Low
Potentiometric surface drawdown in adjacent aquifers causing reduced supply to existing or future groundwater users.	Shallow Groundwater System	Moderate	Moderate	Moderate	• Underground water obligations (report obligations and make good obligations) • Arrow's procedure for hydraulic stimulation Refer Table 9-7 of Appendix L of the EIS for existing measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Very Low	Low		Very Low	Low
	Deep Groundwater System	Low	Very Low	Very Low		Very Low	Very Low

Table 9.3: Assessment of Significance of Depressurisation Impacts (cont'd)

<table>
<tr><th rowspan="2">Impact</th><th rowspan="2">Groundwater system</th><th colspan="3">Unmitigated Impact Significance</th><th rowspan="2">New Mitigation Measures</th><th colspan="2">Residual (mitigated) impact significance</th></tr>
<tr><th>Sensitivity</th><th>Magnitude</th><th>Significance Ranking</th><th>Magnitude</th><th>Significance Ranking</th></tr>
<tr><td colspan="8">Indirect Impacts (cont'd)</td></tr>
<tr><td rowspan="3">Potentiometric surface drawdown in adjacent aquifers causing reduced groundwater availability for GDEs.</td><td>Shallow Groundwater System</td><td>Moderate</td><td>Moderate</td><td>Moderate</td><td rowspan="3">• Underground water obligations (report obligations)
• EA application requirements (management of GDEs)
Refer Table 9-7 of Appendix L of the EIS for existing measures.</td><td>Very Low</td><td>Low</td></tr>
<tr><td>Intermediate Groundwater System</td><td>Moderate</td><td>Moderate</td><td>Moderate</td><td>Very Low</td><td>Low</td></tr>
<tr><td>Deep Groundwater System</td><td>Low</td><td>Very Low</td><td>Very Low</td><td>Very Low</td><td>Very Low</td></tr>
<tr><td rowspan="3">Potentiometric surface drawdown in adjacent aquifers causing impacts to cultural/spiritual values.</td><td>Shallow Groundwater System</td><td>Moderate</td><td>Moderate</td><td>Moderate</td><td rowspan="3">• EA application requirements (management of cultural and spiritual sites of significance)
Refer Table 9-7 of Appendix L of the EIS for existing measures.</td><td>Very Low</td><td>Low</td></tr>
<tr><td>Intermediate Groundwater System</td><td>Moderate</td><td>Very Low</td><td>Low</td><td>Very Low</td><td>Low</td></tr>
<tr><td>Deep Groundwater System</td><td>Low</td><td>Very Low</td><td>Very Low</td><td>Very Low</td><td>Very Low</td></tr>
</table>

Table 9.3: Assessment of Significance of Depressurisation Impacts (cont'd)

Impact	Groundwater system	Unmitigated Impact Significance			New Mitigation Measures	Residual (mitigated) impact significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Indirect Impacts (cont'd)							
Potentiometric surface drawdown in adjacent aquifers due to leakage through coal seam gas wells (well failure) causing groundwater quality impacts from inter-aquifer flows.	Shallow Groundwater System	Moderate	Low	Moderate	• Code of Practice for Constructing and Abandoning Coal Seam Gas Wells in Queensland Refer Table 9-8 of Appendix L of the EIS for existing measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Deep Groundwater System	Low	Low	Low		Very Low	Very Low
Induced flow (leakage) between adjacent aquifers above and below the coal measures causing physical changes to aquifer structure leading to subsidence.	Shallow Groundwater System	Moderate	Very Low	Low	No planned mitigation and management measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Very Low	Low		Very Low	Low
	Deep Groundwater System	Low	Very Low	Very Low		Very Low	Very Low

Table 9.4: Assessment of Significance of Coal Seam Gas Field Development Impacts

Impact	Groundwater system	Unmitigated Impact Significance			New Mitigation Measures	Residual (mitigated) impact significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Well Development and Sub-surface Impacts							
Production well installation – cross contamination of aquifers.	Shallow Groundwater System	Moderate	Low	Moderate	• Code of Practice for Constructing and Abandoning Coal Seam Gas Wells in Queensland. Refer Table 9-8 of Appendix L of the EIS for existing measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Coal Seam Groundwater System	Moderate	Low	Moderate		Very Low	Low
Production well installation – contamination by drilling process.	Shallow Groundwater System	Moderate	Low	Moderate	• Code of Practice for Constructing and Abandoning Coal Seam Gas Wells in Queensland. Refer Table 9-8 of Appendix L of the EIS for existing measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Coal Seam Groundwater System	Moderate	Low	Moderate		Very Low	Low

Table 9.4: Assessment of Significance of Coal Seam Gas Field Development Impacts (cont'd)

Impact	Groundwater system	Unmitigated Impact Significance			New Mitigation Measures	Residual (mitigated) impact significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Well Development and Sub-surface Impacts (cont'd)							
Production well installation – contamination by surface process.	Shallow Groundwater System	Moderate	Low	Moderate	• Code of Practice for Constructing and Abandoning Coal Seam Gas Wells in Queensland. Refer Table 9-8 of Appendix L of the EIS for existing measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Coal Seam Groundwater System	Moderate	Low	Moderate		Very Low	Low
Hydraulic stimulation – contamination by surface process.	Shallow Groundwater System	Moderate	Low	Moderate	• Arrow's procedure for hydraulic stimulation.	Very Low	Low
	Intermediate Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Coal Seam Groundwater System	Moderate	Low	Moderate		Very Low	Low

Table 9.4: Assessment of Significance of Coal Seam Gas Field Development Impacts (cont'd)

Impact	Groundwater system	Unmitigated Impact Significance			New Mitigation Measures	Residual (mitigated) impact significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Well Development and Sub-surface Impacts (cont'd)							
Hydraulic stimulation – contamination by surface process. (cont'd)	Deep Groundwater System	Low	Low	Low		Very Low	Very Low
Hydraulic stimulation – cross-contamination of aquifers.	Shallow Groundwater System	Moderate	Low	Moderate	• Arrow's procedure for hydraulic stimulation.	Very Low	Low
	Intermediate Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Coal Seam Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Deep Groundwater System	Low	Low	Low		Very Low	Very Low

Table 9.4: Assessment of Significance of Coal Seam Gas Field Development Impacts (cont'd)

Impact	Groundwater system	Unmitigated Impact Significance			New Mitigation Measures	Residual (mitigated) impact significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Well Development and Sub-surface Impacts (cont'd)							
Hydraulic stimulation - induced seismicity	Shallow Groundwater System	Moderate	Low	Moderate	• Arrow's procedure for hydraulic stimulation (including avoiding hydraulic stimulation near known faults)	Very Low	Low
	Intermediate Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Coal Seam Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Deep Groundwater System	Low	Low	Low		Very Low	Very Low
Monitoring bore installation – cross-contamination of aquifers.	Shallow Groundwater System	Moderate	Low	Moderate	No new mitigation measures. Refer Table 9-8 of Appendix L of the EIS for existing measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Low	Moderate		Very Low	Low

Table 9.4: Assessment of Significance of Coal Seam Gas Field Development Impacts (cont'd)

Impact	Groundwater system	Unmitigated Impact Significance			New Mitigation Measures	Residual (mitigated) impact significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Well Development and Sub-surface Impacts (cont'd)							
Monitoring bore installation – cross-contamination of aquifers. (cont'd)	Coal Seam Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Deep Groundwater System	Low	Low	Low		Very Low	Very Low
Monitoring bore installation – contamination by drilling process.	Shallow Groundwater System	Moderate	Low	Moderate	No new mitigation measures. Refer Table 9-8 of Appendix L of the EIS for existing measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Coal Seam Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Deep Groundwater System	Low	Low	Low		Very Low	Very Low

Table 9.4: Assessment of Significance of Coal Seam Gas Field Development Impacts (cont'd)

Impact	Groundwater system	Unmitigated Impact Significance			New Mitigation Measures	Residual (mitigated) impact significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Well Development and Sub-surface Impacts (cont'd)							
Monitoring bore installation – contamination by surface process.	Shallow Groundwater System	Moderate	Low	Moderate	No new mitigation measures. Refer Table 9-8 of Appendix L of the EIS for existing measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Coal Seam Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Deep Groundwater System	Low	Low	Low		Very Low	Very Low
Installation of other sub-surface infrastructure (e.g. gathering lines and underground storage tanks) – contamination from leaks and spills.	Shallow Groundwater System	Moderate	Moderate	Moderate	No new mitigation measures. Refer Table 9-8 of Appendix L of the EIS for existing measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Low	Moderate		Very Low	Low

Table 9.4: Assessment of Significance of Coal Seam Gas Field Development Impacts (cont'd)

Impact	Groundwater system	Unmitigated Impact Significance			New Mitigation Measures	Residual (mitigated) impact significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Well Development and Sub-surface Impacts (cont'd)							
Installation of other sub-surface infrastructure (e.g. gathering lines and underground storage tanks) – contamination from leaks and spills. (cont'd)	Coal Seam Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Deep Groundwater System	Low	Low	Moderate		Very Low	Very Low
Surface storage of chemicals, fuels, oils – contamination of groundwater systems.	Shallow Groundwater System	Moderate	Moderate	Moderate	No new mitigation measures. Refer Table 9-8 of Appendix L of the EIS for existing measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Coal Seam Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Deep Groundwater System	Low	Low	Low		Very Low	Very Low

Table 9.4: Assessment of Significance of Coal Seam Gas Field Development Impacts (cont'd)

Impact	Groundwater system	Unmitigated Impact Significance			New Mitigation Measures	Residual (mitigated) impact significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Well Development and Sub-surface Impacts (cont'd)							
Waste generation and storage (including brine) – contamination of groundwater systems.	Shallow Groundwater System	Moderate	Moderate	Moderate	No new mitigation measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Coal Seam Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Deep Groundwater System	Low	Low	Low		Very Low	Very Low
Waste water and sanitation (effluent) – contamination of groundwater systems.	Shallow Groundwater System	Moderate	Moderate	Moderate	No new mitigation measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Low	Moderate		Very Low	Low

Table 9.4: Assessment of Significance of Coal Seam Gas Field Development Impacts (cont'd)

Impact	Groundwater system	Unmitigated Impact Significance			New Mitigation Measures	Residual (mitigated) impact significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Well Development and Sub-surface Impacts (cont'd)							
Waste water and sanitation (effluent) – contamination of groundwater systems. (cont'd)	Coal Seam Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Deep Groundwater System	Low	Low	Low		Very Low	Very Low
Infrastructure Footprint Impacts							
Reduced aquifer recharge due to placement of impervious surface coverings.	Shallow Groundwater System	Moderate	Low	Moderate	No new mitigation measures. Refer Table 9-8 of Appendix L of the EIS for existing measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Very Low	Low		Very Low	Low
	Coal Seam Groundwater System	Moderate	Very Low	Low		Very Low	Very Low
	Deep Groundwater System	Low	Very Low	Very Low		Very Low	Very Low

Table 9.4: Assessment of Significance of Coal Seam Gas Field Development Impacts (cont'd)

Impact	Groundwater system	Unmitigated Impact Significance			New Mitigation Measures	Residual (mitigated) impact significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Infrastructure Footprint Impacts (cont'd)							
General impacts associated with installation of FCFs and CGPFs.	Shallow Groundwater System	Moderate	Moderate	Moderate	No new mitigation measures. Refer Table 9-8 of Appendix L of the EIS for existing measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Coal Seam Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Deep Groundwater System	Low	Low	Low		Very Low	Very Low

Table 9.5: Assessment of Significance of Coal Seam Gas Water Impacts

Impact	Groundwater system	Unmitigated Impact Significance			New Mitigation Measures	Residual (mitigated) impact significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Impact caused by seepage of untreated coal seam gas water from storage facilities.	Shallow Groundwater System	Moderate	Very Low	Low	No new mitigation measures. Refer Table 9-8 of Appendix L of the EIS for existing measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Moderate	Moderate		Very Low	Low
	Coal Seam Groundwater System	Moderate	Moderate	Moderate		Very Low	Low
	Deep Groundwater System	Low	Very Low	Very Low		Very Low	Very Low
Altered groundwater flow direction caused by seepage from coal seam gas water storage facilities.	Shallow Groundwater System	Moderate	Very Low	Low	No new mitigation measures. Refer Table 9-8 of Appendix L of the EIS for existing measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Coal Seam Groundwater System	Moderate	Low	Moderate		Very Low	Low

Table 9.5: Assessment of Significance of Coal Seam Gas Water Impacts (cont'd)

Impact	Groundwater system	Unmitigated Impact Significance			New Mitigation Measures	Residual (mitigated) impact significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Altered groundwater flow direction caused by seepage from coal seam gas water storage facilities. (cont'd)	Deep Groundwater System	Low	Very Low	Very Low		Very Low	Very Low
Impact caused by seepage of brine from storage facilities.	Shallow Groundwater System	Moderate	Very Low	Low	No new mitigation measures. Refer Table 9-8 of Appendix L of the EIS for existing measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Moderate	Moderate		Very Low	Low
	Coal Seam Groundwater System	Moderate	Moderate	Moderate		Very Low	Low
	Deep Groundwater System	Low	Very Low	Very Low		Very Low	Very Low
Unplanned discharge of untreated coal seam gas water to the land surface.	Shallow Groundwater System	Moderate	Moderate	Moderate	No new mitigation measures. Refer Table 9-8 of Appendix L of the EIS for existing measures.	Very Low	Low

Table 9.5: Assessment of Significance of Coal Seam Gas Water Impacts (cont'd)

Impact	Groundwater system	Unmitigated Impact Significance			New Mitigation Measures	Residual (mitigated) impact significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Unplanned discharge of untreated coal seam gas water to the land surface. (cont'd)	Intermediate Groundwater System	Moderate	Moderate	Moderate		Very Low	Low
	Coal Seam Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Deep Groundwater System	Low	Low	Low		Very Low	Very Low
Unplanned discharge of untreated water or brine to the land surface.	Shallow Groundwater System	Moderate	Moderate	Moderate	No new mitigation measures. Refer Table 9-8 of Appendix L of the EIS for existing measures.	Very Low	Low
	Intermediate Groundwater System	Moderate	Moderate	Moderate		Very Low	Low
	Coal Seam Groundwater System	Moderate	Low	Moderate		Very Low	Low
	Deep Groundwater System	Low	Low	Low		Very Low	Very Low

Table 9.5: Assessment of Significance of Coal Seam Gas Water Impacts (cont'd)

Impact	Groundwater system	Unmitigated Impact Significance			New Mitigation Measures	Residual (mitigated) impact significance	
		Sensitivity	Magnitude	Significance Ranking		Magnitude	Significance Ranking
Infrastructure for distribution of produced water.	Impact may occur where untreated water or brine enters the environment from spills or leaks from distribution infrastructure. This impact is assessed under *Installation of other sub-surface infrastructure (e.g. gathering lines and underground storage tanks) – contamination from leaks and spills* in Table 9.4.						

10 CONCLUSIONS

The supplementary groundwater assessment was prepared in response to the comments and submissions received on the EIS. The objectives were to consider the revised project description, information not presented in the EIS, changes to legislation and the regulatory framework, and new relevant technical information, including identification of any significant changes in the potential groundwater impacts associated with the Project to:

- Evaluate whether the impact predictions reported in the EIS and SREIS for Arrow-only production are understated;
- Evaluate the suitability of mitigation and management measures presented in the EIS; and
- Consider whether any additional mitigation and management measures would be required, and whether any are no longer relevant to the Project.

The supplementary groundwater assessment built on the information provided in the EIS through the detailed review and analysis of some key information sources. Specifically, the following areas were focussed on with respect to improving understanding to inform the impact assessment process:

- The role faulting and folding has on the movement of groundwater and how the drawdown associated with depressurisation of the coal seam gas targets may be influenced by these features;
- Areas where the alluvial and sedimentary aquifers may be directly underlain by coal formations and there is the potential for increased hydraulic connectivity between the groundwater systems;
- The potential for coal seam gas production induced subsidence;
- Mechanisms associated with induced seismicity in response to coal seam gas extraction and hydraulic stimulation; and
- The types of GDEs present within the Project area and immediate surrounds, their potential connectivity to various aquifer units, groundwater chemistry characteristics and ecological values.

Further numerical groundwater modelling was undertaken to address specific aspects such as faults, at a local scale. The additional groundwater model scenarios simulated the potential for faults to provide preferential pathways between aquifers, and considered how the effect of such changes to aquifer interconnectivity would influence the potential drawdown impacts caused by the Project. Overall it was considered that the modelling predictions remain unchanged from the EIS and is considered to conservatively represent the potential drawdown resulting from coal seam gas depressurisation.

The impact assessment framework adopted for the EIS was re-applied for potential project impacts confirmed or identified in the SREIS. It was demonstrated that the residual significance assessment in the EIS did not understate the mitigated impacts, and that where additional potential impacts were identified, these could be mitigated such that residual impact significance is low or very low.

A review of mitigation and management measures identified in the EIS showed that the measures are still predominantly relevant for the management of groundwater-related impacts subject to the minor revisions detailed in this report.

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Important information about your Coffey Environmental Report

Introduction

This report has been prepared by Coffey for you, as Coffey's client, in accordance with our agreed purpose, scope, schedule and budget.

The report has been prepared using accepted procedures and practices of the consulting profession at the time it was prepared, and the opinions, recommendations and conclusions set out in the report are made in accordance with generally accepted principles and practices of that profession.

The report is based on information gained from environmental conditions (including assessment of some or all of soil, groundwater, vapour and surface water) and supplemented by reported data of the local area and professional experience. Assessment has been scoped with consideration to industry standards, regulations, guidelines and your specific requirements, including budget and timing. The characterisation of site conditions is an interpretation of information collected during assessment, in accordance with industry practice,

This interpretation is not a complete description of all material on or in the vicinity of the site, due to the inherent variation in spatial and temporal patterns of contaminant presence and impact in the natural environment. Coffey may have also relied on data and other information provided by you and other qualified individuals in preparing this report. Coffey has not verified the accuracy or completeness of such data or information except as otherwise stated in the report. For these reasons the report must be regarded as interpretative, in accordance with industry standards and practice, rather than being a definitive record.

Your report has been written for a specific purpose

Your report has been developed for a specific purpose as agreed by us and applies only to the site or area investigated. Unless otherwise stated in the report, this report cannot be applied to an adjacent site or area, nor can it be used when the nature of the specific purpose changes from that which we agreed.

For each purpose, a tailored 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 potential contamination pose in the context of the agreed purpose. Such risks may be financial (for example, clean up costs or constraints on site use) and/or physical (for example, potential health risks to users of the site or the general public).

Limitations of the Report

The work was conducted, and the report has been prepared, in response to an agreed purpose and scope, within 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 that purpose and scope, requirements, data or information, and they could change if such requirements or data are inaccurate or incomplete.

This report is valid as of the date of preparation. The condition of the site (including subsurface conditions) and extent or nature of contamination or other environmental hazards can change over time, as a result of either natural processes or human influence. Coffey should be kept appraised of any such events and should be consulted for further investigations if any changes are noted, particularly during construction activities where excavations often reveal subsurface conditions.

In addition, advancements in professional practice regarding contaminated land and changes in applicable statues and/or guidelines may affect the validity of this report. Consequently, the currency of conclusions and recommendations in this report should be verified if you propose to use this report more than 6 months after its date of issue.

The report does not include the evaluation or assessment of potential geotechnical engineering constraints of the site.

Interpretation of factual data

Environmental site assessments identify actual conditions only at those points where samples are taken and on the date collected. 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.

Variations in soil and groundwater conditions may occur between test or sample locations and actual conditions may differ from those inferred to exist. No environmental assessment program, no matter how comprehensive, can reveal all subsurface details and anomalies. Similarly, no professional, no matter how well qualified, can reveal what is hidden by earth, rock or changed through time.

The actual interface between different 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 a suitably qualified and experienced environmental consultant through the development and use of the site to identify variances, conduct additional tests if required, and recommend solutions to unexpected conditions or other unrecognised features encountered on site. Coffey would be pleased to assist with any investigation or advice in such circumstances.

Recommendations in this report

This report assumes, in accordance with industry practice, that the site conditions recognised through discrete sampling are representative of actual conditions throughout the investigation area. Recommendations are based on the resulting interpretation.

Should further data be obtained that differs from the data on which the report recommendations are based (such as through excavation or other additional assessment), then the recommendations would need to be reviewed and may need to be revised.

Report for benefit of client

Unless otherwise agreed between us, the report has been prepared for your benefit and no other party. Other parties should not rely upon the report or the accuracy or completeness of any recommendation and should make their own enquiries and obtain independent advice in relation to such matters.

Coffey assumes no responsibility and will not be liable to any other person or organisation for, or in relation to, any matter dealt with or conclusions expressed in the report, or for any loss or damage suffered by any other person or organisation arising from matters dealt with or conclusions expressed in the report.

To avoid misuse of the information presented in your report, we recommend that Coffey be consulted before the report is provided to another party who may not be familiar with the background and the purpose of the report. In particular, an environmental disclosure report for a property vendor may not be suitable for satisfying the needs of that property's purchaser. This report should not be applied for any purpose other than that stated in the report.

Interpretation by other professionals

Costly problems can occur when other professionals develop their plans based on misinterpretations of a report. To help avoid misinterpretations, a suitably qualified and experienced environmental consultant should be retained to explain the implications of the report to other professionals referring to the report and then review plans and specifications produced to see how other professionals have incorporated the report findings.

Given Coffey prepared the report and has familiarity with the site, Coffey is well placed to provide such assistance. If another party is engaged to interpret the recommendations of the report, there is a risk that the contents of the report may be misinterpreted and Coffey disowns any responsibility for such misinterpretation.

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 or engineers based on their interpretation of field logs, field testing and laboratory evaluation of samples. This information should not under any circumstances be redrawn for inclusion in other documents or separated from the report in any way.

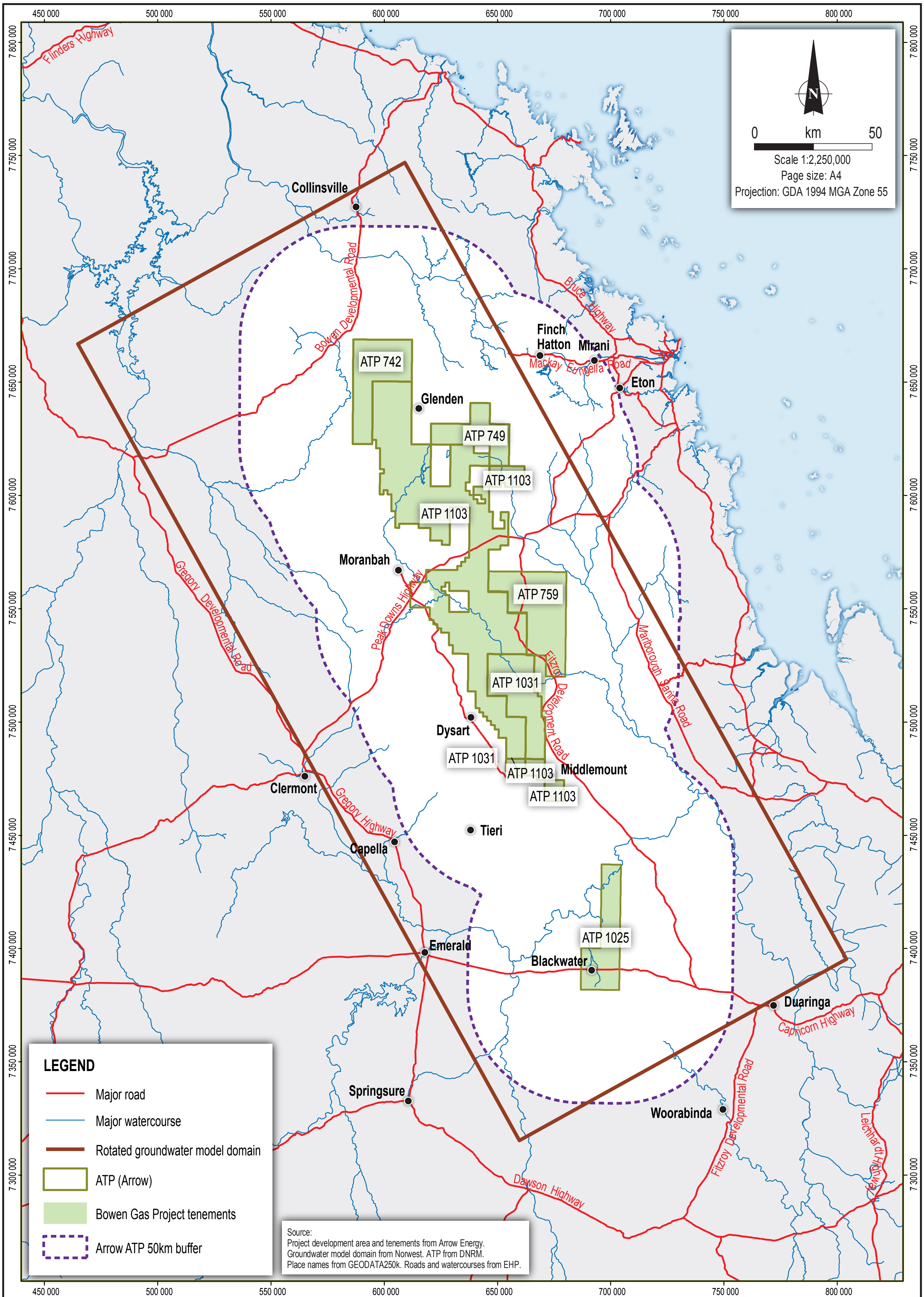
This report should be reproduced in full. No responsibility is accepted for use of any part of this report in any other context or for any other purpose or by third parties.

Responsibility

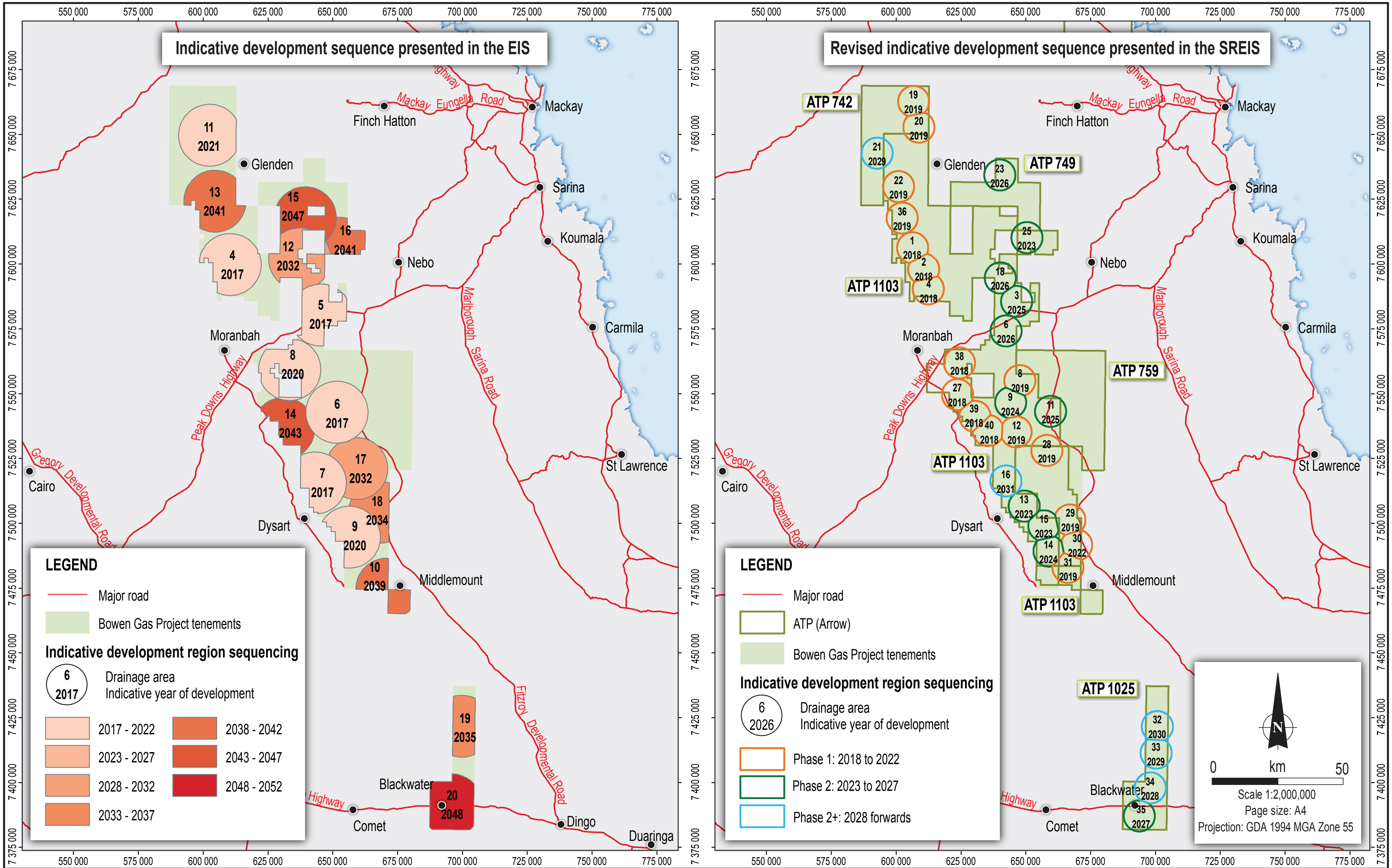
Environmental reporting relies on interpretation of factual information using professional judgement and opinion and has a level of uncertainty attached to it, which is much less exact than other design disciplines. This has often resulted in claims being lodged against consultants, which are unfounded. As noted earlier, the recommendations and findings set out in this report should only be regarded as interpretive and should not be taken as accurate and complete information about all environmental media at all depths and locations across the site.

Figures

Supplementary Groundwater Assessment
Arrow Energy Bowen Gas Project
Supplementary Report to the EIS



coffey	Date: 15.04.2014 MXT: 7043_02_GIS038_v1_3 File Name: 7043_02_F01.01_GIS_GL_2	Arrow Energy Limited Bowen Gas Project	arrow energy go further	Bowen Gas Project supplementary groundwater assessment boundaries	Figure No: 1.1



Source
Project area and development areas from Arrow Energy.
Watercourses, roads and locations of interest from EHP.
EPP tenements from DNRM (November 2013).

coffey

Date: 16.04.2014
MXT: 7043_02_GIS004_v1_7
File Name: 7043_02_F02.01_GIS_GL_2

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Bowen Gas Project

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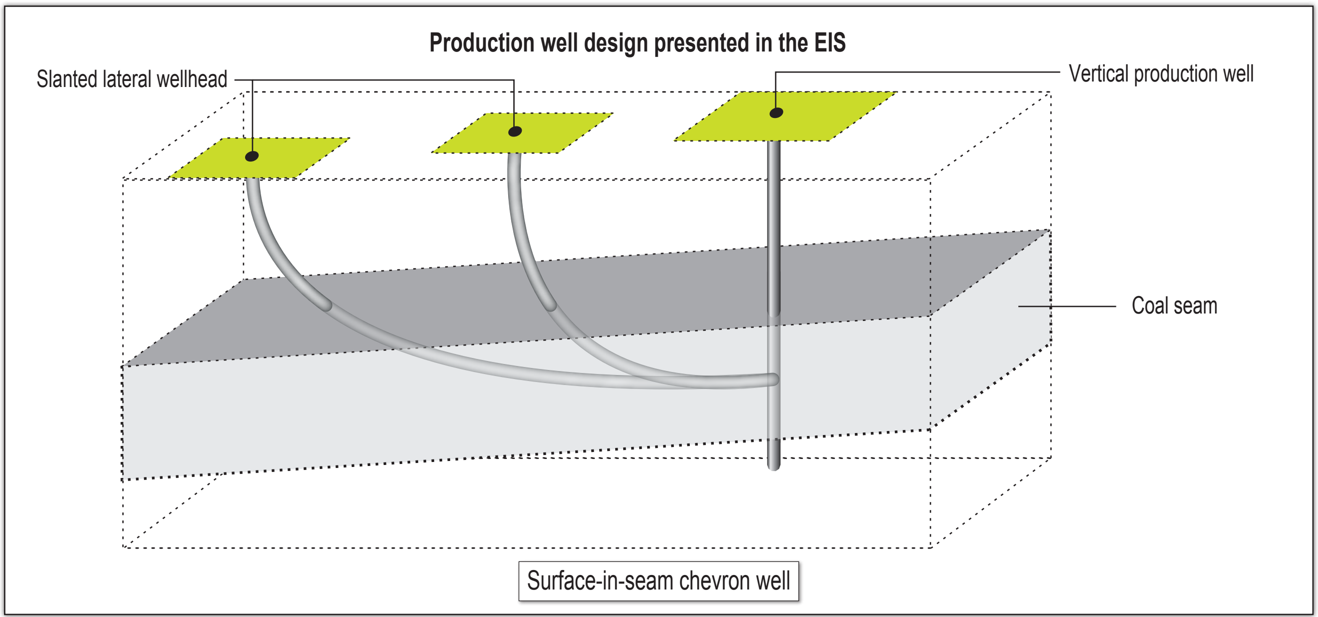
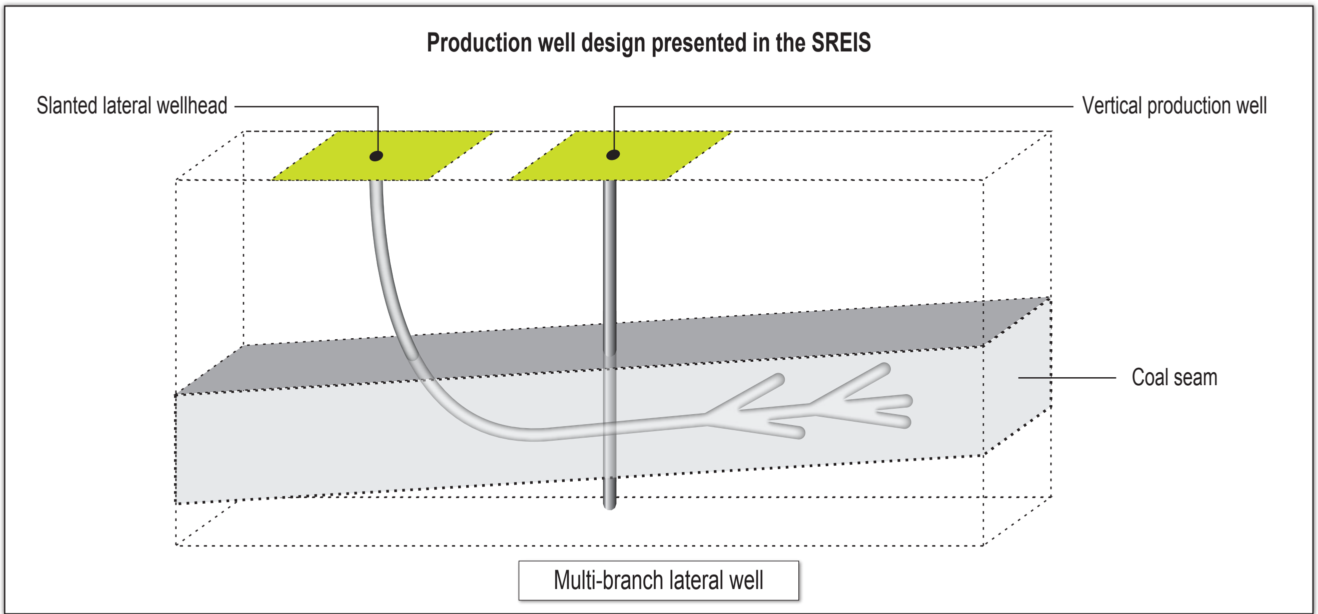
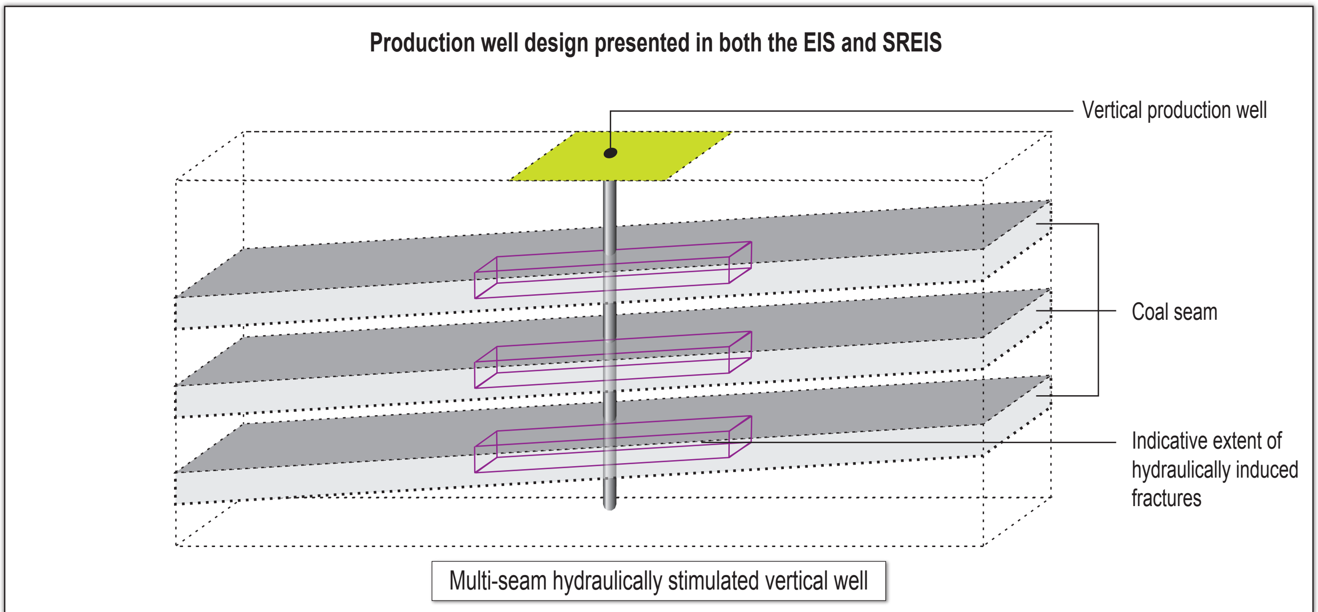
EIS and SREIS indicative development sequences

Figure No: 2.1

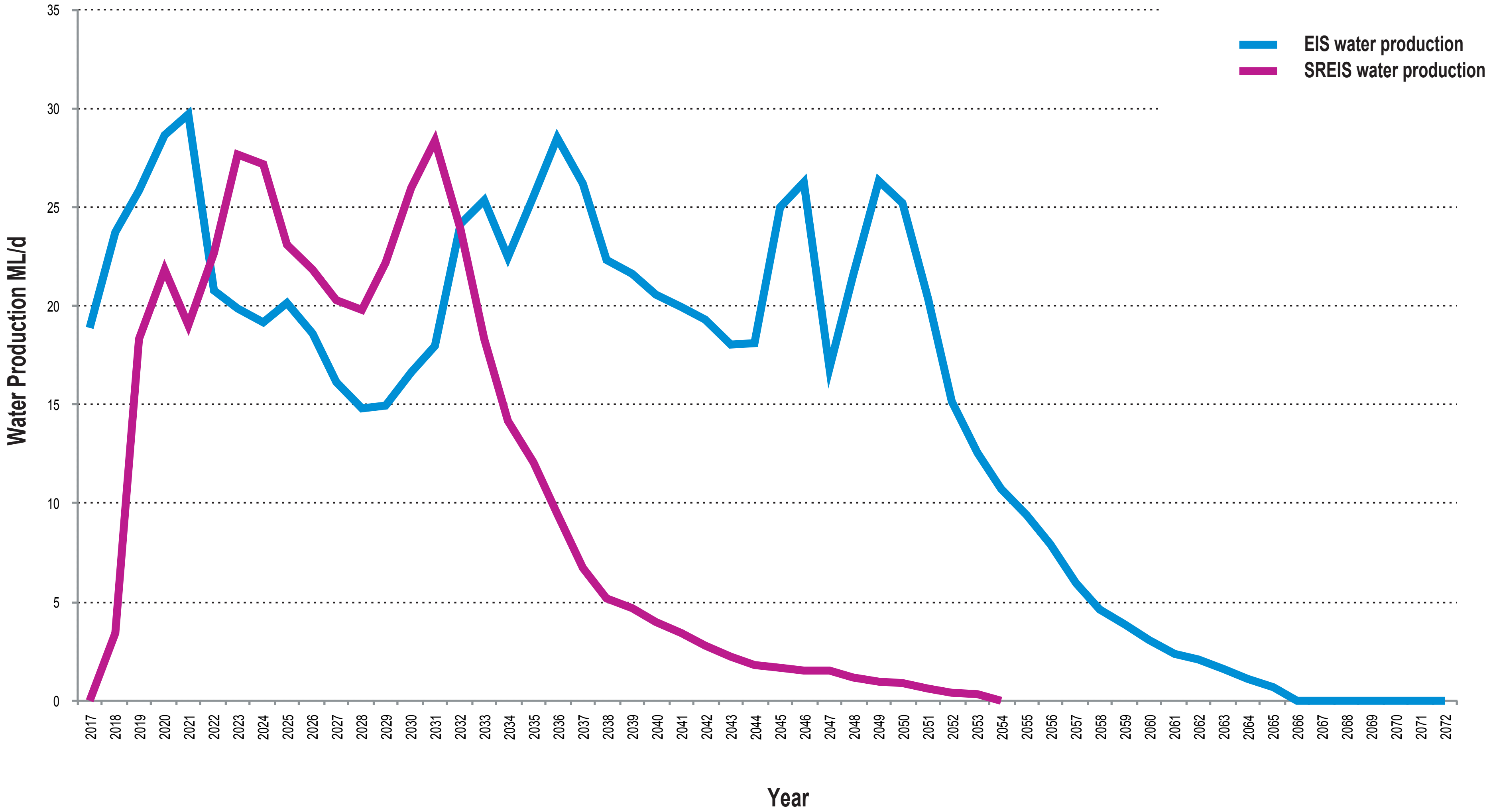




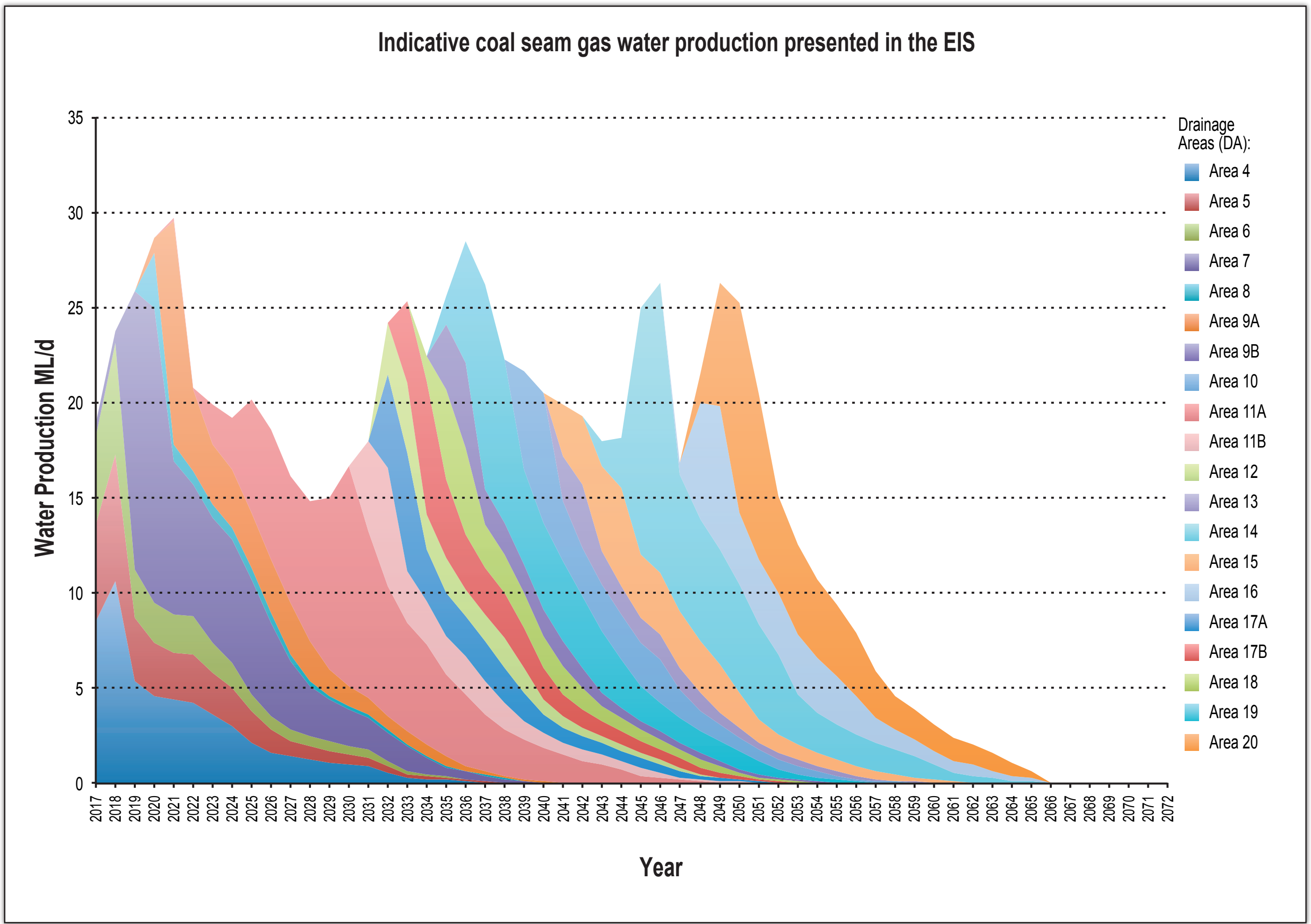


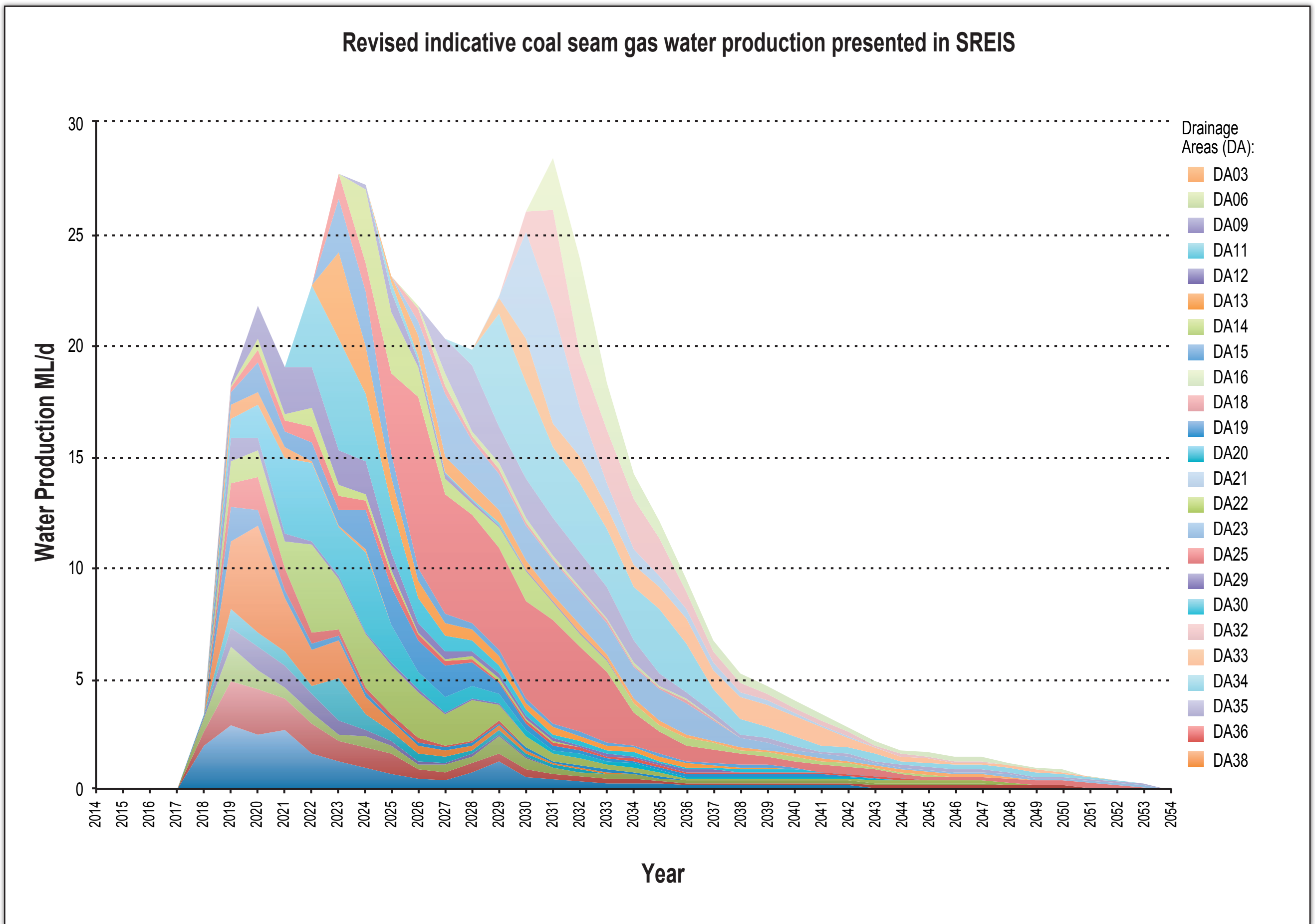
Source: Reproduced from schematics provided by Arrow Energy

coffey	Date: 04.04.2014	Arrow Energy Limited	arrow energy go further	Typical schematics of production well designs presented in the EIS and SREIS	Figure No: 2.2
	File Name: 7043_02_F02.02_GL_4	Bowen Gas Project			



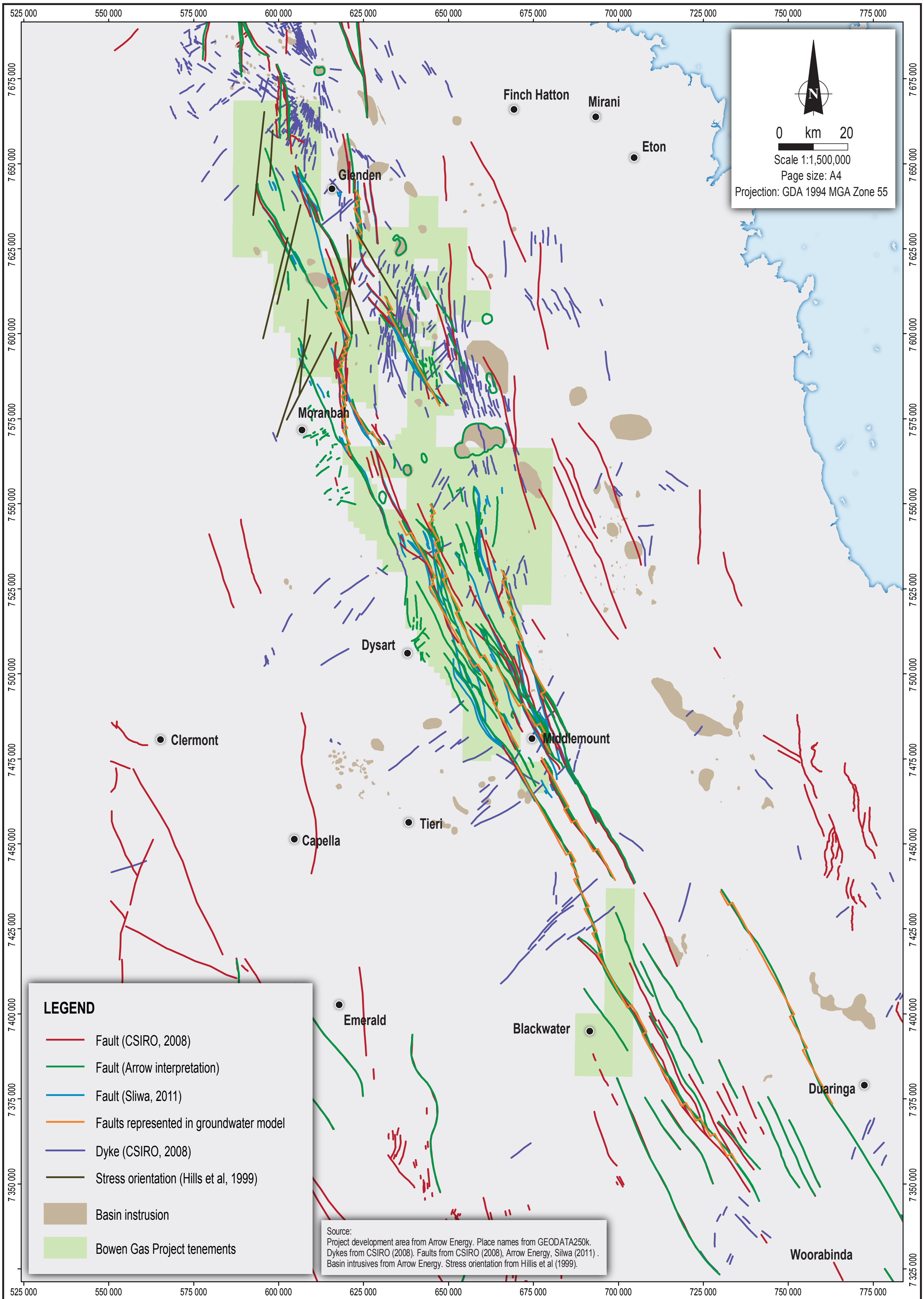
Source: Water production data provided by Arrow Energy	coffey	Date: 02.01.2014 File Name: 7043_02_F02.03_GL_3	Arrow Energy Limited Bowen Gas Project	arrow energy go further	Indicative water production presented in the EIS and SREIS	Figure No: 2.3





Source: Water production data provided by Arrow Energy

coffey	Date: 02.01.2014 File Name: 7043_02_F02.04_GL_5	Arrow Energy Limited Bowen Gas Project	arrow energy go further	Indicative annual average coal seam gas water production in the EIS and SREIS	Figure No: 2.4



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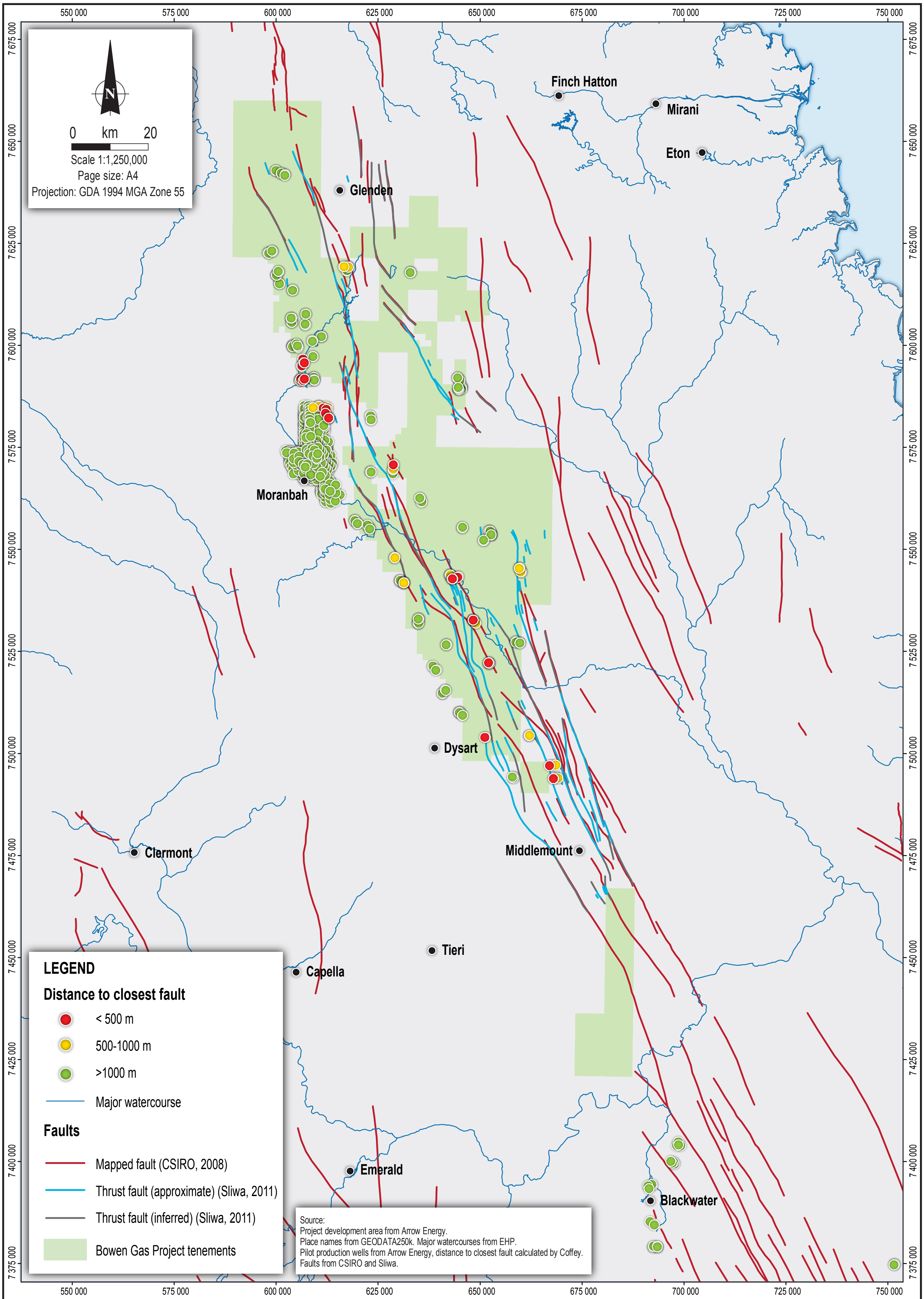
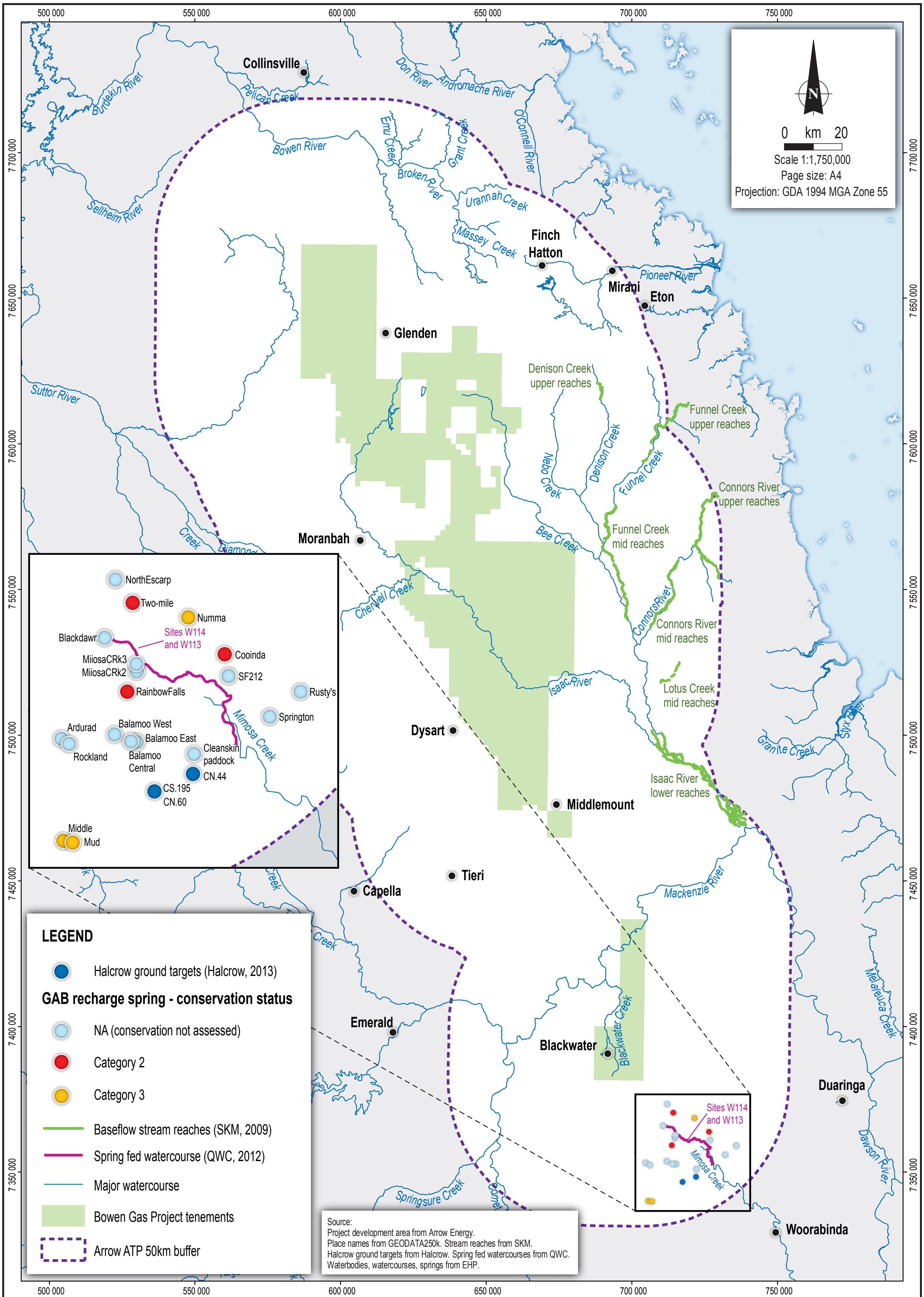
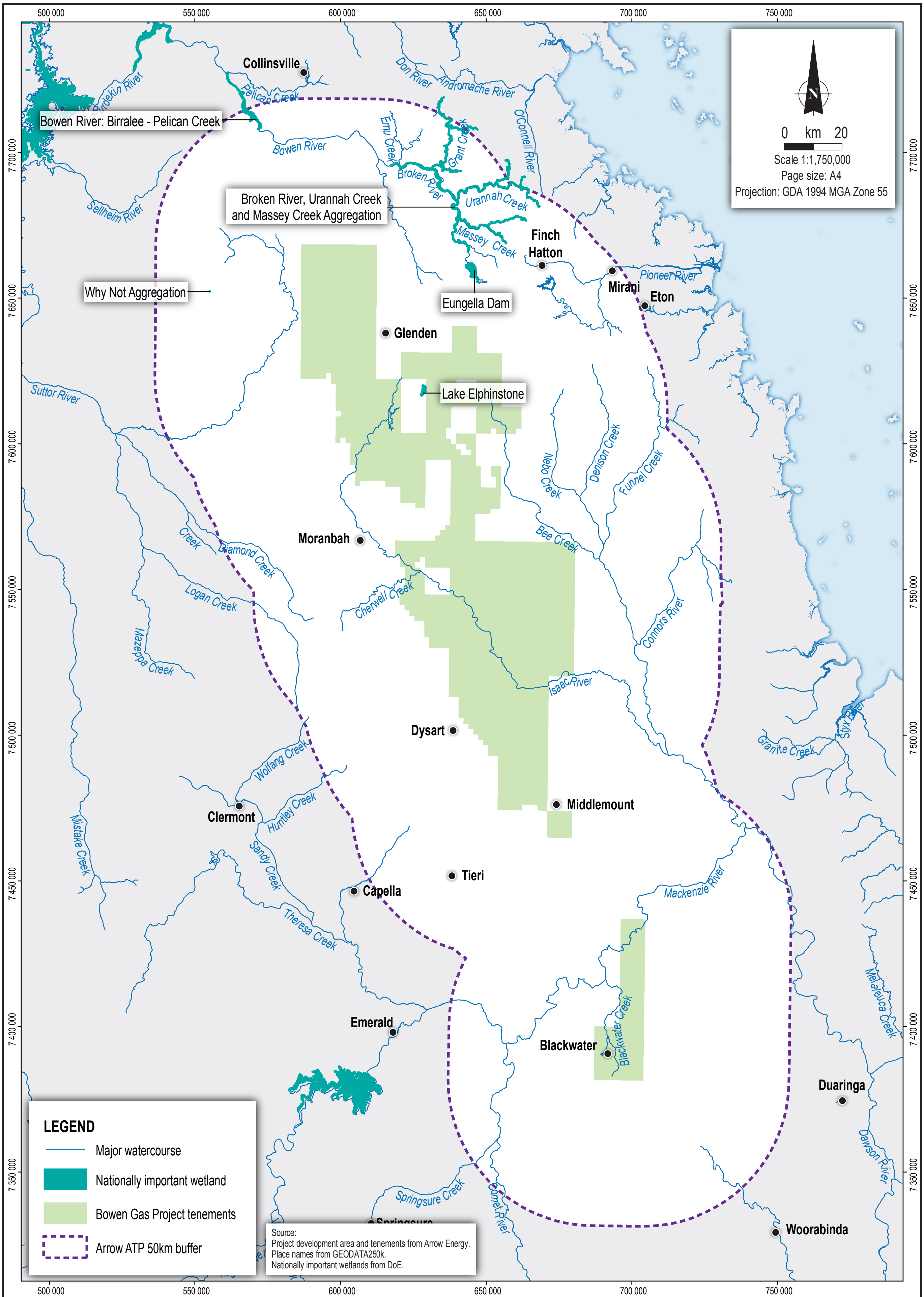


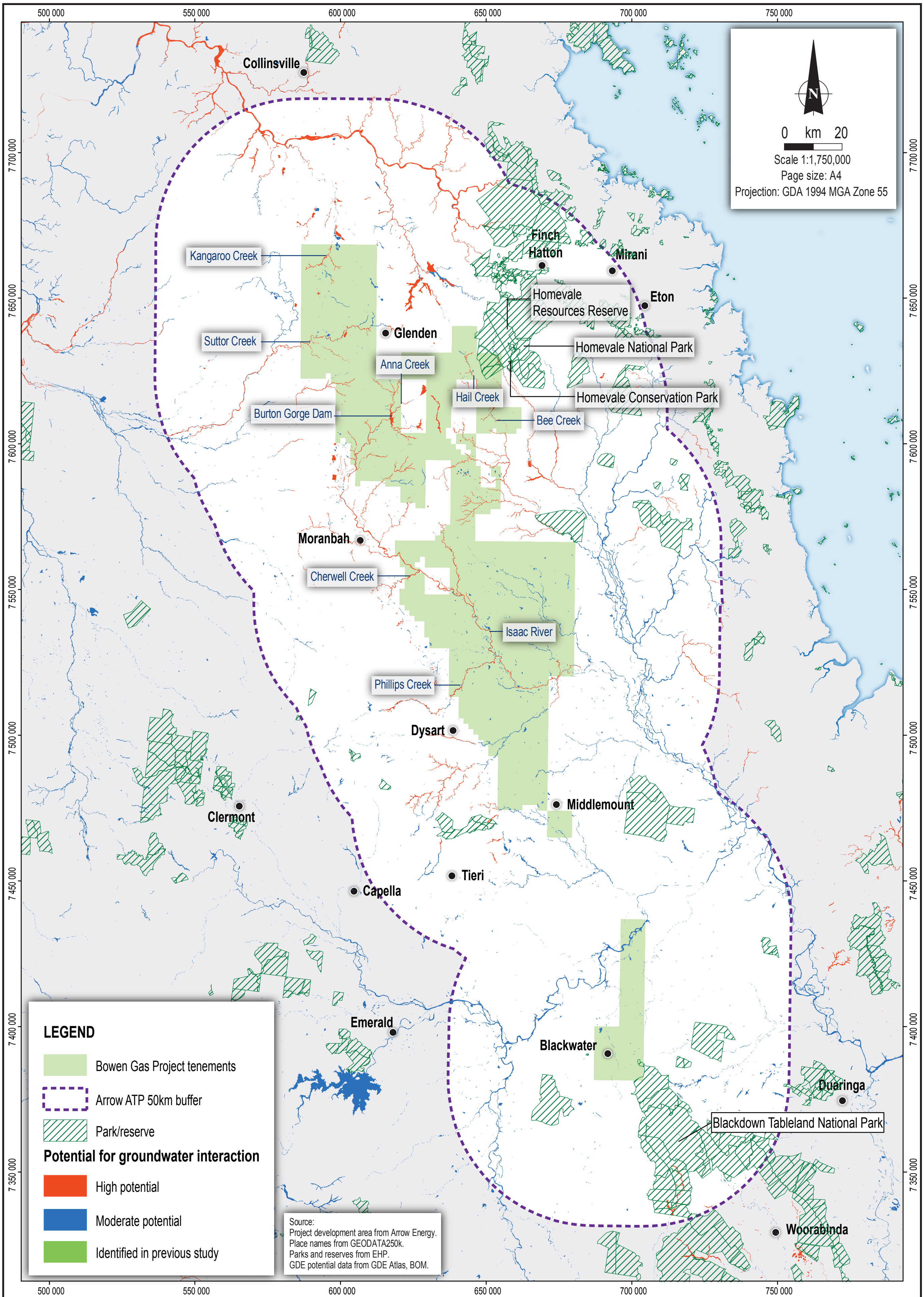
coffey	Date: 17.04.2014 MXT: 7043_02_GIS015_v1_5 File Name: 7043_02_F05.2_GIS_GL_3	Arrow Energy Limited Bowen Gas Project	arrow energy go further	Pilot and production well proximity to known faults	Figure No: 5.2



coffey	Date: 17.04.2014 MXT: 7043_02_GIS010_v1_4 File Name: 7043_02_F05.03_GIS_GL_3	Arrow Energy Limited Bowen Gas Project	arrow energy go further	Mapped spring vents and watercourse springs	Figure No: 5.3



coffey	Date: 17.04.2014 MXT: 7043_02_GIS011_v1_4 File Name: 7043_02_F05.04_GIS_GL_4	Arrow Energy Limited Bowen Gas Project	arrow energy go further	Nationally important wetlands	Figure No: 5.4



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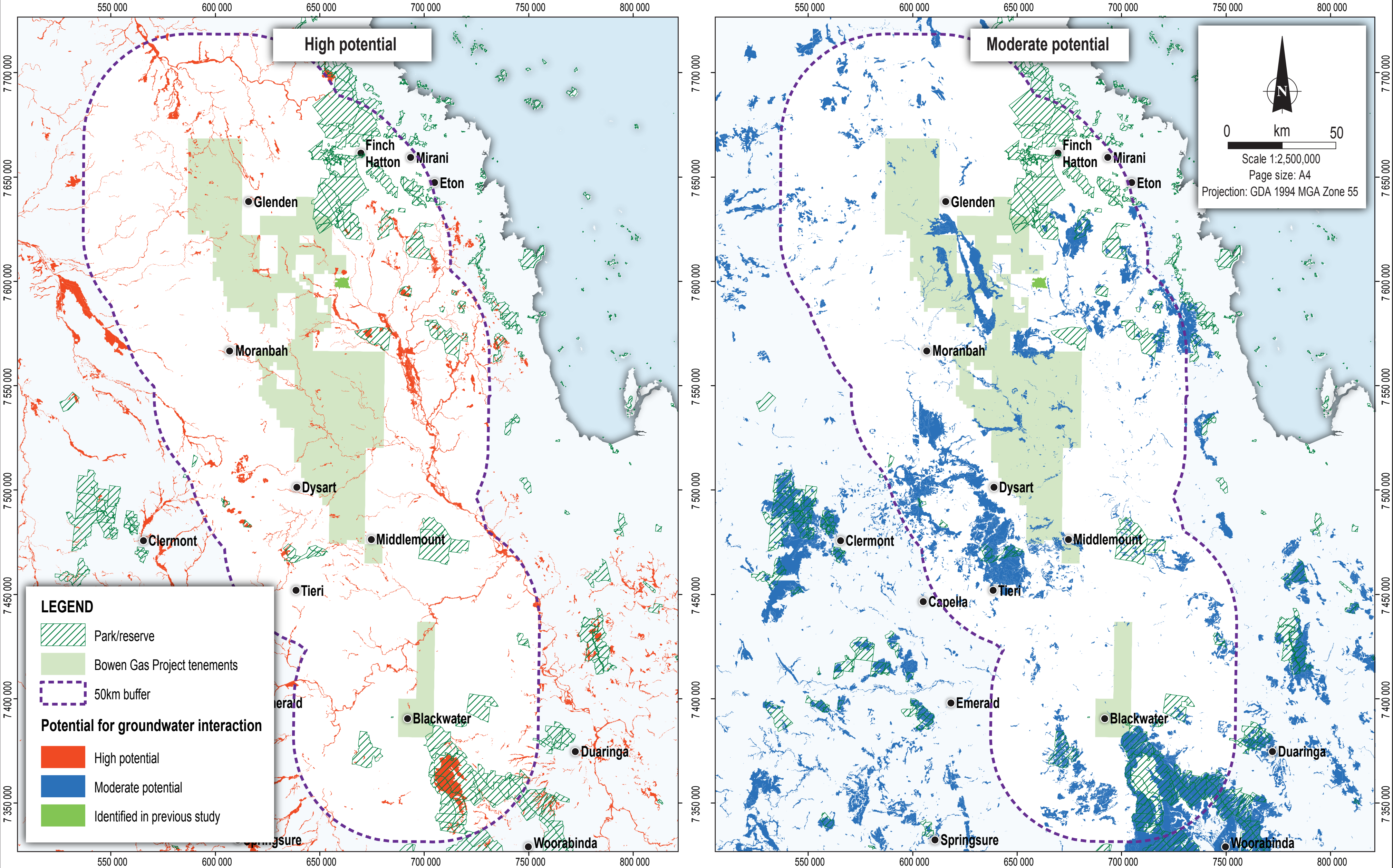


Source:
Project development area from Arrow Energy.
Place names from GEODATA250k.
Parks/reserves from EHP.
GDE potential data from GDE Atlas, BOM.

coffey

Date: 16.04.2014
MXT: 7043_02_GIS013_v1_5
File Name: 7043_02_F05.6_GIS_GL_2

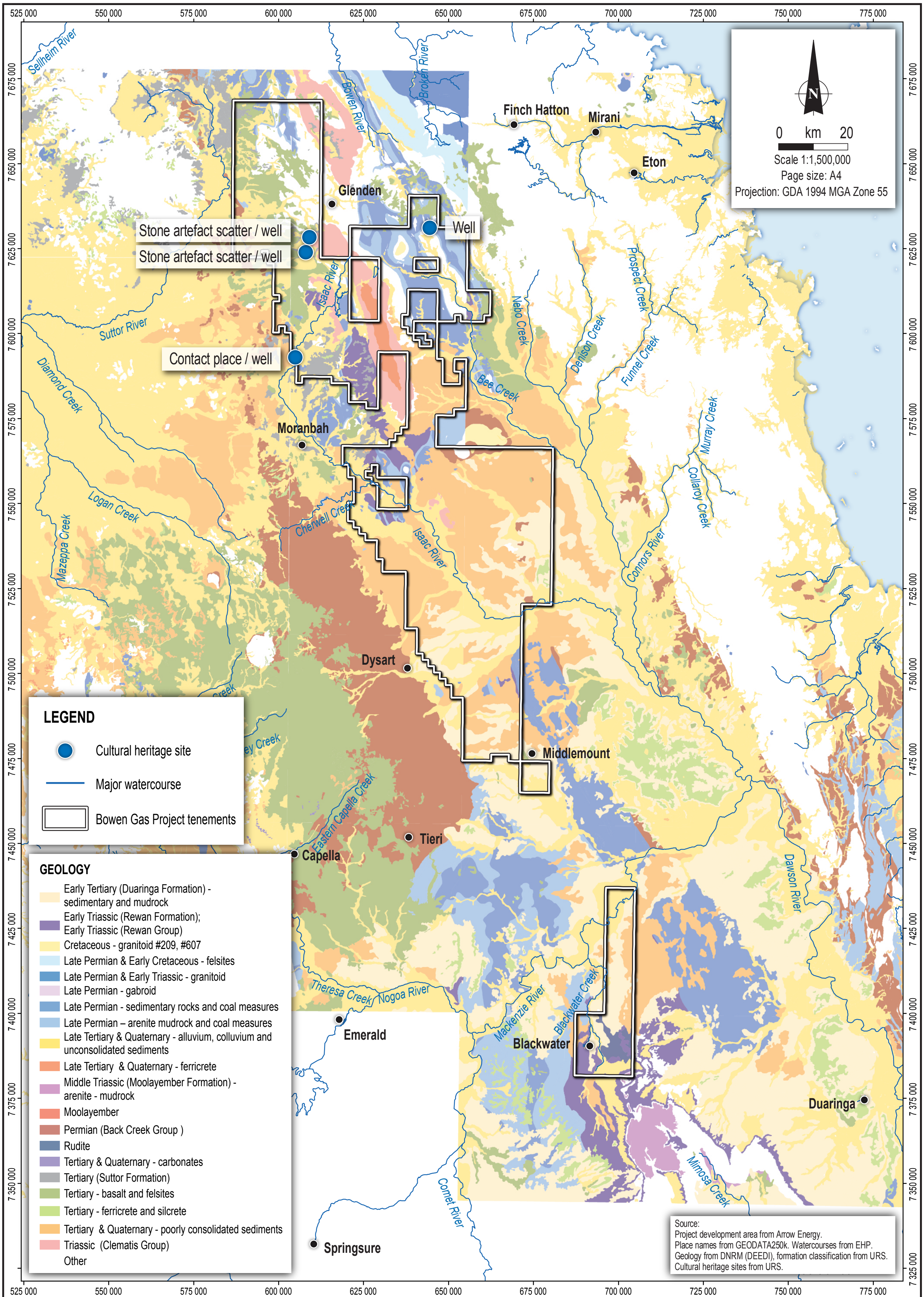
Arrow Energy Limited

Bowen Gas Project

arrow energy go further

Mapped GDEs potentially using the subsurface presence of groundwater

Figure No: 5.6



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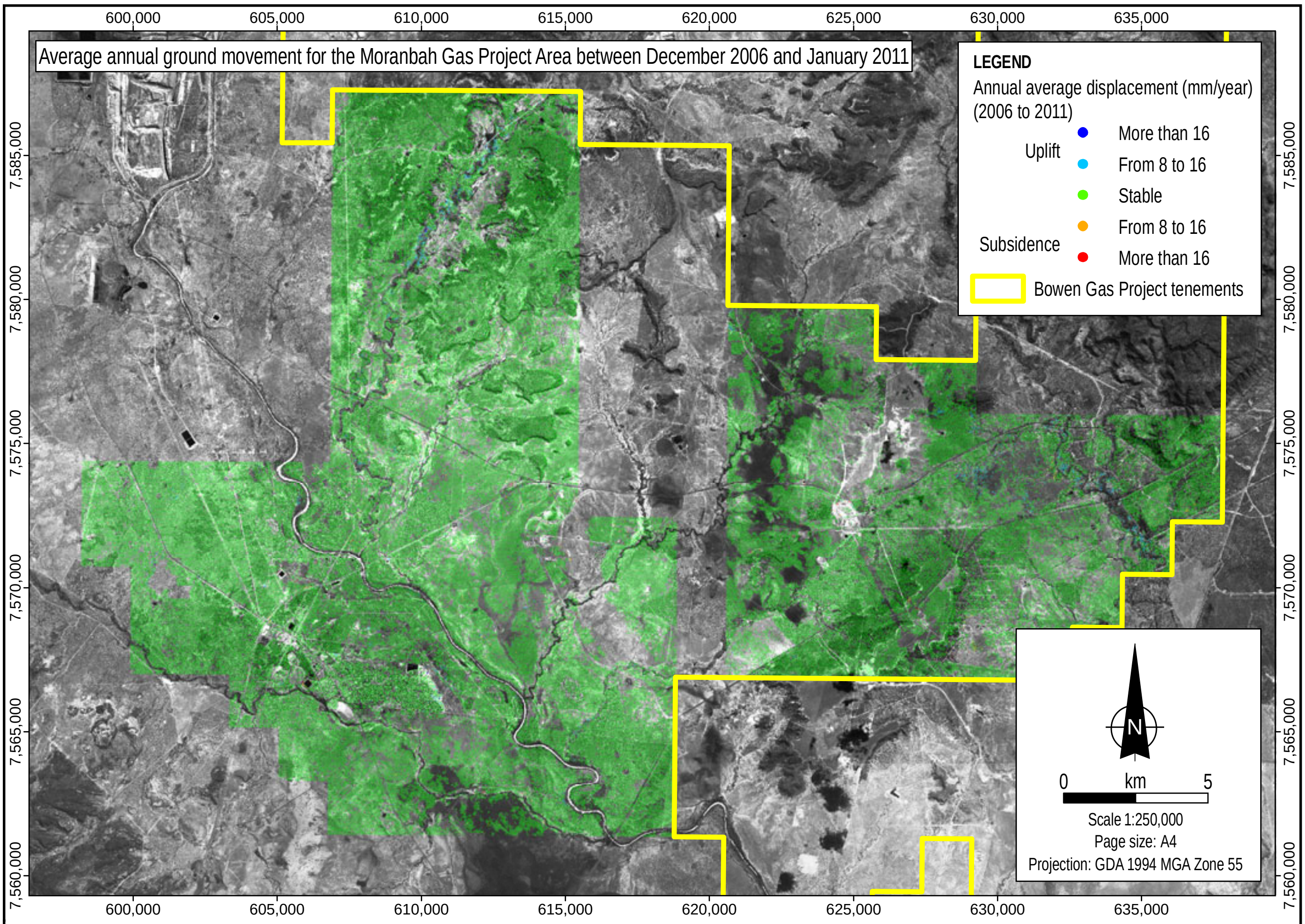

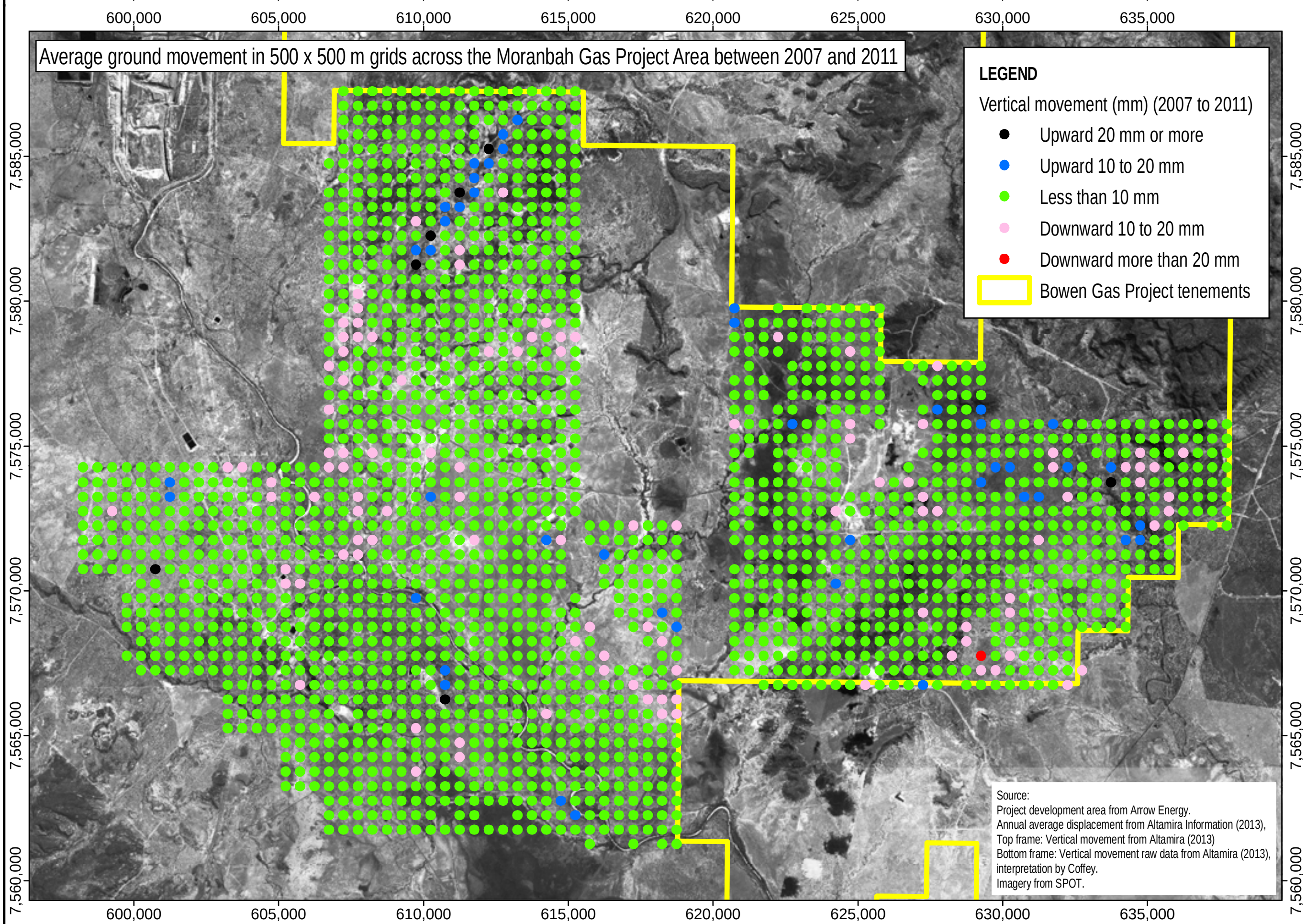

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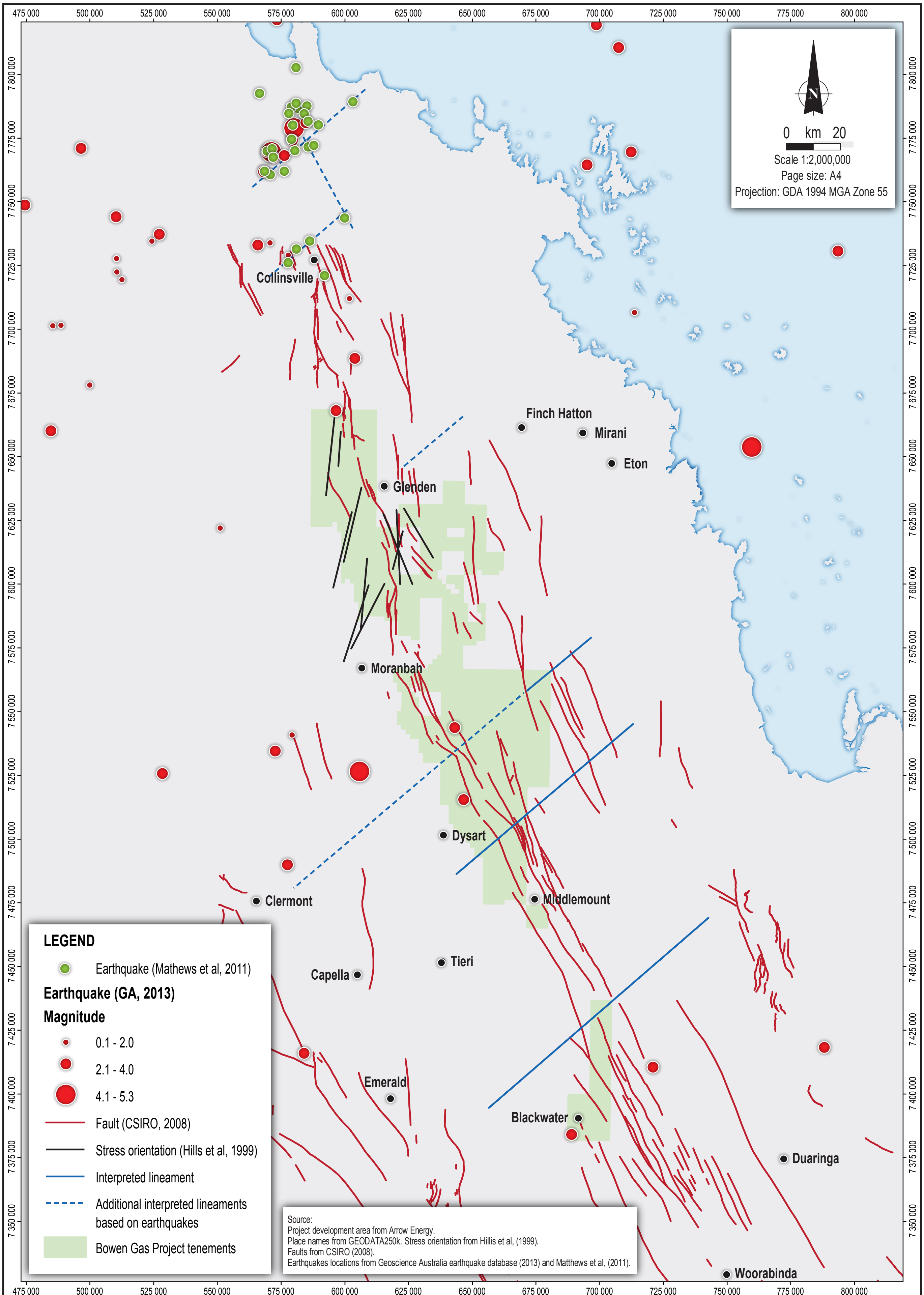

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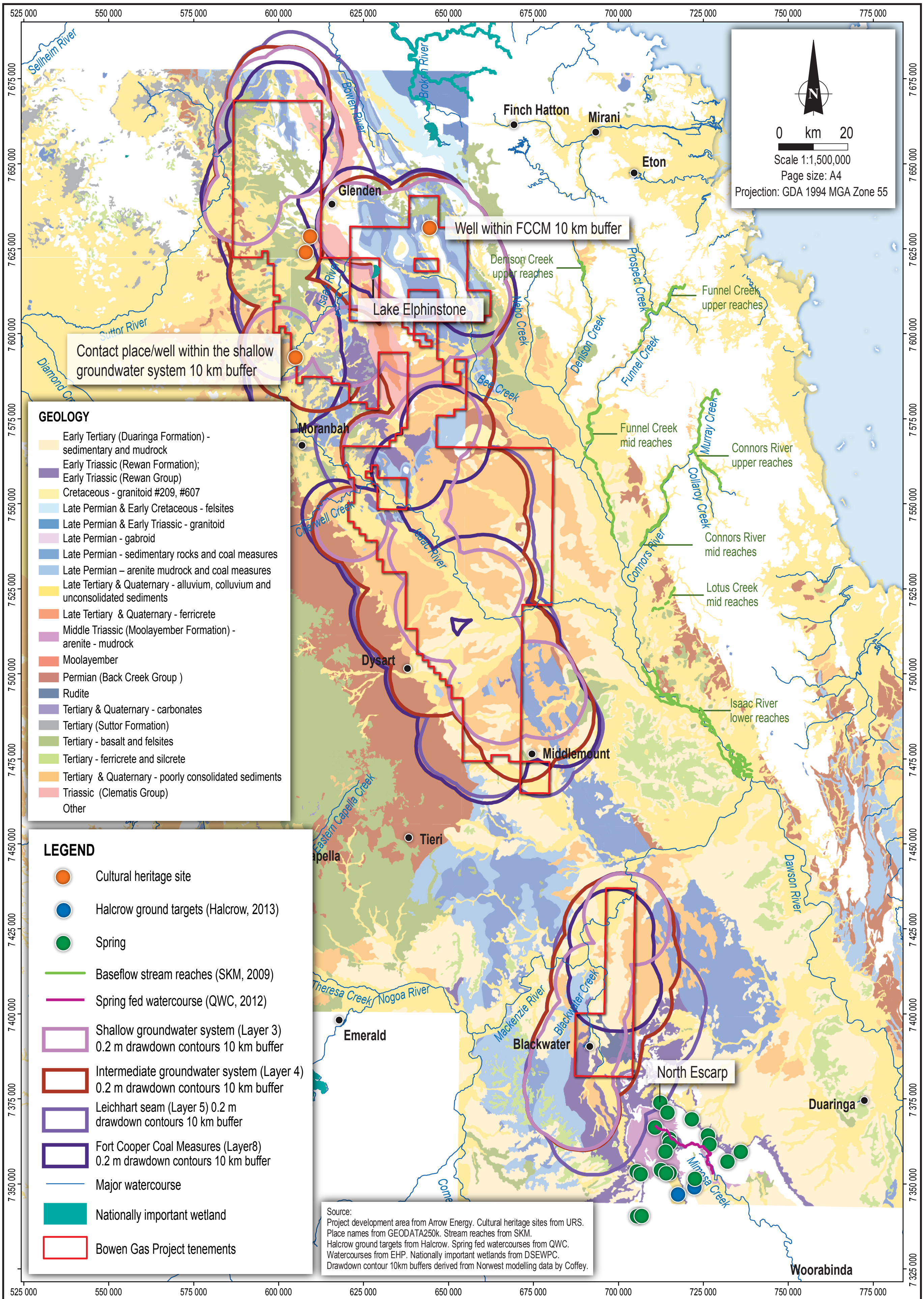

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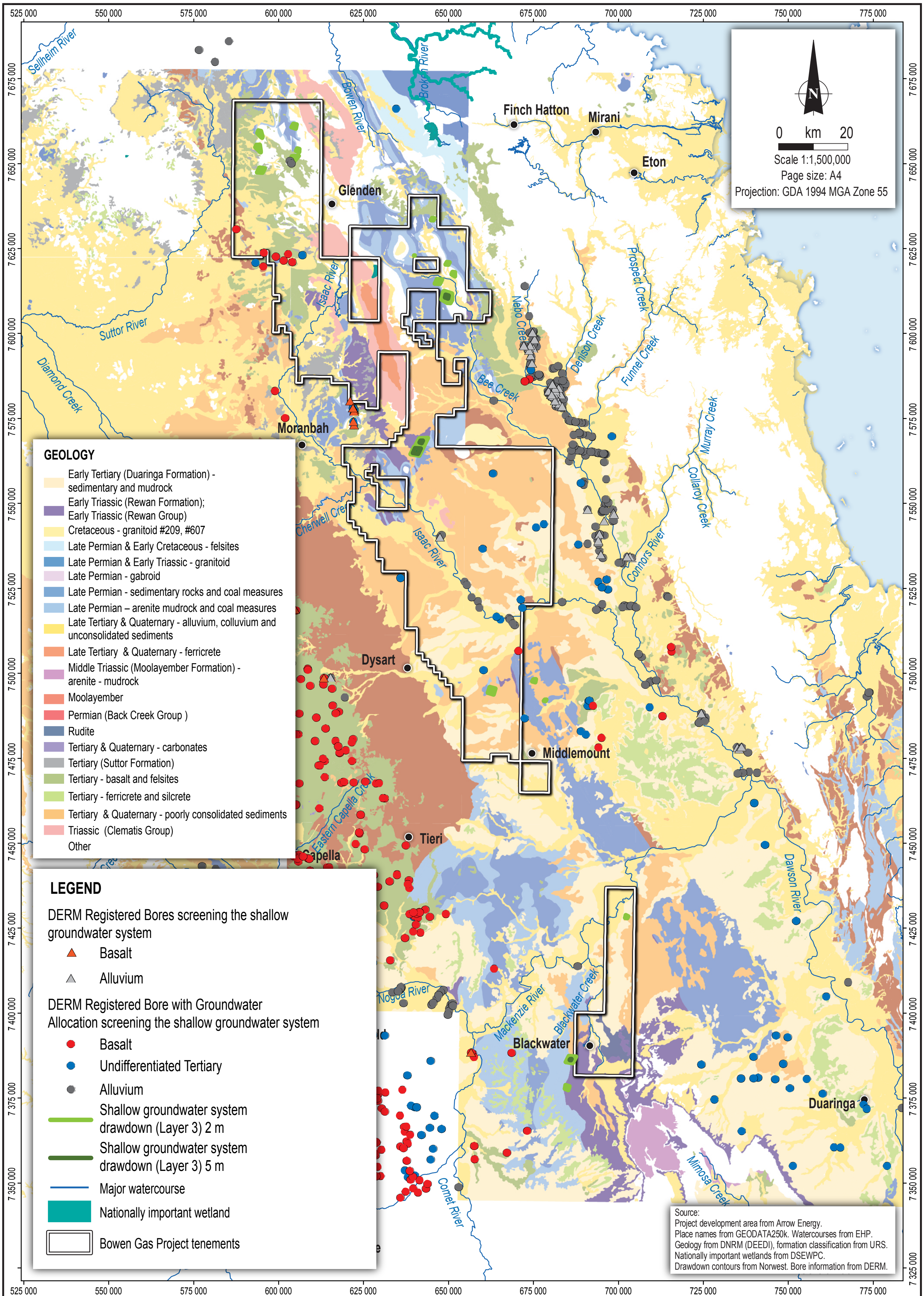


coffey

Date: 17.04.2014

MXT: 7043_02_GIS039_v1_1

File Name: 7043_02_F08.2a_GIS_PF_2

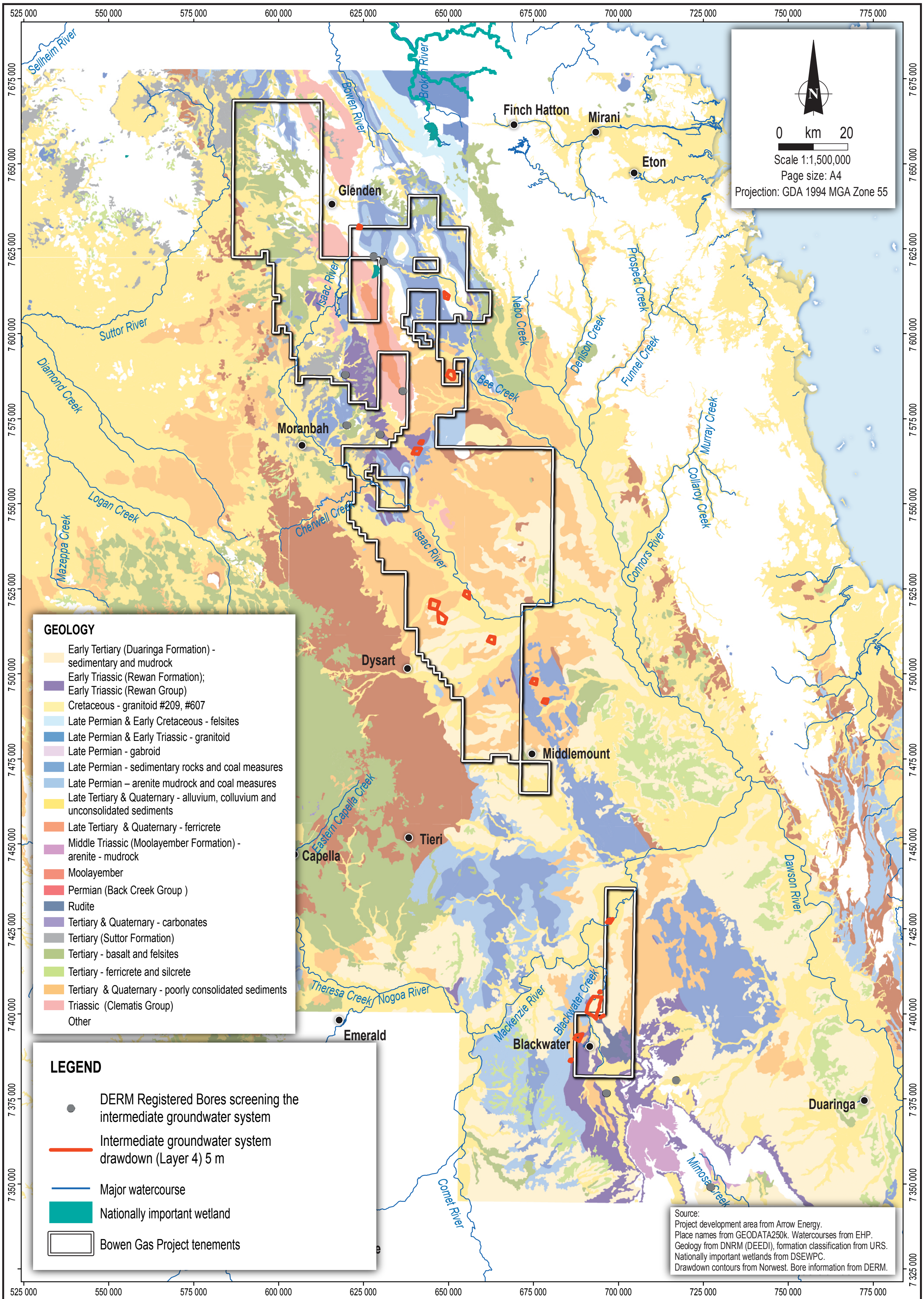
Arrow Energy Limited

Bowen Gas Project

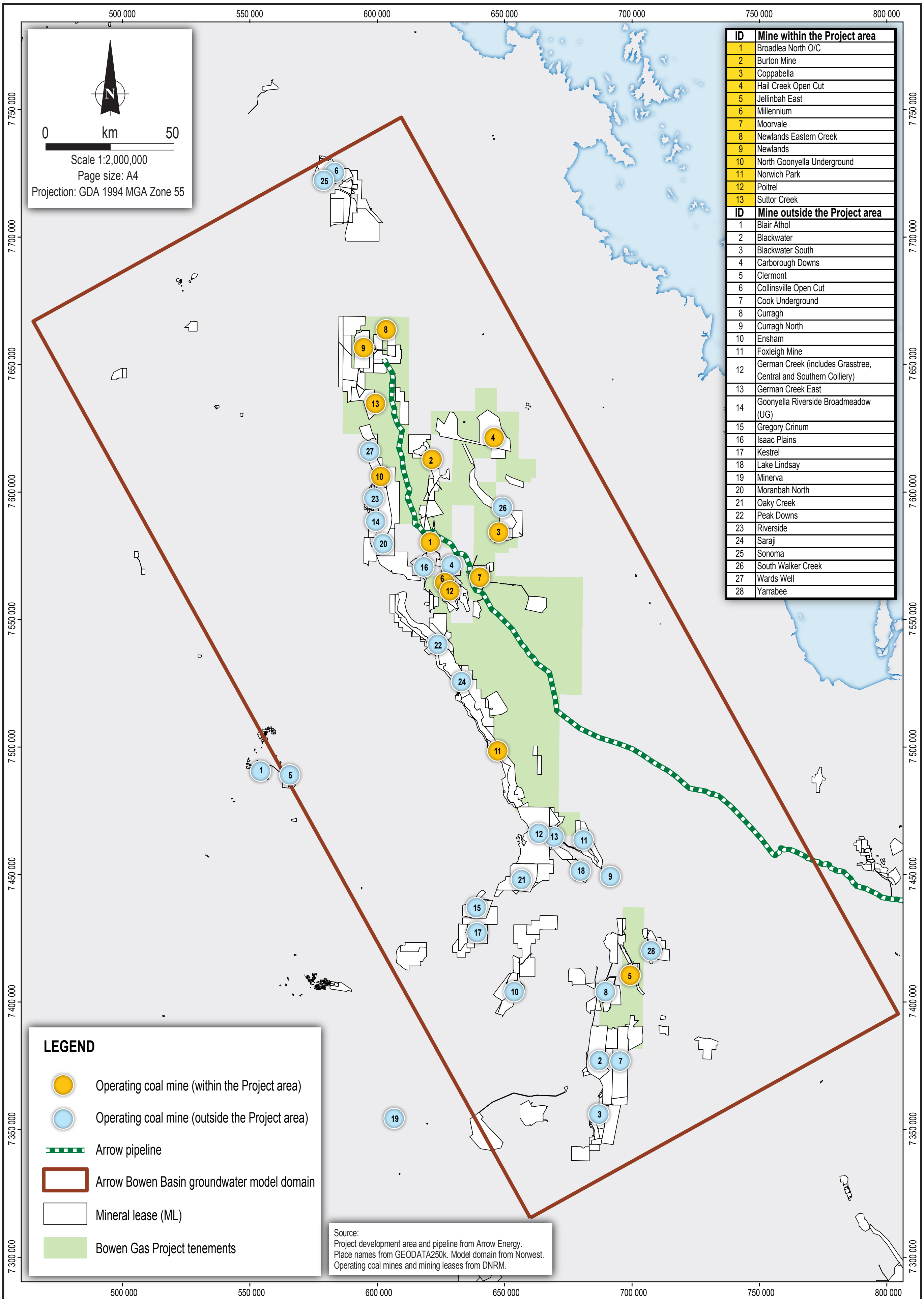
arrow energy go further

Potential impact to existing groundwater users - shallow groundwater system

Figure No: 8.2a



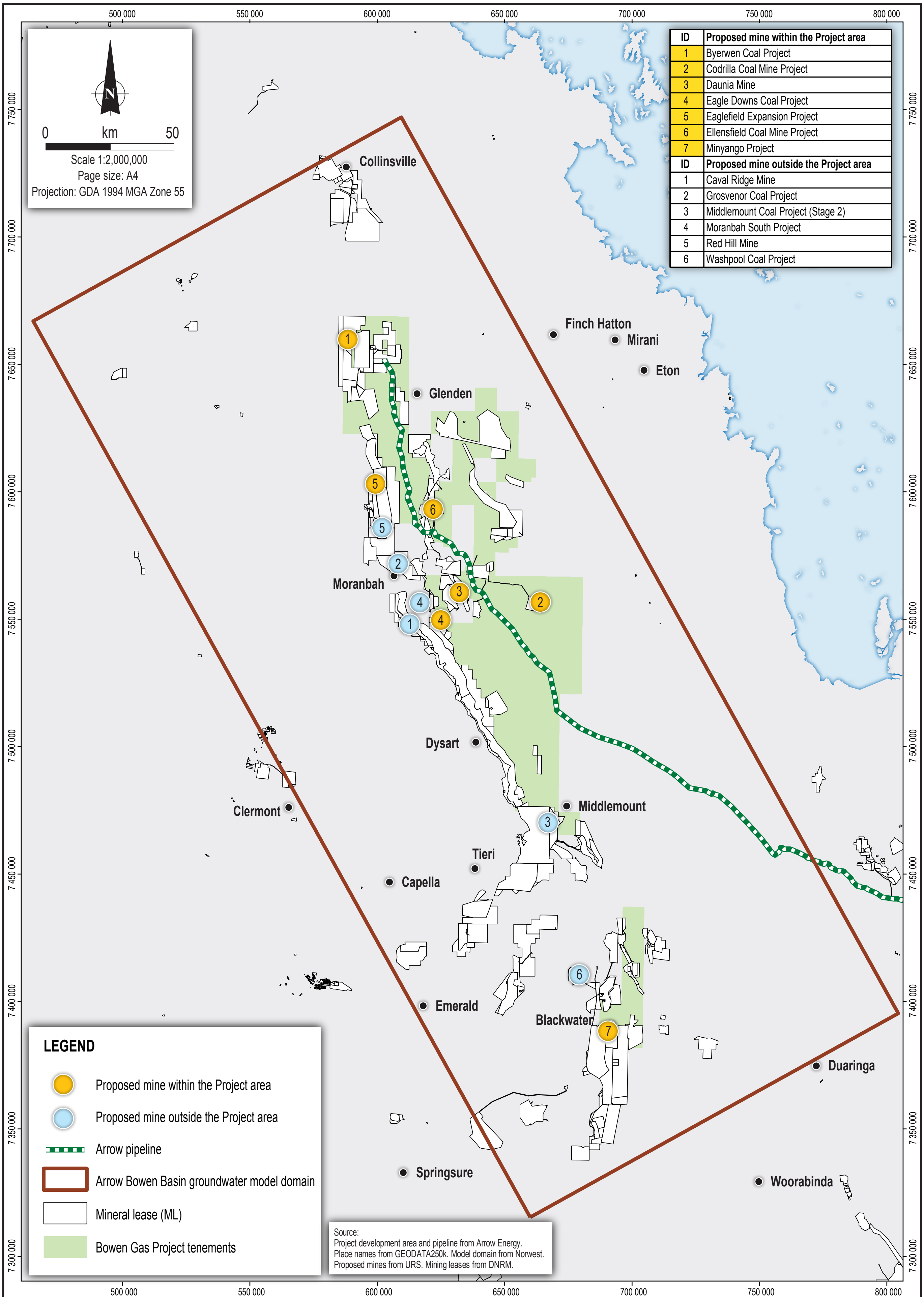
coffey	Date: 17.04.2014 MXT: 7043_02_GIS040_v1_1 File Name: 7043_02_F08.2b_GIS_PF_2	Arrow Energy Limited Bowen Gas Project	arrow energy go further	Potential impact to existing groundwater users - intermediate groundwater system	Figure No: 8.2b



ID	Mine within the Project area
1	Broadlea North O/C
2	Burton Mine
3	Coppabella
4	Hail Creek Open Cut
5	Jellinbah East
6	Millennium
7	Moorvale
8	Newlands Eastern Creek
9	Newlands
10	North Goonyella Underground
11	Norwich Park
12	Poitrel
13	Suttor Creek
ID	**Mine outside the Project area**
1	Blair Athol
2	Blackwater
3	Blackwater South
4	Carborough Downs
5	Clermont
6	Collinsville Open Cut
7	Cook Underground
8	Curragh
9	Curragh North
10	Ensham
11	Foxleigh Mine
12	German Creek (includes Grasstree, Central and Southern Colliery)
13	German Creek East
14	Goonyella Riverside Broadmeadow (UG)
15	Gregory Crinum
16	Isaac Plains
17	Kestrel
18	Lake Lindsay
19	Minerva
20	Moranbah North
21	Oaky Creek
22	Peak Downs
23	Riverside
24	Saraji
25	Sonoma
26	South Walker Creek
27	Wards Well
28	Yarrabee

coffey	Date: 16.04.2014 MXT: 7043_02_GIS018_v1_4 File Name: 7043_02_F08.3_GIS_GL_2	Arrow Energy Limited Bowen Gas Project	arrow energy go further	Operational mines within and surrounding the Project area

Figure No: 8.3



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Date: 16.04.2014
MXT: 7043_02_GIS018_v1_4
File Name: 7043_02_F08.04_GIS_GL_2

Arrow Energy Limited

Bowen Gas Project

arrow energy go further

Proposed mines within and surrounding the Project area

Figure No: 8.4

Appendix A
Arrow Energy Bowen Gas Project
Hydraulic Characteristics of Faults

Supplementary Groundwater Assessment
Arrow Energy Bowen Gas Project
Supplementary Report to the EIS

Fault Hydraulic Characteristics, Well Stimulation Extent, and Hydraulic Connection between Consolidated and Unconsolidated Media

Arrow Energy

Bowen Gas Project

Report Date: 3 April 2014
Reference: ENAUBRIS10704AA-SA

Reviewed by C. Hill, Geoaxiom Pty Ltd, 10 December 2013

When you
think with a
global mind
problems
get smaller

CONTENTS

CONTENTS

DRAWINGS (APPENDED)

1. DATA REVIEW

A technical review has been undertaken for the Arrow Energy (Arrow) Bowen Gas Project (the Project). The purpose of the review was to provide additional information to inform the Supplementary Report to the Environmental Impact Statement (SREIS) for the Project. The key objective of the review was to collate available information relating to:

- Hydraulic characteristics of faults in the Project area, using analogous examples where Basin-specific information was sparse or unavailable;
- The number of faults and other large-scale discontinuities in the Project area, and the potential for seismic activity related to these faults and discontinuities;
- The extent of fracturing caused by well stimulation; and
- The degree of hydraulic connection between unconsolidated and consolidated media.

No site-specific field observations were available for the hydraulic characteristics of the faults in the Project area. For fault hydraulic characterisation, the review is supported by information from published sources for various faults in Australia and around the world. The information selected for inclusion is considered to be analogous to the conditions in the Project area.

2. CURRENTLY KNOWN AND MAPPED FAULTS

The following interpretations of fault data have been found for the northern Bowen Basin:

- CSIRO (2008), from an internet-based poster presentation of the Bowen Basin Structural Geology.
- Sliwa (2011), based on a combination of:
    - o Data from an interpretation presented in Esterle and Sliwa (2002), and
    - o A reported large regional seismic database from coal exploration, acquired by Arrow through data sharing arrangements with other coal mining companies.

  The combination of these datasets produced 212 2D seismic reflection lines and approximately 23,700 boreholes (Sliwa, 2011). Sliwa (2011) reports that the interpretation follows on from an interpretation made by Velseis Pty Ltd. Interpretation of 2D seismic reflection lines to identify faults usually comprises identification of significant sub-horizontal seismic energy reflectors, followed by identifying the continuity of these reflectors across subvertical structures that displace the reflectors.
- The set of faults mapped by Arrow and stored within its geology model in the Petrel platform. This will be referred to as the Arrow Interpretation.

These interpretations are shown on Drawing 1, which also shows stress orientation (Hillis et al, 1999), dykes from CSIRO (2008), and the faults that were incorporated into the regional numerical groundwater model prepared by Ausenco-Norwest on behalf of Arrow for the EIS. Allowing for small errors in digitising of the Sliwa (2011) faults, each dataset shows some inconsistencies with the others. Georeferenced electronic information was available for the CSIRO (2008) and Arrow Interpretation data sets. The CSIRO interpretation appears to have the largest number of faults. Most of the seismic lines shown in Sliwa (2011) were aligned WSW-ENE, normal to the main direction of the interpreted faults.

Properly processed reflection seismic cross-sections generally allow reasonably reliable location of faults and estimated slips. However, the cross-sections cannot provide any information on the hydraulic characteristics of a fault. The faults shown on Drawing 1 are useful for assessment of fault patterns and density, however information relating to the width of a fault’s disturbed zone (or some measure of the transmissive characteristics of the fault) has a level of uncertainty precluding its use for hydraulic characterisation. Despite this, there are methods of interpreting broad scale preliminary estimates of hydraulic characteristics of faults from the slip, or other large scale measureable quantity (for example, Jourde et al., 2002; Flodin et al., 2001; Paul et al., 2009), in the absence of site-specific information.

The hydraulic characteristics of fault planes can only be reliably assessed from hydraulic results (such as hydraulic testing, observations during drilling, and long-term hydraulic head behaviour). In the absence of this information from field investigations conducted by Arrow in the Project area, other national and international examples with similar characteristics to the Bowen Basin have been used to estimate the potential hydraulic behaviour of faults in the project Area. Arrow actively avoids faults when planning its drilling programs.

The majority of faults in the northern Bowen Basin are described as thrust faults (Esterle and Sliwa, 2002; Arrow, 2013a), associated with the Burton-Jellinbah Thrust Belt (Arrow, 2013a). Arrow (2012) states that low angle thrust faults are known to exist in the western portion of the Bowen Basin, and that on the eastern side, faulting is generally high angle in nature.

Arrow (2013a) divides the faults in the Project area into three main categories as listed in Table 1, based on drilling observations and, where available, seismic interpretation.

Table 1: Categorisation of Faults in the Project Area (Arrow, 2013a).

Fault Type	Throw (m)	Strike Length (km)
Normal	5 to 20	2 to 10
Thrust (Burton-Jellinbah Thrust Belt)	50 to 100 where intersected	10 to 20 (defined in Arrow 2013a as applying to a project scale)
Low Angle (reverse or thrust)	5 to 10	Possibly 2 to 5

A visual examination of the mapped faults in Drawing 1 suggests only a small proportion of them have a strike length of 5km or less. Low angle faults have a lower potential than other faults for creating enhanced vertical hydraulic connection.

The regional numerical groundwater model prepared for the Bowen Basin EIS groundwater model and used for impact assessment incorporated 14 major faults (Drawing 1), which appear to have been guided by the Arrow Interpretation.

2.1. Analysis of Fault Slip

URS (2012) present four stratigraphic cross-sections (URS, 2012, Figures 3-4 to 3-7) showing major lithologies, faults, and vertical displacement caused by faults. These cross-sections have been used to generate a database of fault slip for the 150°/3 30° faults. In some cases, displacement is shown a s varying vertically along the faults, implying movement (possibly as discrete events) over geological time during active basin sedimentation. Appendix A shows the locations of the points where a fault is shown on these cross sections (and where a measurement of slip was made from the cross sections), and a table of measured slips. Where a measurement point is not shown on a mapped fault, that fault was not present on the corresponding cross section from URS (2012). The measurements are the maximum slip observed along the fault, regardless of depth. The accuracy of the measurements, in transferring from the figures in URS (2012), is about ±15m.

The database comprises 26 points. At one location (Point 22, on the Jellinbah Fault), the slip was too large for a common marker to be correlated and was undefined (greater than 1090m). For the remaining points, the average slip is 80m with a standard deviation of 80m (both quantities rounded to the nearest 10m). Esterle and Sliwa (2002) describe the Jellinbah fault as a regional thrust fault with

600 to 800m of slip. They report that all their mapped thrust faults are interpreted as subsidiary structures to the Jellinbah thrust fault.

3. LINEAMENTS

Lineaments are identified linear features that may include faults or other structures. In the Bowen Basin, certain lineaments are associated with mapped surface alluvial sediments.

The extent of alluvial sediments in the northern Bowen Basin was derived from information obtained from the Queensland Department of Mines and Energy internet database. When incorporated with stress orientation measurements and basin-wide structural geology, systematic patterns of bodies containing sediment deposited in reasonably high-energy environments, are useful in interpreting the presence of lineaments. Drawing 2 shows the extent of major alluvial bodies in the northern Bowen Basin, overlain with the faults and dykes interpreted by the CSIRO (2008) overlaid. Also shown are lineaments interpreted as part of this review, based on alluvial depositional patterns, topography, and seismic events. These lineaments are sub-parallel to most of the seismic lines in the same areas, making them difficult to capture and identify on the seismic cross-sections. They may be masked by overprinting of surface sediments, and by the visual disorder on the lithology map resulting from the small, complexly shaped lithologic groups. Information presented later in this report (Section 6.3.5) suggests that these lineaments are strike-slip faults.

The two main groups of large-scale discontinuities appear to be as follows:

- Mapped faults, with an average strike of approximately 150°/330° with respect to MGA north.
- Interpreted strike-slip faults, with an average strike of approximately 70°/250° with respect to MGA north. The uncertainty in the strike direction, as inferred from alluvial bodies, is considered small.

The regional stress orientation (Hillis et al., 1999) is approximately 40°/220° with respect to MGA north (see Drawing 1).

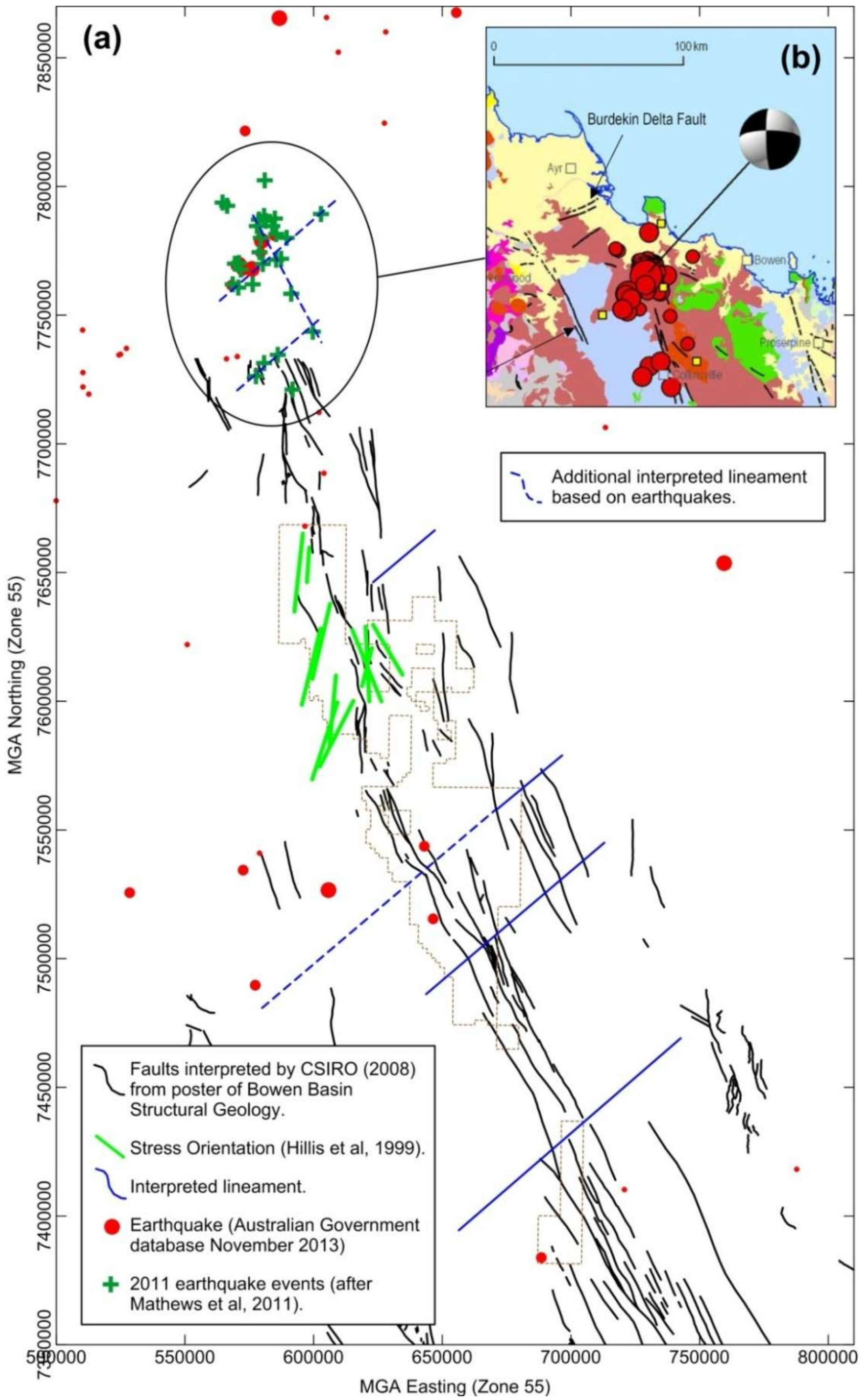
Lineaments of similar strike direction to the interpreted 70°/250° strike-slip faults of this study are discussed in Esterle and Sliwa (2002) in their assessment of the regional basement structure of the Bowen Basin. They present interpreted deep basement lineaments on an image of the Bouguer gravity anomaly for the Bowen Basin. These lineaments have an approximate strike of 65°/245°. Esterle and Sliwa (2002) report that these lineaments were identified as a series of “corridors” by Mallett et al (1988) because “*although many significant structures are influenced by* [the lineaments] *and reflect their presence, no single discrete feature normally characterises them.*”. They report that Mallett et al (1988) used closure of map scale folds or shifts in their axes, zones of increased fault disruption, steps in the boundaries of basin elements or structural zones, and lines of intrusive bodies, as criteria for identifying the lineaments. Drainage patterns do not appear to have been used.

Large scale drainage patterns are known to be controlled by the pattern of large scale discontinuities, which host weakened zones that are preferentially eroded. For the Project area, drainage patterns suggest extensive 70°/250° discontinuities. The largest interpreted strike-slip fault occurs in the middle of the central lease area (see Drawing 2). It is extended from an analysis of earthquake locations (refer to Figure 1, and Section 4, below). If the lineament is a strike-slip fault, it has the potential to have slipped many 10s of kilometres. No information is available with which to assess its structure.

4. EARTHQUAKES

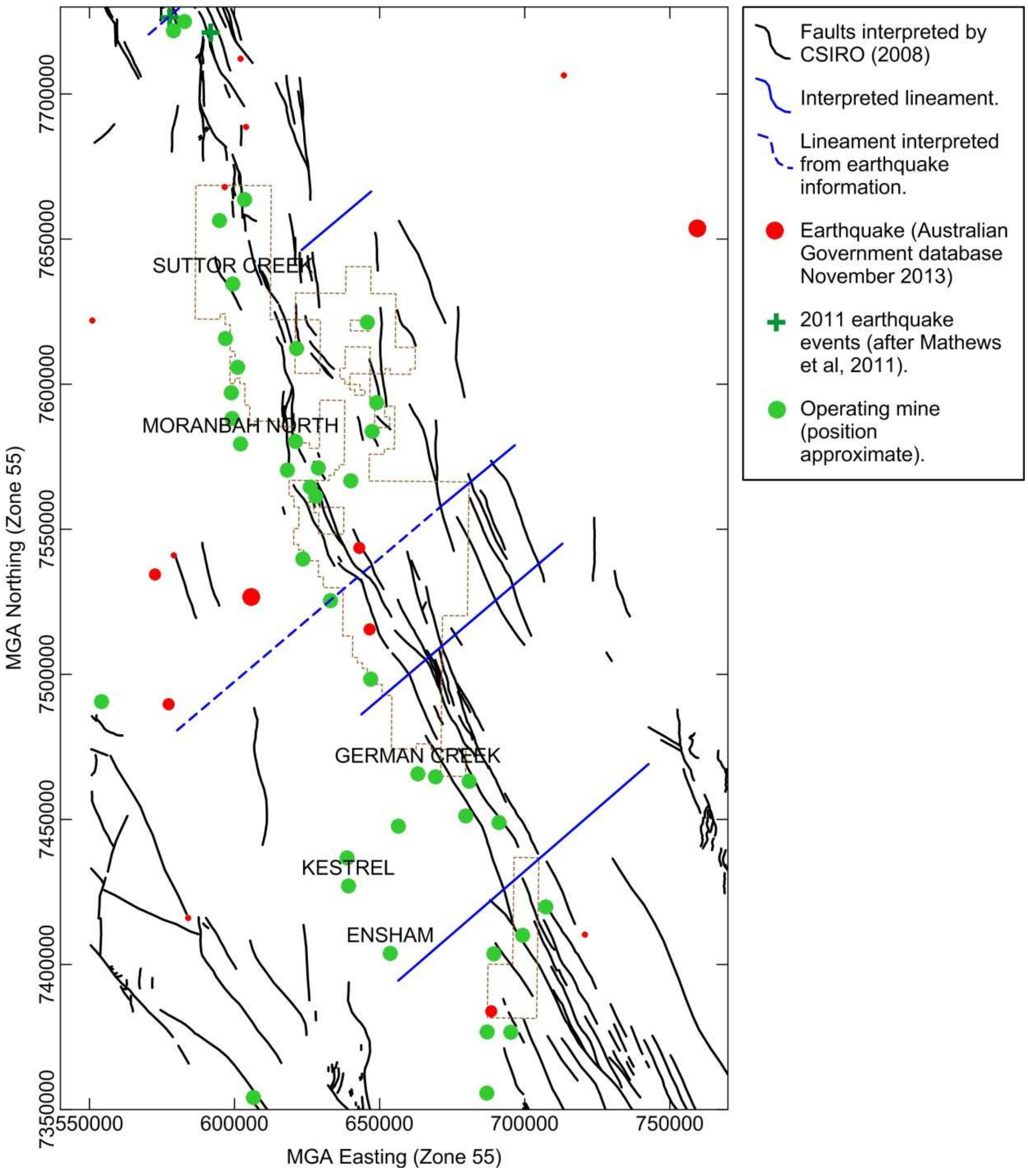
Figure 1a shows recorded earthquakes from the Australian Government database (http://www.ga.gov.au/earthquakes/searchQuake.do, accessed 7 November 2013) for a 1 million km2 window centred on the northern Bowen Basin). In Figure 1, eEarthquake intensities are proportional to the symbol size. Also shown are the earthquakes interpreted as forming part of the April 2011 Bowen earthquake and associated aftershocks, as interpreted by Mathews et al (2011), displayed without intensity proportioning. The April 2011 earthquake occurred to the northeast of the Project area. Figure 1b also shows the Mathews et al (2011) data as presented in that paper, showing intensities, for reference.

Figure 1: (a) Earthquakes registered with the Australian Government database for the period 1950 to 2013, and events interpreted for the 2011 Bowen earthquake (from Mathews et al, 2011). (b) Data from (a) as presented in Mathews et al (2011) for reference.



The government database does not contain some of the northern group of the Mathews et al (2011) events, and none of the southern group of Mathews et al (2011) events. This could be because some aftershocks were recorded with temporary geophones installed after the initial earthquake. Figure 2 shows the information of Figure 1 overlaid with the approximate positions of operating coal mines (as sourced from the Queensland Government internet database).

Figure 2: Earthquake information of Figure 1 overlaid with approximate locations of operating coal mines.

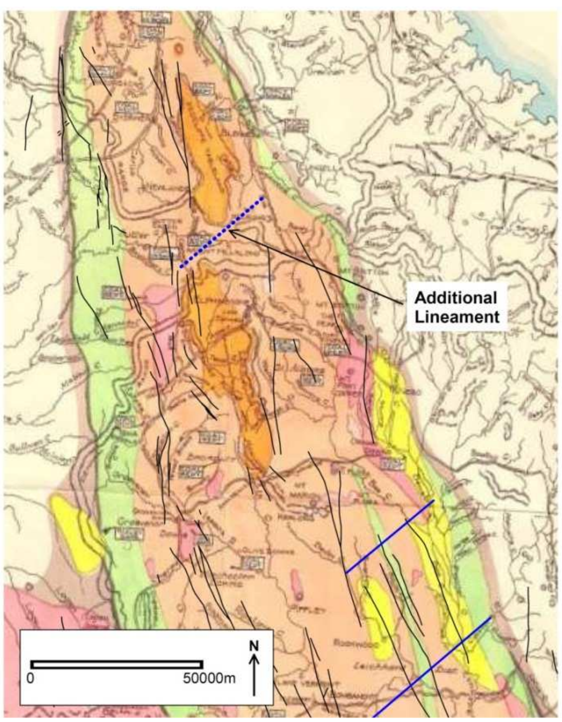


The spatial pattern for the 2011 earthquake events suggests a preference for release of increasing energy (generated by the regional stress field) along a strike parallel to the interpreted 70°/250° strike-slip faults (see Figure 1). The government database shows a weak but perceptible pattern supporting this.

The pattern of earthquake locations shows no discernible relationship with the mine locations, however the government database is not likely to show any seismic monitoring, if undertaken, by coal mining operations, unless events were captured by the monitoring array used by the government, or the information was supplied to the government. Defunct coal mines are also not shown, removing an element of interpretation (since earthquake events in the government database date from the 1950s). However, this is not thought to have a significant impact on results, since the major expansion of coal mines in the Bowen Basin less than 20 years ago. There appears to have been little earthquake activity in the main mining area, in the last 60 years.

There is the potential for significant lateral movement to have occurred along the strike of interpreted strike-slip faults. Figure 3 shows an additional strike-slip fault interpreted from a regional lithological subdivision as shown in a 1949 geology map of the northern Bowen Basin. Lateral movement along strike of up to 10s of kilometres appears to have occurred along this possible fault. Geophysical survey results (see above) suggest that lateral movement along strike may have occurred along interpreted 70°/250° strike-slip faults further south. Vertical movement along 150°/330° faults appears to be rarely more than a few hundred metres. Information presented below (Section 6.3.5) suggests the fault zones, if present, of the interpreted 70°/250° strike-slip faults will have greater K than the fault zones of the 150°/330° faults, based on slip magnitudes (refer to the conceptual model in Section 9.3.1.).

Figure 3: An additional lineament of strike 70°/250° interpreted from regional lithological associations from a geology map of 1949 (sourced from the QLD Government Historical Atlas, 11 November 2013, http://www.qhatlas.com.au/map/locality-and-geological-map-bowen-basin-coal-basin-central-queensland-1949).



The western boundary of the Sydney Basin shares some similarities with the northern Bowen Basin (transition from extra-basin media to intra-basin Permian units, stress orientation, and strike of the boundary). While some features of the western boundary of the Sydney Basin also differ from the Bowen Basin (for example, the topographic setting), that zone is interpreted to represent a valid analogue for the western part of the northern Bowen basin. In that area of the Sydney Basin, lineaments of strike 50°/230° have been successfully targeted by consultants (referenced in unpublished reports) for enhanced water supply (for example, water supply wells at Wolgan Valley near Lithgow, where the targeted lineament, associated with a major drainage course, exhibited significantly enhanced K along its plane, compared to K measurements made in piezometers off the lineament).

5. GEOPHYSICS

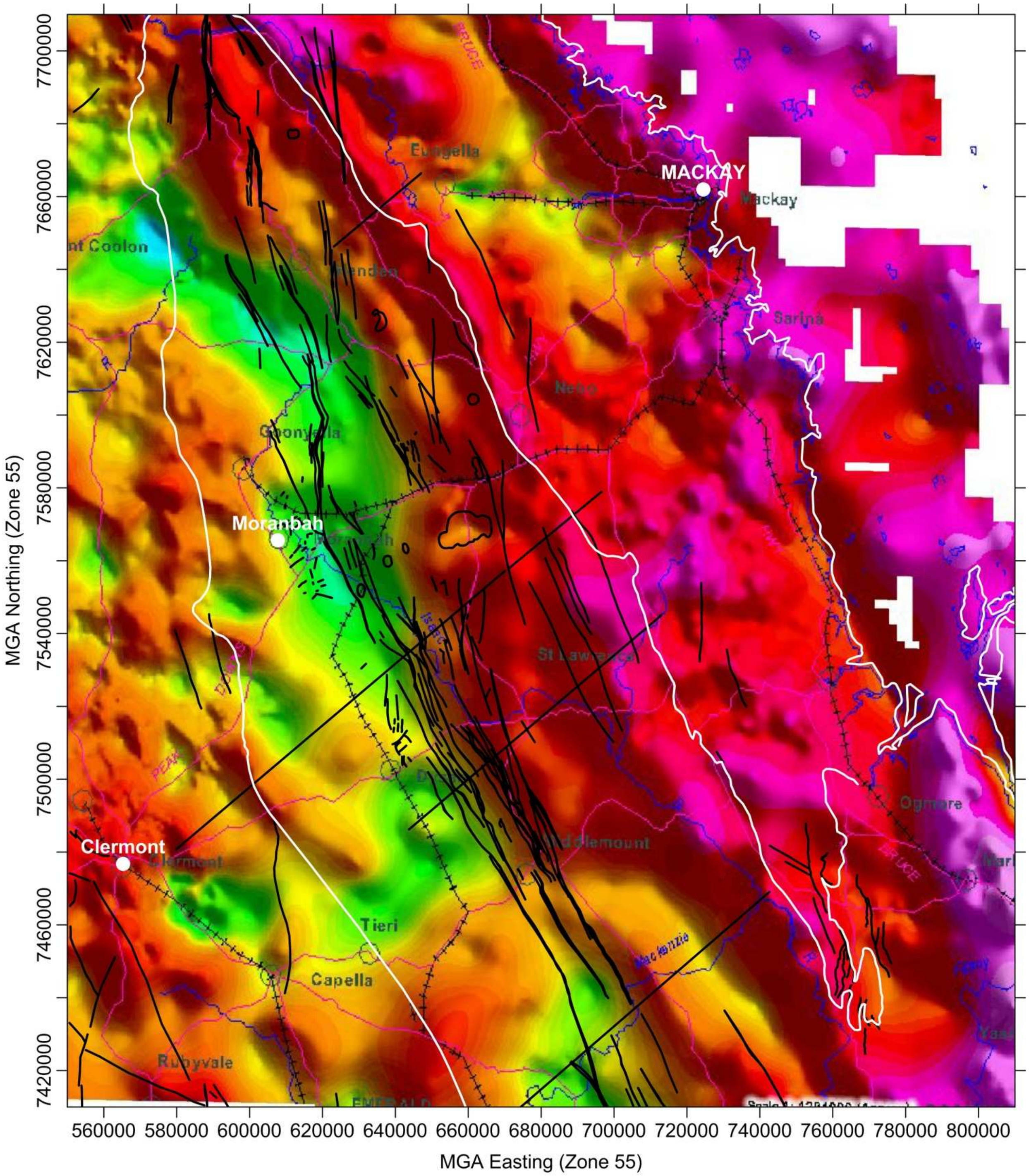
Sliwa (2011) presents a number of seismic reflection sections with single interpreted reflectors, however the vertical axes for these sections are not depth (but may be two-way travel time).

The Bouguer gravity anomaly and the total magnetic field strength for the northern Bowen Basin were sourced from the Queensland Department of Natural Resources and are shown in Figures 4 and 5 respectively.

The main fault swarm in the middle of the basin, between northings 7470000 and 7540000, is associated with higher density, more highly magnetised media, and may result from a concentration of stress in stiffer or more brittle media. Lower density media are apparent on the western edge of the greater fault population.

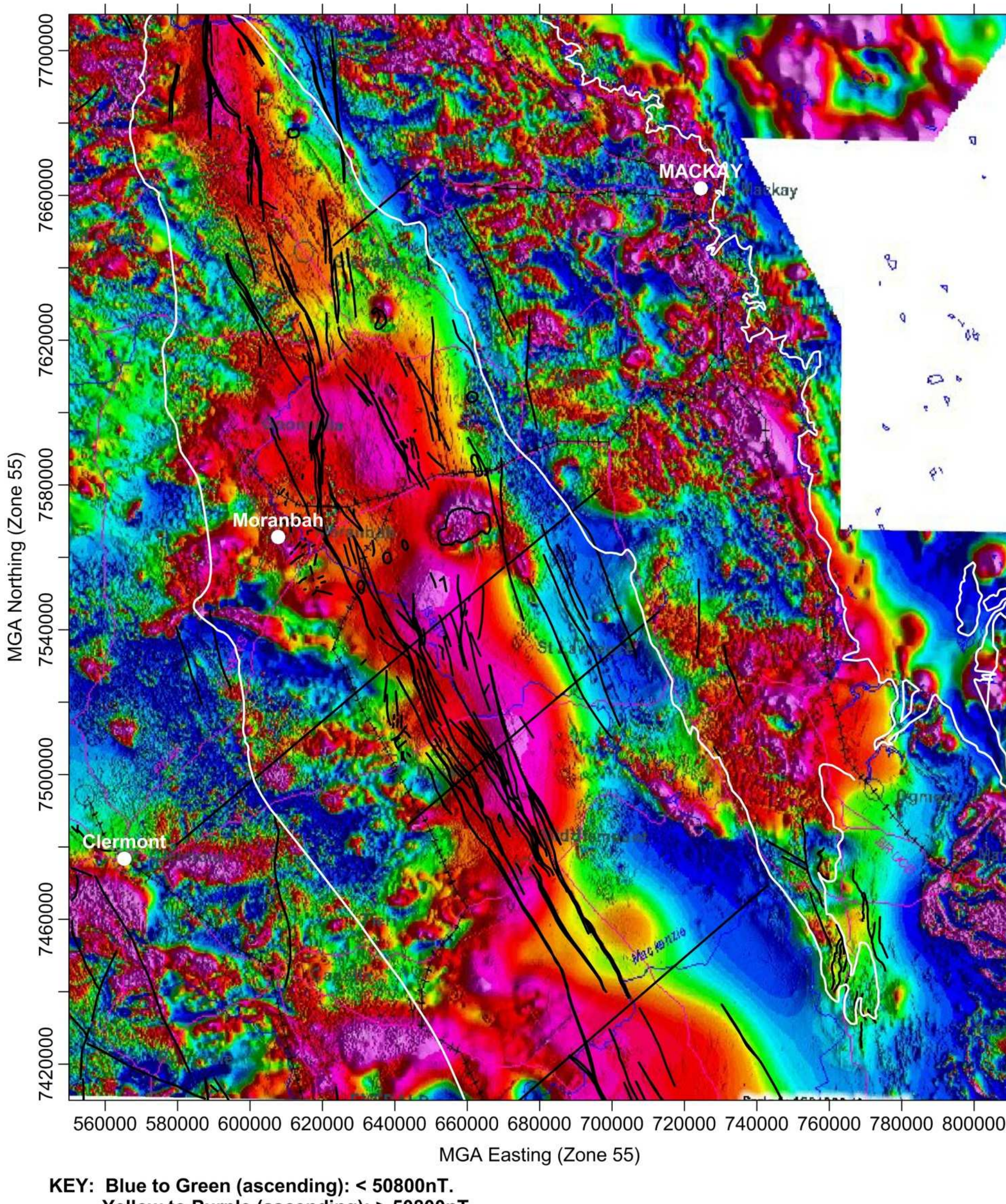
Variations in the magnetic field strength identify large intrusions near the surface or at depth. These intrusions show some relationship to the faulting pattern. No faults are mapped for a small area about 35km northeast of Moranbah, characterised by the unusual combination of high magnetic field strength and low density media.

Figure 4: Bouguer gravity anomaly for the northern Bowen Basin.



KEY: Blue to Green (ascending): < -100mgal.
Yellow to Purple (ascending): > -100mgal.

Figure 5: Total magnetic field strength for the northern Bowen Basin.



KEY: Blue to Green (ascending): < 50800nT.
Yellow to Purple (ascending): > 50800nT.

6. HYDRAULIC CONDUCTIVITY

Decker et al (1990) provide an early and rare published appraisal of the hydraulic conductivity (K) of subsurface media in the Bowen Basin. The study was undertaken for the purpose of coal seam gas development. They recognised the dependence of K on insitu stress and carried out exploration in areas subdivided into stress domains. They report that overseas experience suggested enhanced coal K along fragmented fault planes and secondary fractures associated with fault movement. However, testing at a locality near Broadmeadow in the Bowen Basin indicated a generally low K which decreased towards a reverse fault zone despite heavily fragmented coal zones. Results of exploration indicated a dependence of measured K on vertical and horizontal stress. In some cases, low K was found in low stress environments; here, high K measurements were attributed wholly to tectonically induced fracturing along fault planes. The results of their work suggested that low stress settings were important in maximising gas production.

6.1. Requirements for Coal Seam Gas Development

Unlike underground coal mining, coal seam gas extraction is heavily dependent on the hydraulic characteristics of the reservoir for extraction of the resource. Decker et al (1990) identify the critical parameters affecting the viability of coal seam gas development. They conclude that the key to coal seam gas development is striking a balance for each of the following two conflicting processes:

- Coal methane content increases with depth, however coal seam K decreases with depth.
- Coal with higher rank has increased methane storage capacity, however coal with lower rank has a higher desorption pressure and can produce at a smaller groundwater drawdown.

Since high K fractured media are sought for coal seam gas development, the potential presence of faults in the media becomes an important consideration for impact assessment.

6.2. Unfaulted Fractured Media

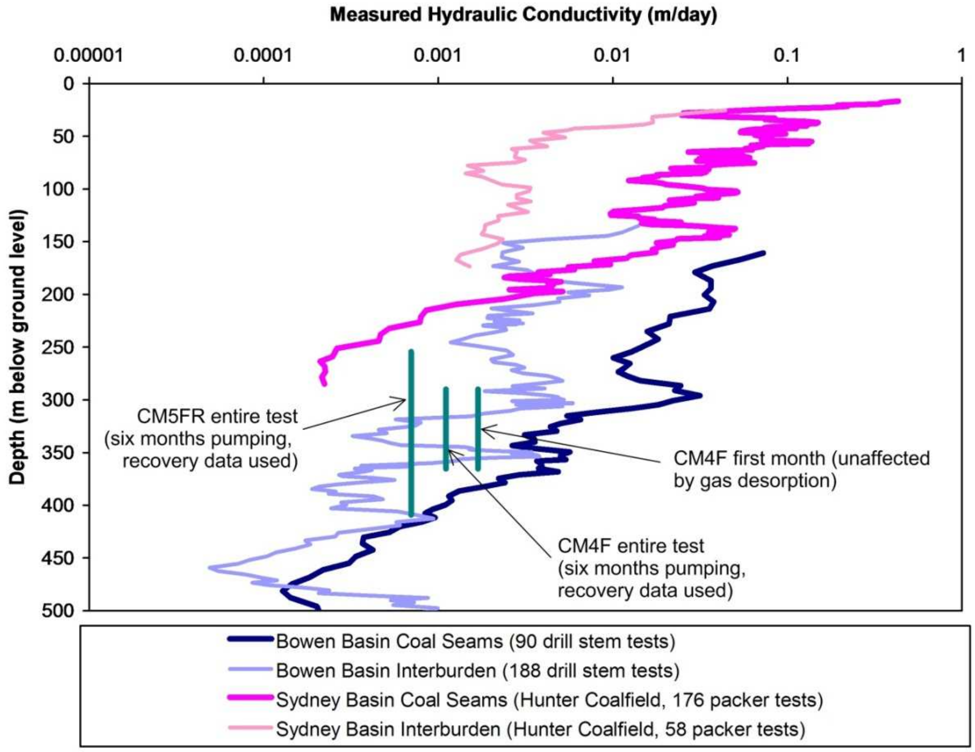
A database of 479 drill stem tests (hydraulic tests undertaken in coal exploration boreholes) was sourced from Arrow Energy. The database comprises an integrated dataset of tests from several mines in the northern Bowen Basin. Tested lithologies are identified for a portion of the tests. Of these tests, those undertaken over test intervals of between 3m and 12m have been selected (totalling 278 tests) in order to compare with a database of packer tests undertaken in the Hunter Coalfield of the Sydney Basin. Figure 6 shows the 10-point running geometric mean as a function of depth for the following four lithologies:

- Hunter Coalfield coal seams (176 packer tests) and interburden (58 packer tests).
- Northern Bowen Basin coal seams (90 drill stem tests) and interburden (188 drill stem tests).

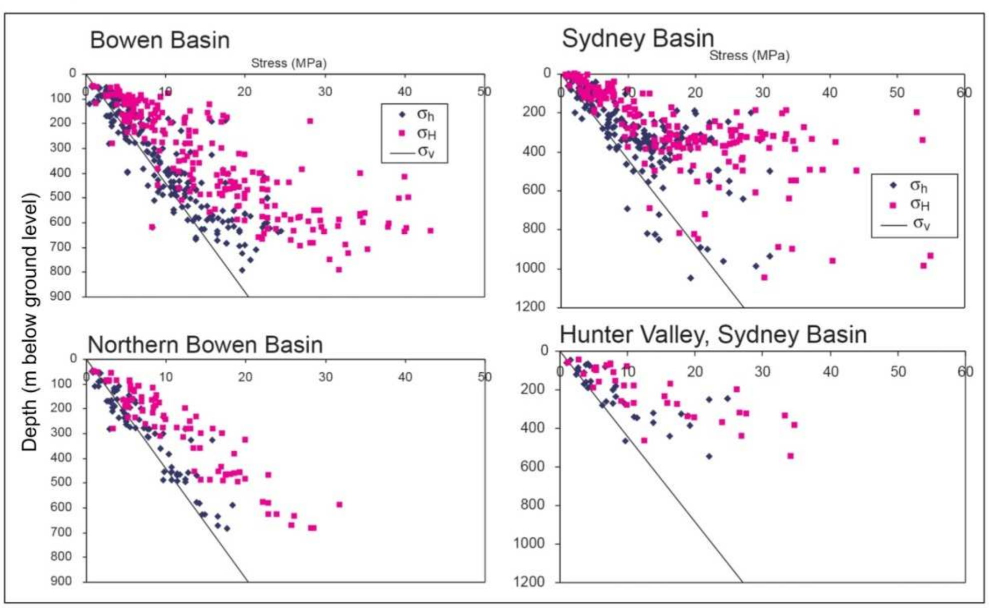
Each data set shows a log standard deviation of about 1 decade around the geometric mean at a particular depth, which is normal for fractured media. The datasets clearly identify a reducing K with depth, caused by increasing overburden pressure.

In Figure 6a, the measured K of coal seams in either basin is about 3 times higher (on average) than the corresponding interburden of the same basin. The coal and interburden K profiles for the Bowen Basin are displaced to the right of the Hunter Valley coal and interburden K profiles by about 1 decade (that is, they are about 10 times higher, on average, than their Sydney Basin counterparts). The lateral displacement in K profiles is most likely due to the magnitude of the horizontal stress field in both areas (Hillis et al, 1999), shown in Figure 6b. At a depth of about 300m, the principle horizontal stress (S_{Hmax}) is about 12MPa in the northern Bowen Basin and about 18MPa in the Hunter Coalfield, located in the northeastern part of the Sydney Basin. The Bowen Basin appears to be in a lower stress state than its counterpart, the Sydney Basin. The data suggest that lower horizontal stress magnitudes in the Bowen Basin would result in higher conductivities, pre-disposing the Bowen Basin to easier gas extraction.

Figure 6: Hydraulic Conductivity and regional stress magnitude in the northern Bowen Basin and the Hunter Coalfield of the Sydney Basin.



(a) Measured hydraulic conductivity (K) from drill stem or packer tests in the Bowen and Sydney Basins. The lines represent running 10-point geometric means of the respective K versus depth distributions. Each distribution has a standard devation of about 1 decade around the geometric mean, at a given depth. This is normal for typical fractured media.

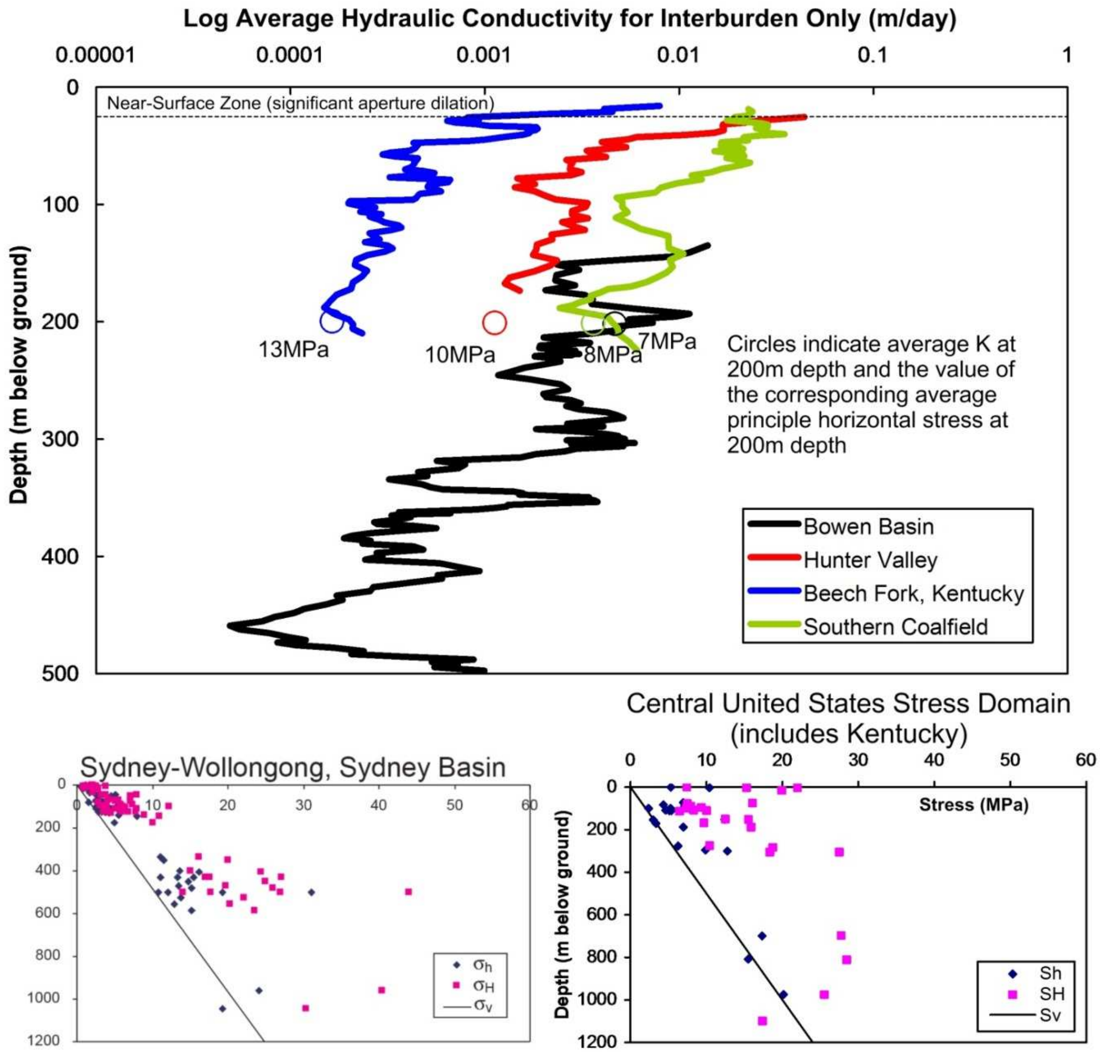


(b) Measured insitu stress in the Bowen and Sydney Basins (after Hillis et al, 1999).

Drill stem tests predominantly measure the lateral component (Kh) of the hydraulic conductivity tensor (K). The dependence of Kh on both vertical and horizontal stress is likely to be due to the inclination of the defects in the medium (that is, the defects are neither completely horizontal nor completely vertical), so that both vertical and lateral stresses will be decomposed by each rock block into lateral and vertical components when they act on defect apertures.

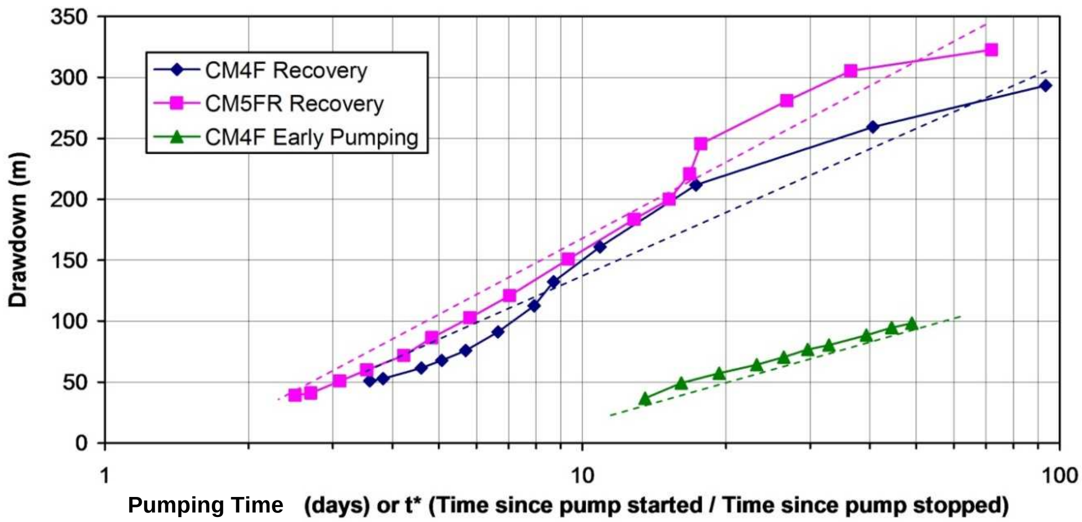
The relationship between K and principle horizontal stress magnitude is explored further by considering only the stiffer media within the profile. This includes interburden (mostly sandstone sequences with some claystone sequences) only, and excludes coal seams. Figure 7 shows the running 10-point log-average K down the depth profile for Permian Coal Measures (excluding coal seams) at a site in Kentucky (Hutcheson et al 2000a, 2000b), the Southern Coalfield (Reid, 1996), and the Hunter Valley and Bowen Basin data referenced above. Figure 7 also shows the measured principle horizontal stress in the Southern Sydney Basin (Hillis et al, 1999) and in the Central United States Stress Domain (which includes Kentucky) (Cole, 2008). Average stress magnitudes for a depth of 200m as interpreted from field measurements (see Figures 6 and 7) are labelled in Figure 7 at the average K for each K distribution. The relationship between K and horizontal stress is clear.

Figure 7: Hydraulic Conductivity and regional stress magnitude for Permian Coal Measures (excluding coal seams) at three locations in Australia and one in the USA. Stresses for the US site are for a specific stress domain (Illinois, Kentucky, Michigan, Minnesota, Missouri, Ohio, after Cole, 2008). Data for Beech Fork are from Hutcheson et al. (2000a, 2000b), and data for the Southern Coalfield are from Reid (1996).



Arrow (2013b) carried out long-term pumping tests on two hydraulically fractured wells (CM4F and CM5FR) followed by numerical simulation of the host media, to assess the economic potential of coal seams for gas production in the Baralaba Area. The tested aquifer volume was extraordinarily large compared to drill stem tests. Drawdown measurements from these tests have been used to interpret the transmissivity of the host media. The first month of pumping at CM4F was unaffected by gas desorption, and was analysed using drawdown measurements made during pumping. The latter part of each test period was affected by gas desorption and non-uniform pumping rates. Late time K was therefore interpreted using recovery measurements following termination of pumping. Figure 8 shows the interpretation of these data (Jacob's method was used). Figure 6a shows interpreted K values for comparison to drill stem test results. Late time results indicate K values that are slightly lower than the basin average, indicating potential effects caused by low-K boundaries (for lateral flow).

Figure 8: Pumping test analysis of drawdown and discharge measurements for CM4F and CM5FR.



Well and Pumping Phase	CM004F Recovery	CM005FR Recovery	CM004F Early Pumping
Drawdown Rate (m/decade)	150	210	100
Pumping Rate (L/day)	11000	11000	11200
Transmissivity (m2/day)	0.0134	0.0096	0.0205
Hydraulic Conductivity (m/day)	1.11E-03	6.98E-04	1.69E-03

6.3. Faults

In groundwater systems that are at virtual equilibrium, the perturbation in the hydraulic head field caused by a fault may be imperceptible. In rare cases, such as substantial climate fluctuations with wavelengths that are much smaller than the time required for fault equilibration, the perturbation may be perceptible. Use of a hydraulic head field to assess for the presence of a fault usually requires an imposed stress with significant head changes.

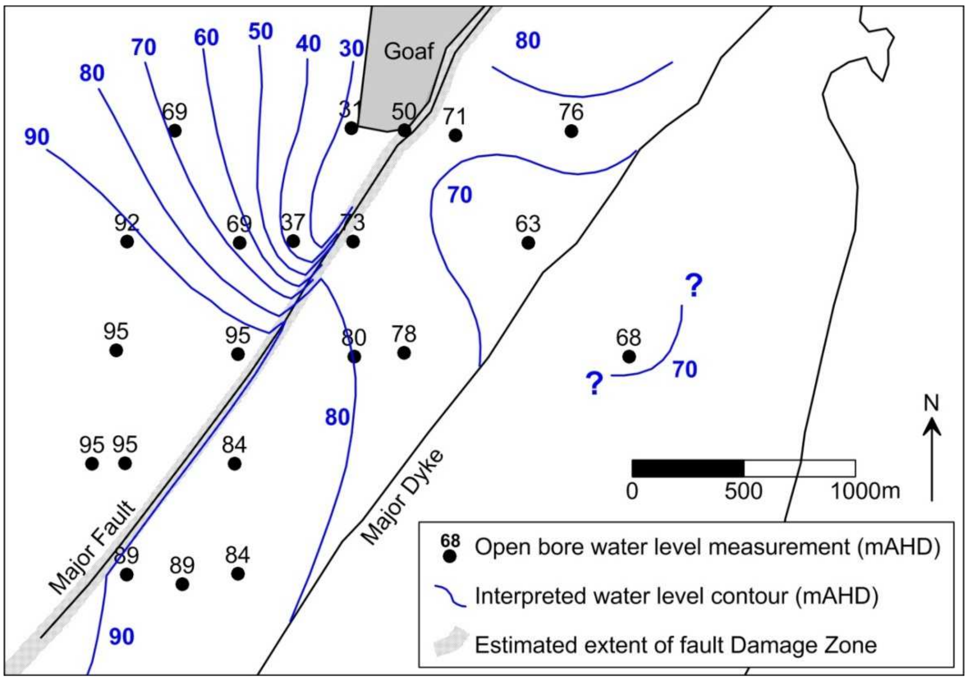
6.3.1. Faults as Barriers Perpendicular to Groundwater Flow

An example of a fault acting as a barrier to groundwater flow perpendicular to the fault plane is provided by a major fault in the Hunter Coalfield, penetrating the Whittingham Coal Measures. This fault is a typical thrust fault within Permian Coal Measures and so has some similarities to faults in the northern Bowen Basin. Water level monitoring data for the fault are shown in Figure 9. In this example, water levels in open resource bores showed significant drawdown only on one side of the fault, due to dewatering at a nearby goaf. The water levels are not representative of the watertable, but are transmissivity-weighted averages of the hydraulic head profile at each bore. After several years of completion of mining in the goaf, the fault still maintained a maximum discontinuity in the hydraulic head field of about 50m. This example shows the low K of the fault in a direction normal to the fault (compared to the surrounding medium), but provides no information on K parallel to the fault.

Although the fault line and goaf body shown in Figure 9 are from surveyed mapping information, the width of the fault damage zone is an interpretation only, having been estimated qualitatively from the eastern boundary of the goaf. The goaf boundary is not likely to be the limit of the damage zone, but is more likely to represent the point at which additional mining effort required to overcome floor, face, and roof instability in the workings (caused by the damage zone) outweighed the value of the extracted coal.

This behaviour has been observed qualitatively at several other mines in the Hunter Coalfield (mainly indirectly, through observation of inflows). Based on this, it appears that K perpendicular to the fault plane for most thrust faults in the Hunter Valley is likely to be lower than K of the surrounding medium.

Figure 9: Water levels measured in open boreholes drilled to below the mined seam at a mine in the Hunter Coalfield. Only stable measurements taken at least 2 weeks apart were used.

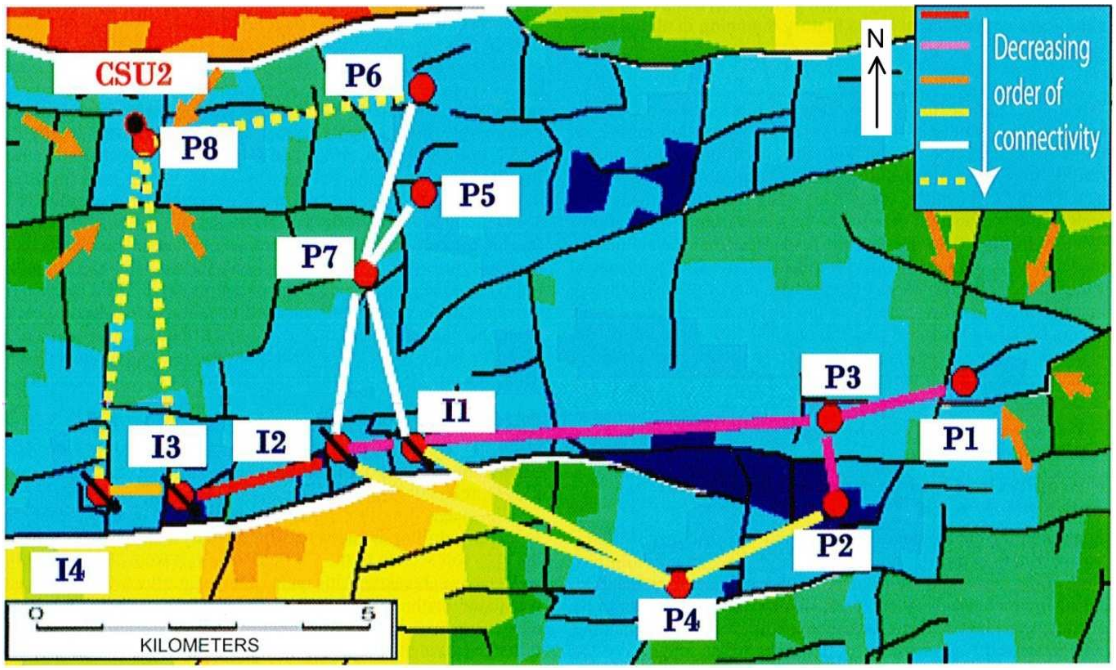


6.3.2. Faults as Enhanced Flow Paths Parallel to Groundwater Flow

Paul et al (2009) carried out numerous hydraulic and tracer tests on production wells in the CS gas field (alternating fluvial-deltaic sandstone, siltstone, and mudstone) located in the Timor Gap between Australia and Indonesia. They report normal faulting (extensional tectonics) for the CS field, with seismic data showing dip-slips of up to 300m on some of these faults. In this gas field, the principle horizontal stress field is aligned approximately 50°/230°, with the most significant faults oriented e ast-west. A conjugate fault set is also present, aligned north-south. Stress measurements indicate $S_{Hmax} > S_v > S_{hmin}$, indicating a strike-slip faulting regime. These elements of the physical setting bear similarity to the elements of the Bowen Basin physical setting.

Testing included drawdown monitoring at the pumped well and other wells, and tracer tracking, to assess the hydraulic connection between wells. The results of hydraulic testing indicated elevated K near, and parallel to, the faults (Figure 10, after Paul et al, 2009). The east-west faults showed larger K than the north-south faults. Numerical model calibration to 2.5 years of hydraulic head, discharge, and gas production data achieved significantly better matches with the fault damage zone concept included. This process provided the catalyst for Paul et al (2009) to derive a conceptual model for K of faults for use in numerical simulation. This conceptual model is discussed below in Section 9.

Figure 10: Lines of increased hydraulic head communication during pumping (representative of higher hydraulic conductivity) between wells of the CS gas field (after Paul et al, 2009). Elevated hydraulic conductivity was interpreted in an east-west direction, proximal to major faults. Colouring relates to the elevation of the pay zone.



6.3.3. The Nojima Fault

The Nojima Fault is a seismically active NE-SW striking right-lateral strike-slip fault with a minor reverse component, located in Japan. It has an estimated slip of about 500m (Mizoguchi et al, 2008). The slip magnitude and strike-slip regime makes it a useful case study in assessing faults in the Bowen Basin. The fault has undergone seismic events far larger than any events on record for the northern Bowen Basin, and has been extensively studied for the purpose of disaster management. Lockner et al (1999) and Mizoguchi et al (2008) interpret the results as indicating a thin, low strength, low-permeability core flanked by zones of high permeability rock that have undergone relatively limited total shear. Lockner et al (1999) interpret the results as being in good agreement with the idealized fault zone model considered by them. They conclude that the observations imply that the post-seismic fault zone will act as a high permeability fluid conduit for fluid flow in the plane of the fault to depths of as much as 3 to 5 km. In contrast, the core of the Nojima Fault is likely to act as a barrier to fluid flow across the fault, however this barrier is notably thin and may have a complex structure.

Results from one of the investigation boreholes is shown in Figure 11 (after Lockner et al, 1999), which illustrates the fault structure with the observed permeability contrasts. In this figure, not all available permeability measurements are shown. Permeabilities shown in Figure 11 were measured under a confining stress of 50MPa (approximately equal to an overburden depth of 3km). The fault was intersected at a depth of 624m in the GSJ borehole. Lockner et al (1999) estimate that the equivalent permeabilities for a depth of 624m would be about 50 times larger than the measurements made at 50MPa (approximately the same as a 3km depth). Using this approximation, the peak damage zone K at a depth of 624m would be about 3.4×10^{-4} m/day. This fits within a reasonable margin into the conceptual model where decreasing K decreases with depth conceptual model for the fault damage zone shown in Figure 26 below. Lockner et al (1999) implicitly assumed decreasing fault zone K with depth.

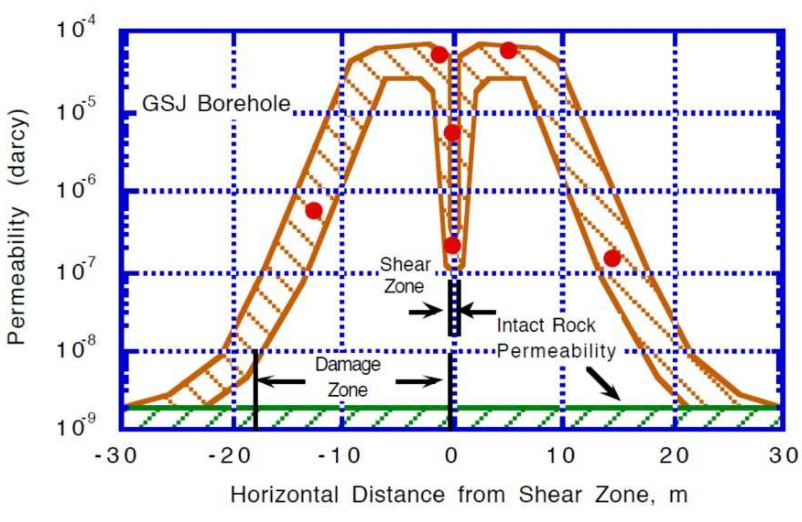
Mizoguchi et al (2008) concluded that the fault zone (when taken as single entity) has an anisotropic permeability structure, with high permeability parallel to the fault and low permeability perpendicular to it, with fluid tending to migrate parallel to the fault rather than across it. They present a table of results for permeability measured in the following three directions, within 10m of the core centreline (permeability results in parentheses):

- Parallel to the fault plane:
  - Parallel to the direction of slip (log average of 1.3 x 10^{-11} m^2 (11m/day) from 10 samples).
  - Perpendicular to the direction of slip (log average of 4.3 x 10^{-9} m^2 (3630m/day) from 6 samples).
- Perpendicular to the fault plane (log average of 5.6 x 10^{-11} m^2 (47m/day) from 6 samples).

These results suggest the damage zone flanking the fault core does not have a lower permeability perpendicular to the fault plane. The results indicate that the Nojima Fault damage zone flanking the core has high omni-directional permeability, without lower permeability perpendicular to the fault plane.

The K results for the Nojima fault are relatively high, and are presented here as an example case study of typical results for a seismically active fault. They may not be representative of the hydraulic characteristics of the faults in the northern Bowen Basin based on seismicity considerations, but are used for comparison to the results of the adopted conceptual model (see Section 9.3 below).

Figure 11: Permeability of core specimens from the GSJ borehole for the Nojima Fault zone (after Lockner et al, 1999). Permeability measurements were made under a confining stress of 50MPa.



6.3.4. The Yair Fault

The Yair Fault is a left-lateral fault located within the Dead Sea transform in Israel (Ran et al., 2013). The transform is of Cenozoic age and extends over 1000km, with lateral shifts of approximately 105km, a total width of approximately 10km, and vertical slips ranging between 1 and 10km, with movement on the transform having created pull-apart structures. The tectonic setting and slip magnitudes bear similarity to the northern Bowen Basin.

Ran et al. (2013) studied the hydraulic characteristics of the Yair Fault in detail, using field and laboratory tests to account for scale effects. Their fault model follows those of the authors above, with an added subdivision of the fault damage zone into a fractured area and a fragmented area (based on observed defects and rock structure). They estimated hydraulic conductivities of 0.0026m/day for the fault core and a range of 0.12 to 295m/day for the damage zone, at a depth of about 35m. These results are used for comparison in the conceptualisation of the hydraulic characteristics of faults in the northern Bowen Basin, shown in Figure 26 below.

6.3.5. Strike-Slip Faults

Given the azimuth of the principle horizontal stress field within the northern Bowen basin, and their likely slip along strike, the interpreted 70°/250° lineaments are interpreted to be strike-slip faults. Du Rouchet (1981, in Sonnenberg and Weimer 1993) describes strike-slip faults and provides a schematic illustration of their formation (Figure 12). A key aspect is the angle between the major horizontal stress direction and the fault strike.

Wibberley and Shimamoto (2003) carried out a detailed study of permeability of the Median Tectonic Line (MTL) in southwest Japan. The MTL is a high-angle strike-slip fault (known as a wrench fault) estimated to have a strike-slip of between 200 and 1000km. It is considered useful as a representative of a tectonically active strike-slip regime, and provides a conservatively upper bound on fault zone K for a strike slip faulting regime.

The MTL separates two different lithologies (gneiss and mylonite). Measurements of permeability on core samples at confining pressures between 20 and 200MPa (to simulate variable depth) indicated a hydraulic property distribution (Figure 13) similar to the Nojima Fault. Their fault core includes the core and damage zones of the authors above. For a confining pressure of 50MPa (approximately equivalent to 3km depth), the fault damage zone shows permeabilities approximately 100 times larger than the fault core and unfaulted media. Extrapolating the results for 50MPa and 200MPa confining pressures, the K of the core and damage zone for a depth of 500m are estimated as 0.0023m/day and 0.048m/day respectively. These values are shown on Figure 26 below.

Figure 12: Schematic representation of strike-slip fault formation (after Du Rouchet 1981, in Sonnenberg and Weimer 1993).

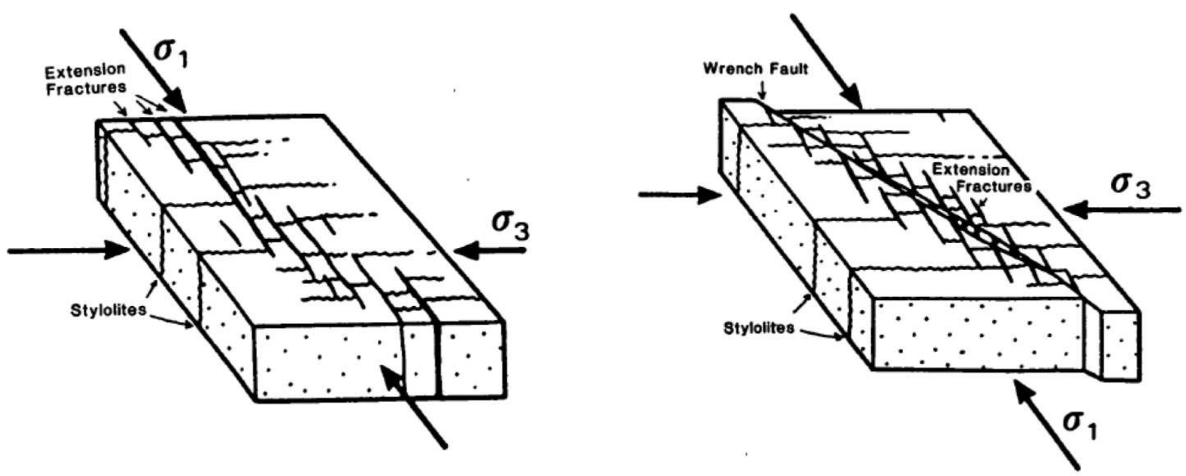


Figure 13: Hydraulic conductivity distribution of the MTL in plan view (after Figure 11 of Wibberley and Shimamoto 2003).

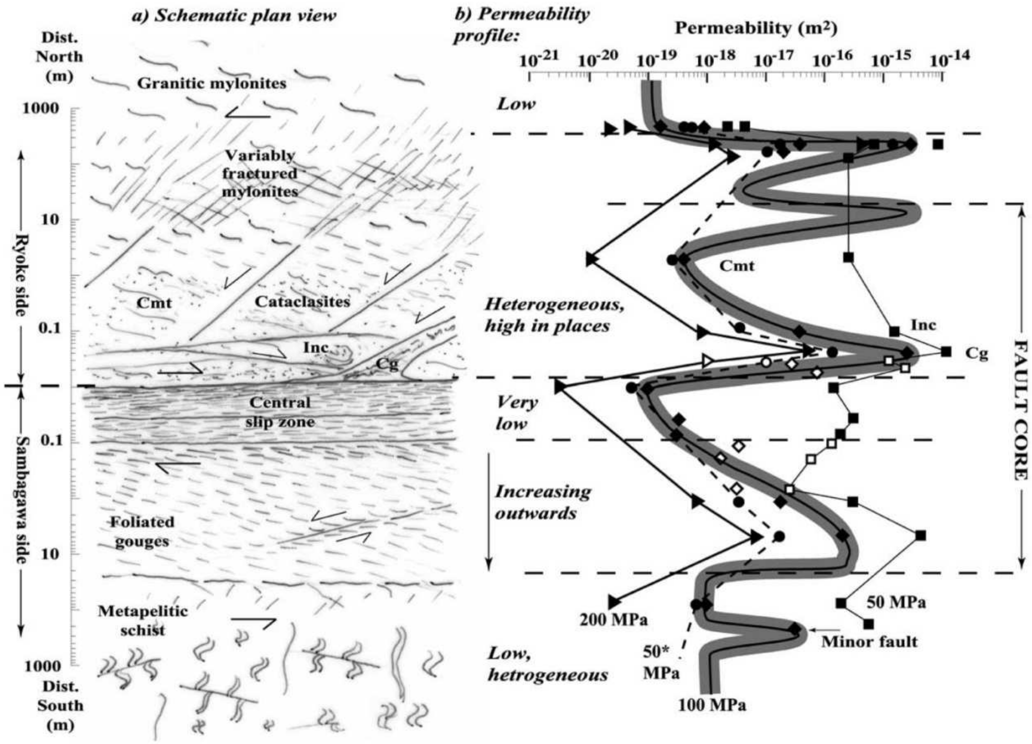


Fig. 11. Sketch summary of the main elements of permeability structure across the Median Tectonic Line. (a) Summary of the structural zones; (b) summary permeability data distribution for different confining pressures (stated at the base, with * denoting data from the deconfining path), for 20 MPa pore pressure, given the mapped distribution of fault rocks shown in Figs. 1–3. Note that the distance axis is logarithmic in both directions away from the Ryoke/Sambagawa contact. ‘Cmt’ and ‘Inc’ denote cemented and incohesive foliated cataclasites, respectively, and ‘Cg’ denotes crenulated gouge.

6.3.6. Fault Age and Implications for Hydraulic Conductivity

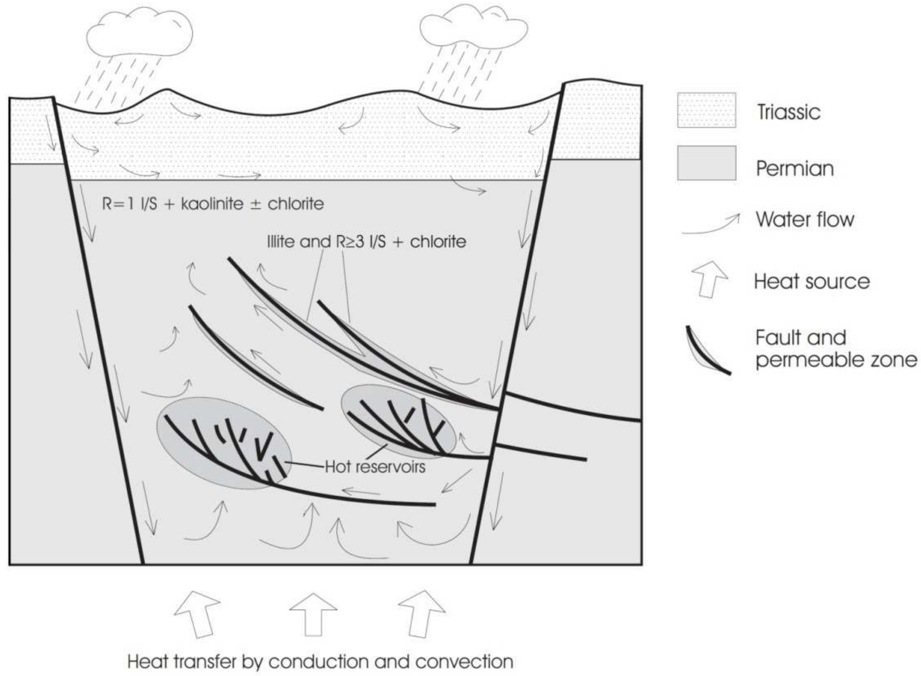
Lockner et al (1999) recognised the important question of how rapidly the enhanced K of the fault damage zone will be reduced by sealing and crack healing processes. They report that their observation of increased strength and decreased K in the deep damage zone of the NIED borehole of the Nojima Fault suggests that these processes can have significant influence on fault zone mechanics over the lifetime of an active fault. The time period of any potential healing and re-strengthening process is an important consideration. For example, if the process can complete over a single earthquake cycle, the initial K characteristics for the next earthquake can have a significant influence on repeat time, stress drop, and rupture nucleation (Lockner et al, 1999).

Uysal et al (2000) present a conceptual model for hydrothermal fluid migration in the northern Bowen Basin. In this model, several thermal events caused temperature-driven fluid flow events in Late Triassic times. The model proposes deep normal faults which formed in the northern Bowen Basin, as a result of the Late Triassic extensional tectonics, which enabled deep penetration of meteoric waters, initiating a hydrothermal process (Figure 14). Resulting hot fluids are believed to have been focused upwards along fracture and fault zones in the central parts of fractured media prisms bounded by the deep normal faults. This process caused clay and carbonate mineralisation resulting from interaction of hot fluids with volcanogenic rocks in the Permian Coal Measures.

Uysal et al (2000) concluded that the absence of mineral authigenesis postdating the Late Triassic clay and carbonate mineralisation in mudrocks and sandstones indicates that major fluid flow did not accompany regional high heat flow during Late Jurassic to Early Cretaceous times. They speculate that this may have been due to reduced K caused by the interpreted Late Triassic carbonate and clay mineralisation and the lower temperature of the event. Drill stem tests (see above) suggest comparatively high K, therefore the reduced K may have occurred at depths below those tested by the drill stem tests.

Draper (2005) believes mineralisation in the Bowen Basin is associated with volcanics on the eastern side (for example, Cracow) or Permian sediments in the Clermont area (for example, Miclere), as well as Cretaceous intrusions in the northern part of the basin.

Figure 14: Conceptual model of hydrothermal fluid migration in the Northern Bowen Basin in late Triassic times (after Uysal et al, 2000).



7. EXTENT OF ARTIFICIAL HYDRAULIC FRACTURING

7.1. Literature Review

The extent of fracture generation during hydraulic well stimulation depends on the fluid pressure used in the process. This pressure is dependent on rock strength factors such as lithology, compressive stress, and the pressure-depth setting.

In a case study in the Lower Barnett Shale (USA), Wessels et al (2011) estimated a lateral extension of about 300m (1000 feet) from fracture stimulation, using microseismic monitoring. Within this radius, the test resulted in the occurrence of seismic events in a thrust fault in the shale. The presence of the fault was discriminated by the type of seismic event, able to be measured according to the observation method (source mechanism inversion with a wide-azimuth surface or near surface array, or a minimum of two typical observation wells).

Wessels et al (2011) also report that microseismicity generated by activation of natural fractures during hydraulic stimulation is mechanically dependent upon injection pumping whereas fault activity is not. Therefore, natural fracture events will take place during pumping, and fault activation events will take place during a longer period of time (due to the higher stress imposed on the fault that is slowly released) (Downie et al, 2010).

Johnson et al (2010), in a study of fracture extent in two wells in the Walloon Coal Measures of the Surat Basin, found the following:

- Bore Ridgewood 5: A maximum lateral extent of about 100m from the well, and a vertical extent of about 130m.
- Bore Ridgewood 6: A maximum lateral extent of about 85m from the well, and a vertical extent of about 30m.

Ground tilt extended much further as would be expected, however inflection points are not calculated.

Davies et al (2012), from interpretation of a large database of microseismic monitoring results , estimated the probability of extent of vertical fractures from stimulation for five groups of shale. For four of these groups, there is a 50% probability for an upward propagating stimulated fracture to have an extent of between about 50m and 70m or less. There is a 90% probability that the extent of an upward propagating fracture would be in the range 120m to 150m or less. They also discuss downward propagating fractures, which are of less concern for impact assessment.

In underground coal mining in the Hunter Valley, it has been found that microseismic events usually do not occur up to the full height of desaturation above a longwall panel. For fracture stimulation, the extent of microseismic events may not indicate the extent of defect dilation. Johnson et al (2010) employed surface tiltmeters (in conjunction with microseismic monitoring) to evaluate fracture extent. The inflection point of surface tilt is usually a good indicator of the extent of subsurface movement.

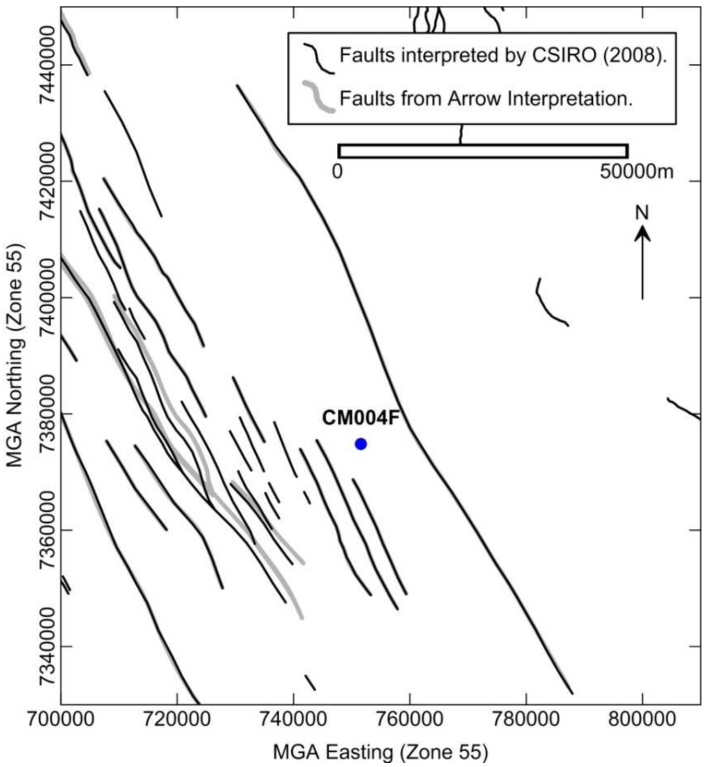
7.2. Observations from the Bowen Basin

Borehole CM004F (from Arrow's Coomoobooraloo field) is reported to have been fracture stimulated prior to testing (Arrow, 2013b). Figure 15 shows the location of the bore relative to faults mapped by the CSIRO and others (bore coordinates are assumed to be with respect to the MGA). The bore is distant from the nearest interpreted fault or lineament (although unknown features may be closer). The review of K data indicates the capture zone of the well may have intersected one or more flow barriers (possibly thrust faults). If a barrier was a fault, the result suggests that its fault core K was not measurably increased by fracture stimulation at CM004F. The closest mapped fault (in a radial direction) to CM004F is approximately 6km away. Therefore, fracture dilation from well stimulation most likely did not extend that distance from the bore.

Microseismic monitoring of Arrow bores 012F (Olive Downs) (Pinnacle, 2011) and 060F, 050F, and 052F (Red Hill) (Pinnacle, 2013) indicated interpreted seismic events extending laterally as follows:

- Likely extension of 80m to 95m for Olive Downs 012F (however some elements of the fracturing process failed during implementation, and the achieved fracture extent from the well was less than expected).
- Up to 242m for Red Hill 060F and 253m for 050F and 052F.

Figure 15: Location of CM004F.



8. HYDRAULIC CONNECTION BETWEEN UNCONSOLIDATED AND CONSOLIDATED MEDIA

The vertical hydraulic connection between alluvial deposits and underlying fractured rock media is an important factor in assessing potential groundwater drawdown in alluvium due to drawdown in underlying rock. It is a fundamental parameter in quantifying the impact to alluvial groundwater supplies from depressurisation of underlying consolidated fractured media. A review of relevant information is provided below for assessing the nature of the hydraulic connection.

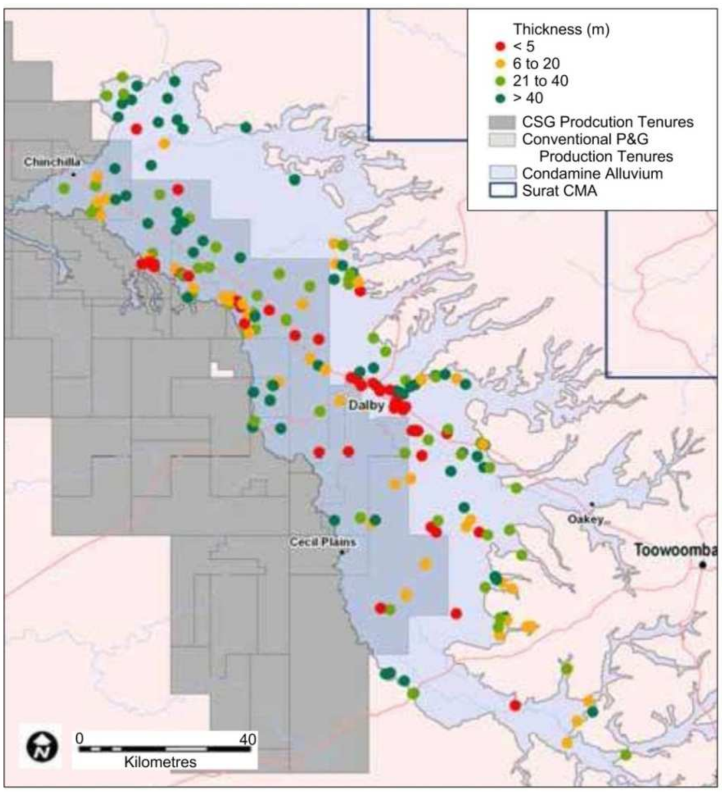
Several investigations throughout NSW sedimentary basins (for example, the Lachlan River alluvial system) suggest it is typical to find a layer of low K at the interface between sediments and underlying rock. The mode of formation of such interfaces suggests a high probability for the presence of a low K interface. During an erosional phase, the fractured rock ground surface reduces, with a surface layer of residual weathering products (soil) migrating downwards with the ground surface. At the beginning of the depositional phase, the first sediments may be deposited on the existing soil surface. Further compaction and alteration of the soil may lead to further reduced K. Erosional and depositional phases are usually present simultaneously within a large basin, mainly related to ground elevation and morphology. Host rocks comprising altered or metamorphosed media create lower K interfaces (small grain size distributions) however interlayered claystone and sandstone can create interfaces with variable grain size distributions.

8.1. Surat Basin

The Queensland Water Commisison (QWC) (2012) (now identified as the Office of Groundwater Impact Assessment (OGIA)) presents information on the transition zone between the Condamine Alluvium and the Walloon Coal Measures of the Surat Basin. That report describes the presence of a layer of weathered clay and low K material between the lowermost productive parts of the Condamine Alluvium and the uppermost coal beds in the underlying Walloon Coal Measures (Lane, 1979, in QWC, 2012). The layer is described as a combination of low K basal alluvial clays of the Condamine Alluvium and the weathered upper part of the Walloon Coal Measures, with both units usually indistinguishable from each other. Together these units are referred to as the transition layer. QWC (2012) reports only a few bores with lithological logs describing the thickness of this layer. Available data suggest that its thickness averages around 30m however some locations with nil thickness occur (where productive alluvial sands and gravels lie directly on coal measures). Figure 16 shows the thickness of the transition layer as inferred in QWC (2012) from borehole logs. No direct measurements of K for this layer were available, however based on the nature of the material encountered in boreholes, they estimated a likely K range of 8 x 10^{-6} to 0.15m/day.

QWC (2012) report that there has not been a widespread deterioration in water quality in the Condamine Alluvium, despite higher water levels in the underlying coal measures, which suggests a relatively small amount of flow between these units. They interpret that the interconnection between the alluvium and coal measures is therefore unlikely to be strong.

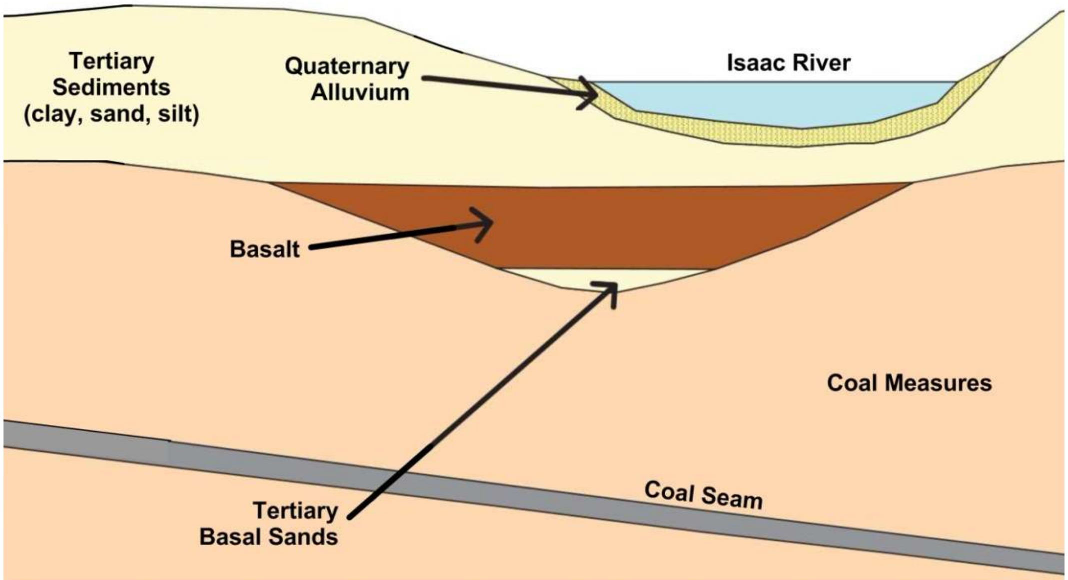
Figure 16: Thickness of transition layer between Condamine Alluvium and Walloon Coal measures, as inferred by QWC (2012) (after Figure 4-5 of QWC 2012).



8.2. Moranbah North Case Study

A case study is available for the Bowen Basin, comprising hydraulic head monitoring data over, and adjacent to, longwall mining at the Moranbah North longwall mine (JBT, 2010). This mine is located close to Arrow's current coal seam gas extraction operation associated with the Moranbah Gas Project. Local lithology comprises consolidated coal measures overlain by Tertiary (or younger) sediments and basalt. Figure 17 (JBT, 2010) shows the stratigraphic relationship between the strata.

Figure 17: Stratigraphy at Moranbah North Coal Mine (after JBT, 2010).



The response of groundwater in basalt and Basal Sands to mining in the coal measures is useful to review, because the basalt and Basal Sand zones are both likely to have a palaeosol horizon at the interface with underlying coal measures (for basalt the palaesol is likely to have been significantly heat affected). Coal seam gas wells and longwall panels create separate types of drainage boundary conditions for subsurface media at some distance from these boundaries. The main differences in these boundary conditions are as follows:

- Coal seam gas well: Ground deformation expands from a perforated interval. The perforated interval is a controllable parameter and is usually confined to the coal measures. The drainage boundary is a virtual line sink at atmospheric pressure inside the borehole (water level a few metres above the mined seam). Several wells clustered together can form a three-dimensional sink.
- Longwall panel: The height of complete groundwater drainage (H, equal to the top of the collapsed zone) is generally a function of the mined height (t), panel width (w), and overburden thickness (d). The height of complete groundwater drainage may not necessarily be limited to the coal measures. The drainage boundary is three-dimensional with sub-vertical sides, following the panel footprint.

Figure 18 shows piezometer and mined longwall locations at the Moranbah North mine. None of the mapped faults collated above (and shown in Drawing 1) are present at the mine site. Piezometers over mined panels show significant depressurisation in the mined seam. Piezometers outside the panel footprint have been grouped into four zones for analysis. Each zone is taken to be a virtual point position with respect to its size (compared to the size of the longwall block) or with respect to the orthogonality of the longwall block. Table 2 lists available completion details for the monitoring piezometers used for analysis.

Figure 18: Moranbah North mine workings and piezometer locations as at 2010.

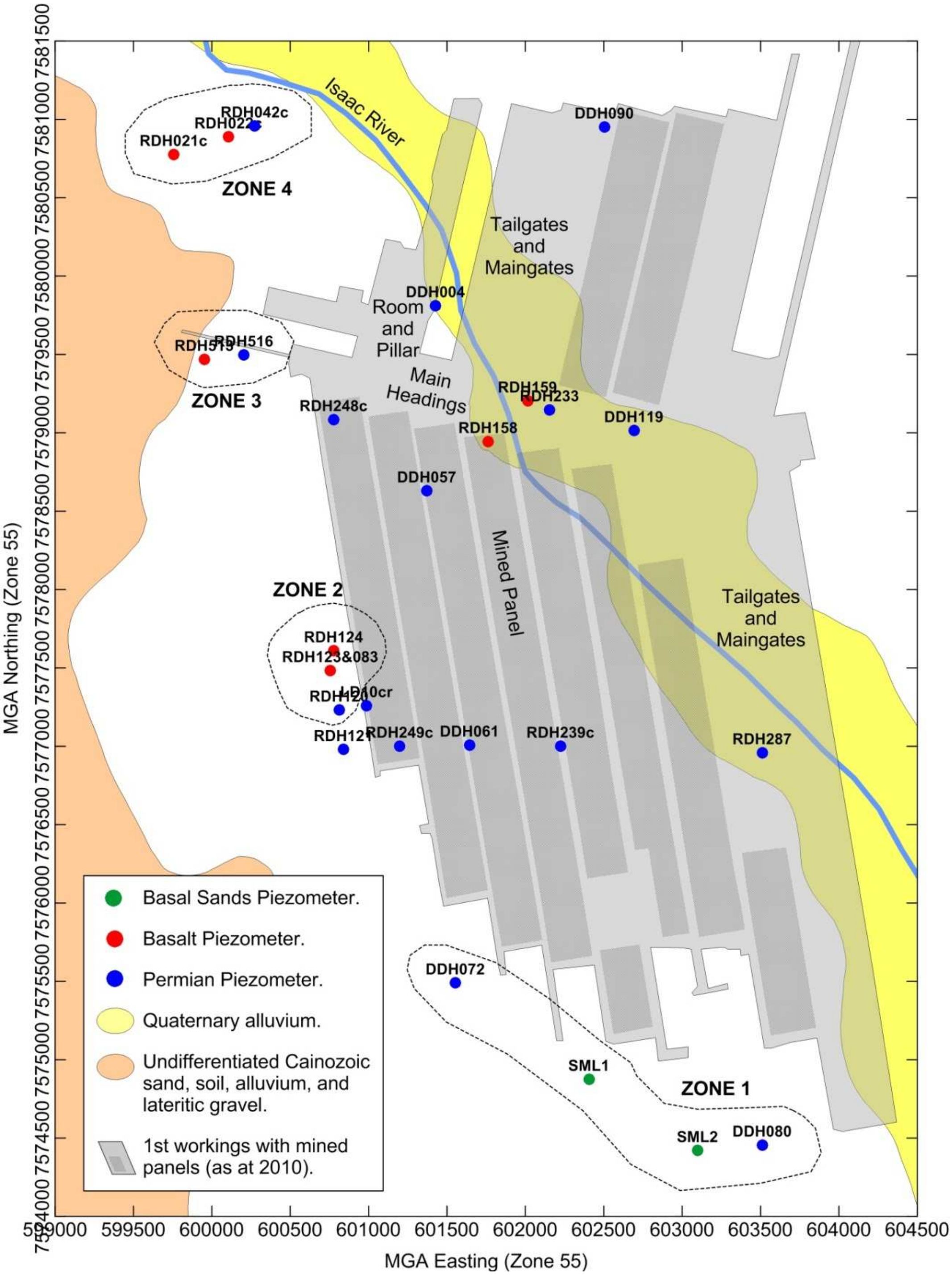


Table 2: Completion Details for Groundwater Monitoring Piezometers at Moranbah North Mine.

Zone	Piezometer	Easting (MGA Zone 55)	Northing (MGA Zone 55)	Ground Elevation (mAHD)	Depth (mbgl)	Screened Lithology	Average Distance from nearest mined panel (m)	Approximate Total Drawdown (m)		Drawdown in Tertiary Sequence as a Proportion of Drawdown in Mined Seam
								Mined Seam	Tertiary Basalt or Basal Sands	
1	SML1	602406	7574875			Basal Sands	500m south	80	20	25%
	SML2	603099	7574420			Basal Sands				
	DDH072	601553	7575490	265.1		Permian (GM Seam)				
	DDH080	603511	7574455	235.7		Permian (GM Seam)				
2	RDH123	600756	7577483	248.8	69	Basalt	200m west	60	20	33%
	RDH124	600777	7577609	243.4	67	Basalt				
	RDH120	600812	7577231	252.3	121	Permian (GM Seam)				
3	RDH513	599952	7579468	252.7	67	Basalt	500m west	20	0	Nil
	RDH516	600204	7579496	252.3	96	Permian (GM Seam)				
4	RDH021c	599757	7580776	245.7	85	Basalt	1600m north northwest	30	0*	Nil
	RDH042c	600274	7580958	238.8	66	Permian (GM Seam)				
N/A	RDH158	601763	7578944	234.44	>51	Basalt	Over Workings	N/A		
	RDH159	602015	7579203	235.83	>37	Basalt				

* Water level rose steadily by 18m between 1997 and 2010 (not considered to be due to natural causes).

Prior to analysis of monitoring data for the off-panel piezometers, an assessment was made of the likely magnitude of H for the Moranbah North mine, as this bears directly on the drainage process in the shallow groundwater system. Monitoring data for shallow piezometers over mine workings are available for RDH158 (over the centre of a mined panel) and RDH159 (over the main headings). Figure 19 shows the hydrographs for these piezometers. RDH158 went dry in August 2003. The time derivative of the water levels indicates a high probability of complete desaturation of the basalt sequence, however deeper piezometers are not available to confirm this. RDH159 was reported dry (with the piezometer base at 31m below ground) on 6 June 2003, however earlier measurements indicate water levels at 37m below ground, from which it is surmised that ground movements may have blocked the piezometer at 31m depth in January 2003. The time derivative of the water levels suggests saturation may have been maintained below the piezometer screen of RDH159, most likely because the piezometer is located over 1st workings. This suggests the top of the collapsed zone (H) above the panels may be intersecting Tertiary and younger sequences, inducing lateral flow from these sequences into the collapsed zone.

Figure 19: Hydrographs for RDH158 and RDH159 at Moranbah North Mine.

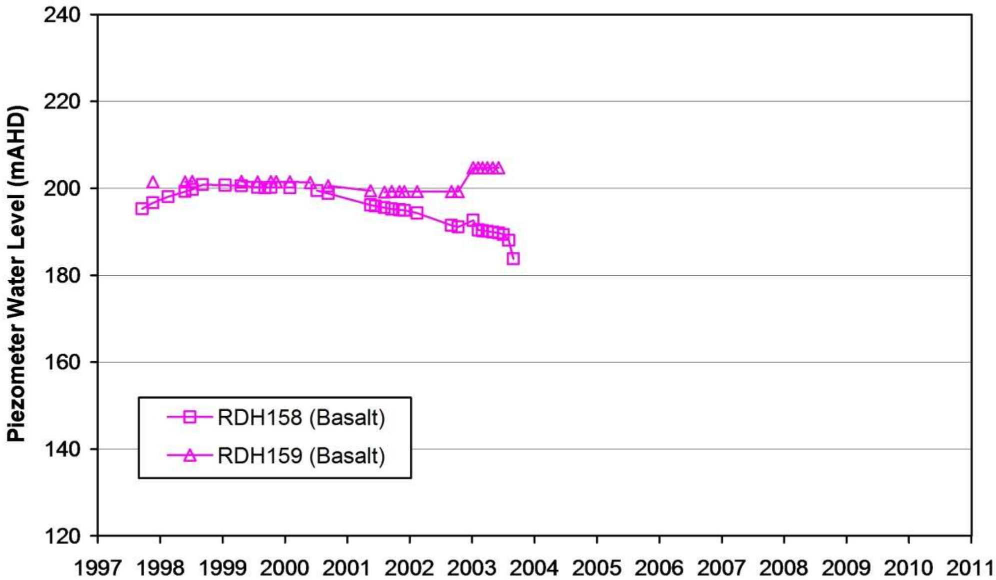
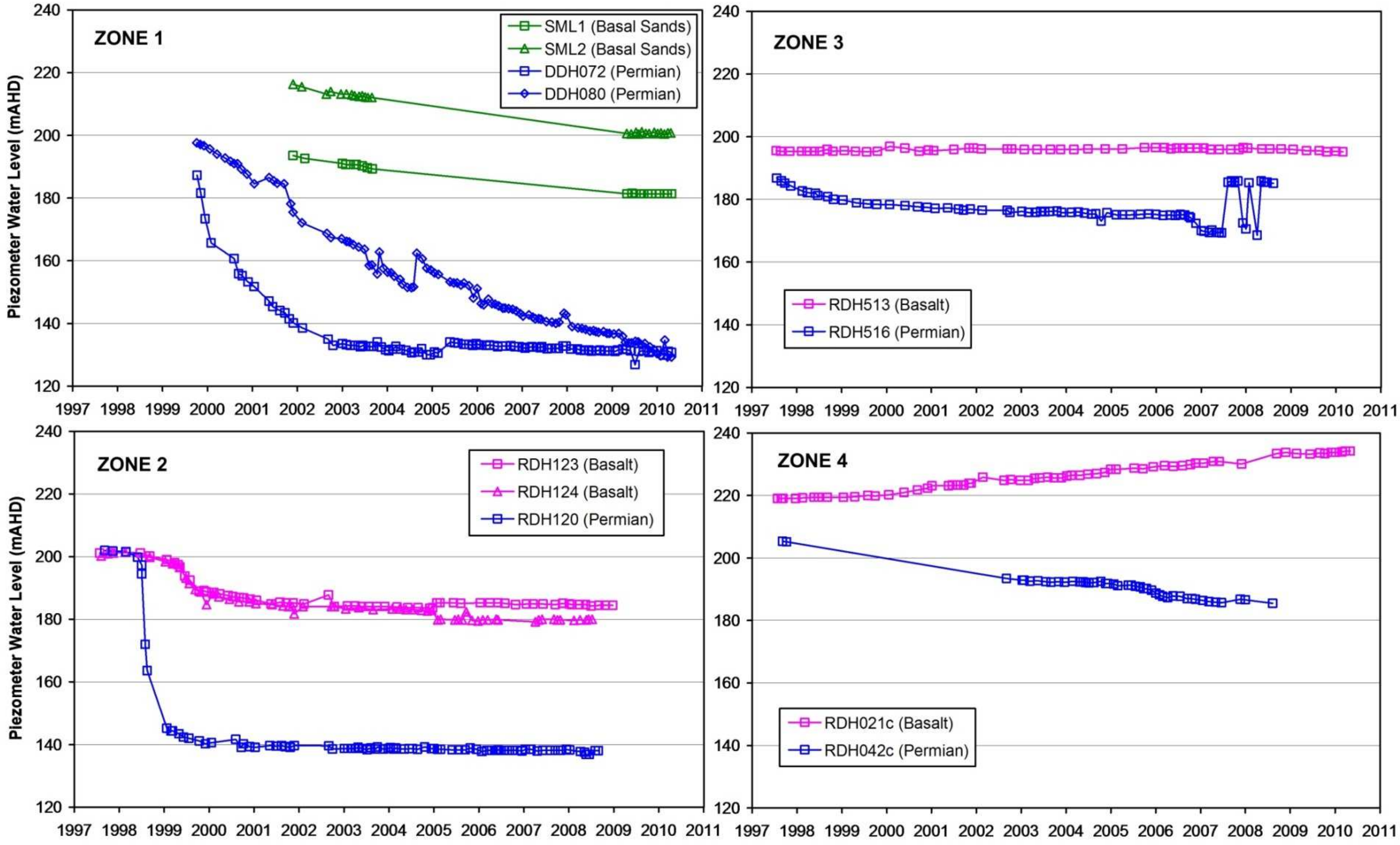


Figure 20 shows the hydrographs for each of the piezometer zones. Basal Sand piezometers (Zone 1) show about 20m of probable drawdown (from pre-mining) compared to about 80m for the Permian piezometers. The Basal Sands drawdown is likely to have been caused by vertical and lateral hydraulic head gradients (and subsequent flow), since an atmospheric drainage boundary is likely to have been created in the shallow strata (that is, the collapsed zone has reached the Tertiary sequence or higher).

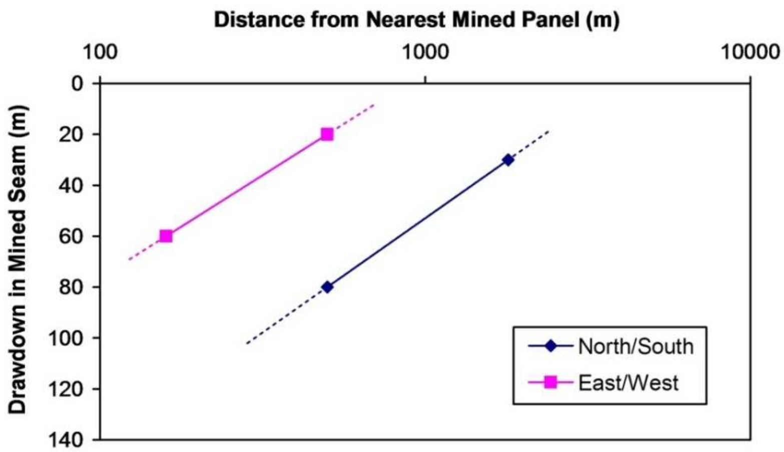
Basalt has undergone drawdown from mining in Zone 2. No mining-induced drawdown can be clearly identified in Zone 3, and in Zone 4 the basalt is undergoing water level rise from what may be an artificial cause. The data suggest that no drawdown in the Tertiary sequence is seen at distances of 500m or more from the panels, however the plan geometry of the Tertiary sequence is unknown (it may not be equilateral in extent, nor of equal thickness, creating a non-uniform drawdown aureole). In addition, the hydrographs for DDH080 and RDH042c had not yet reached equilibrium by the end of the monitoring period.

Figure 20: Hydrographs for off-panel groundwater monitoring piezometers at Moranbah North Mine.



The information also provides an insight to the lateral anisotropy of the K field in the coal measures. Figure 21 shows the drawdown in the GM seam versus distance from the panels. There is a clear preference for depressurisation to evolve in a north/south direction, probably along the same direction as the 150°/330° fault system. This is normal for fractured media, since they are rarely laterally isotropic. The lateral K field for such a medium is subject to the fractal interrelationship of defect populations at varying scales of observation. In this case, the large scale defect system oriented 150°/330° appears to be the controller for the midd le scale defect system sensed over encompassed by the panels and piezometers, providing enhanced K in that direction.

Figure 21: Drawdown in the GM Seam at Moranbah North Mine.



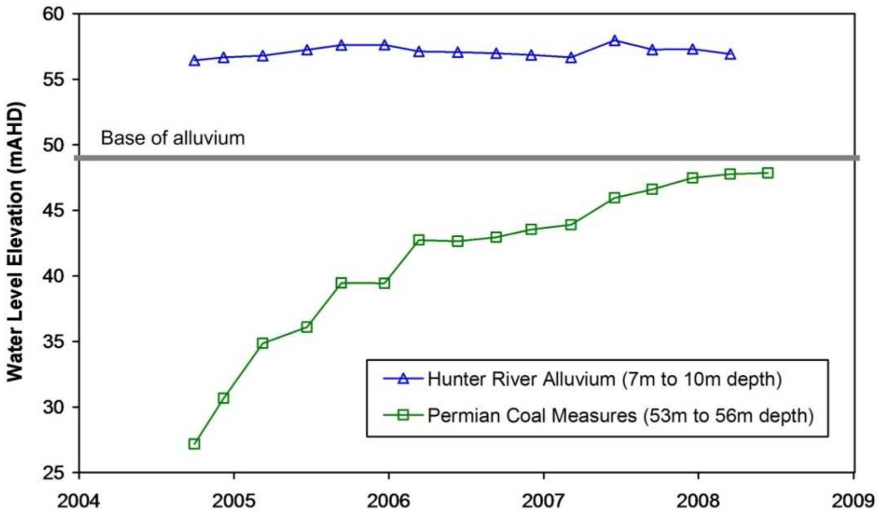
8.3. Hunter Valley Case Study

Unpublished information for a large operating open-cut coal mine in the Hunter Valley demonstrates the stability of alluvial water levels during drawdown in underlying Permian coal measures. A monitoring site with nested piezometers located approximately 100m south of the Hunter River and 200m north of an opencut highwall hosted a piezometer screened within surface alluvium of the Hunter River and a piezometer screened within the coal measures. The pit was mined to about 70m depth opposite the piezometer nest (more than 10m below the base of the Coal Measures piezometer screen). The alluvial body was not intersected by the mine pit, eliminating the possibility of lateral drainage from the alluvium due to the pit. Monitoring data are shown in Figure 22. Monitoring commenced after emplacement of mine spoil against the highwall adjacent to the monitoring nest. The monitoring data show recovering water levels in the coal measures.

Measurements indicate the alluvial hydraulic head is relatively stable, while the coal measures hydraulic head recovers from more than 20m below the base of the alluvium to a few metres below the base. The alluvial water level is the same as, and controlled by, the river stage, so that the stability of the alluvial groundwater level does not necessarily imply nil downward leakage to the coal measures, but means that any downward leakage from the alluvium to the coal measures is replenished by water from the river channel.

In practice, quantification of K of the transition layer is difficult for the case of highly productive alluvium in hydraulic connection to a flowing river channel, because downward vertical leakage from the alluvium can be replenished by river water.

Figure 22: Drawdown in Permian Coal measures and alluvium near the Hunter River (NSW).



9. CONCEPTUAL MODELS FOR HYDRAULIC CHARACTERISTICS OF FAULTS

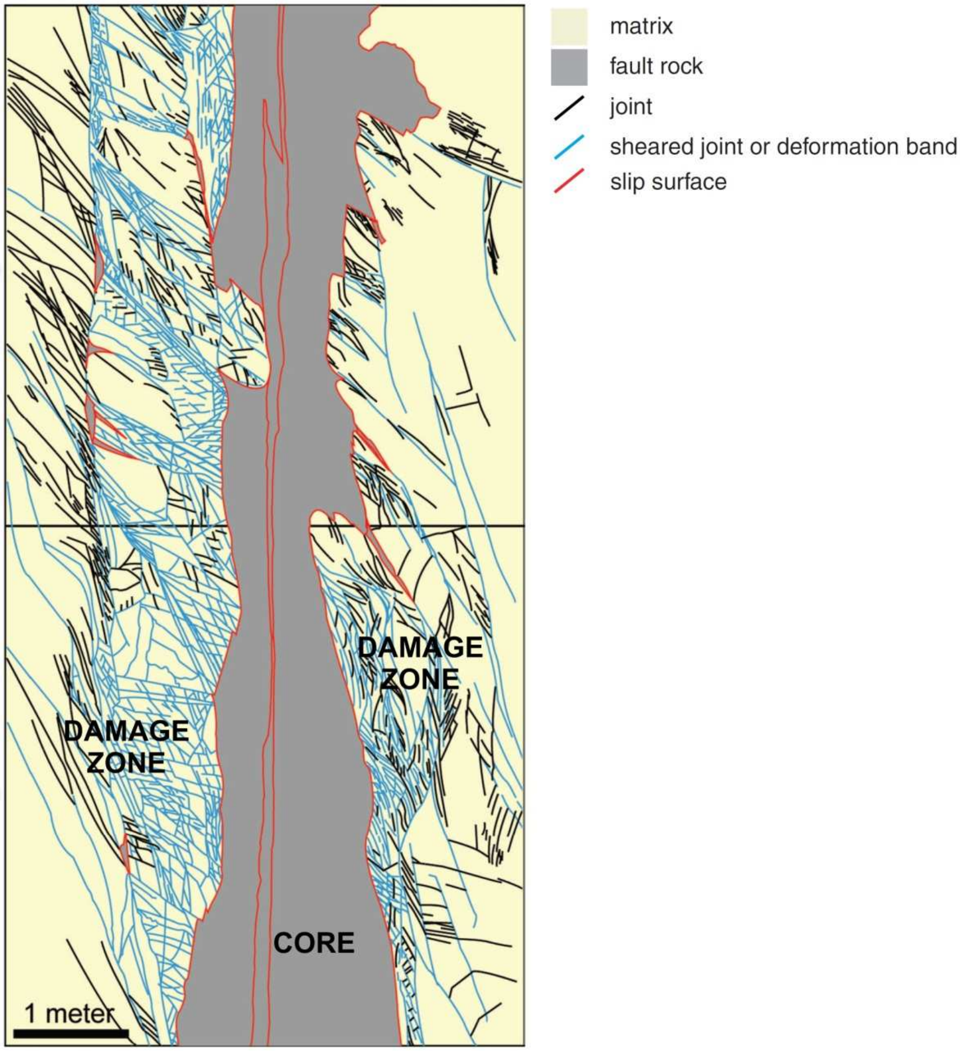
9.1. Flodin et al (2001)

Given the absence of site-specific data allowing hydraulic characterisation of faults in the northern Bowen Basin, the conceptual model of Jourde et al (2002) and Flodin et al (2001) for hydraulic characterisation of thrust faults is selected based on several advantages as discussed below. Their model is based on a detailed study of the structural and lithological characteristics of the Aztec Sandstone, a high-porosity aeolian sandstone. They define two main zones associated with a thrust fault, as shown in Figure 23:

- A central fine-grained fault core generally bound on either side by slip surfaces, which are planar features that accommodate large amounts of shear displacement. The fault core contains only the most deformed features (fault rock, fault breccia, and slip surfaces) of a fault zone.
- A damage zone on both sides of the fault core, containing attendant structures related to the growth of the fault. They note that as a consequence of the formation mechanism, most of the damage zone elements are subvertical.

Jourde et al (2002) and Flodin et al (2001) derive relationships for K of the fault core (Kc) and K of the fault damage zone (Kd) by upscaling detailed field measurements of localised zones of faults in the Aztec Sandstone. This procedure is robust, and given the nature of the subject lithology, may be a useful quantification process where fault hydraulic data are not available for sedimentary basins. This conceptual model is adopted in the analysis that follows, and is applied to the northern Bowen Basin. In most investigations, Kd is usually not seen unless the fault zone is penetrated. Since most faults or lineaments are subvertical, Kd usually remains masked during subvertical drilling.

Figure 23: Hydraulic Conceptual Model of a Thrust Fault with a Vertical Slip of 150m (modified from Jourde et al, 2002) viewed along a Cross-Section normal to the Strike of the Fault.



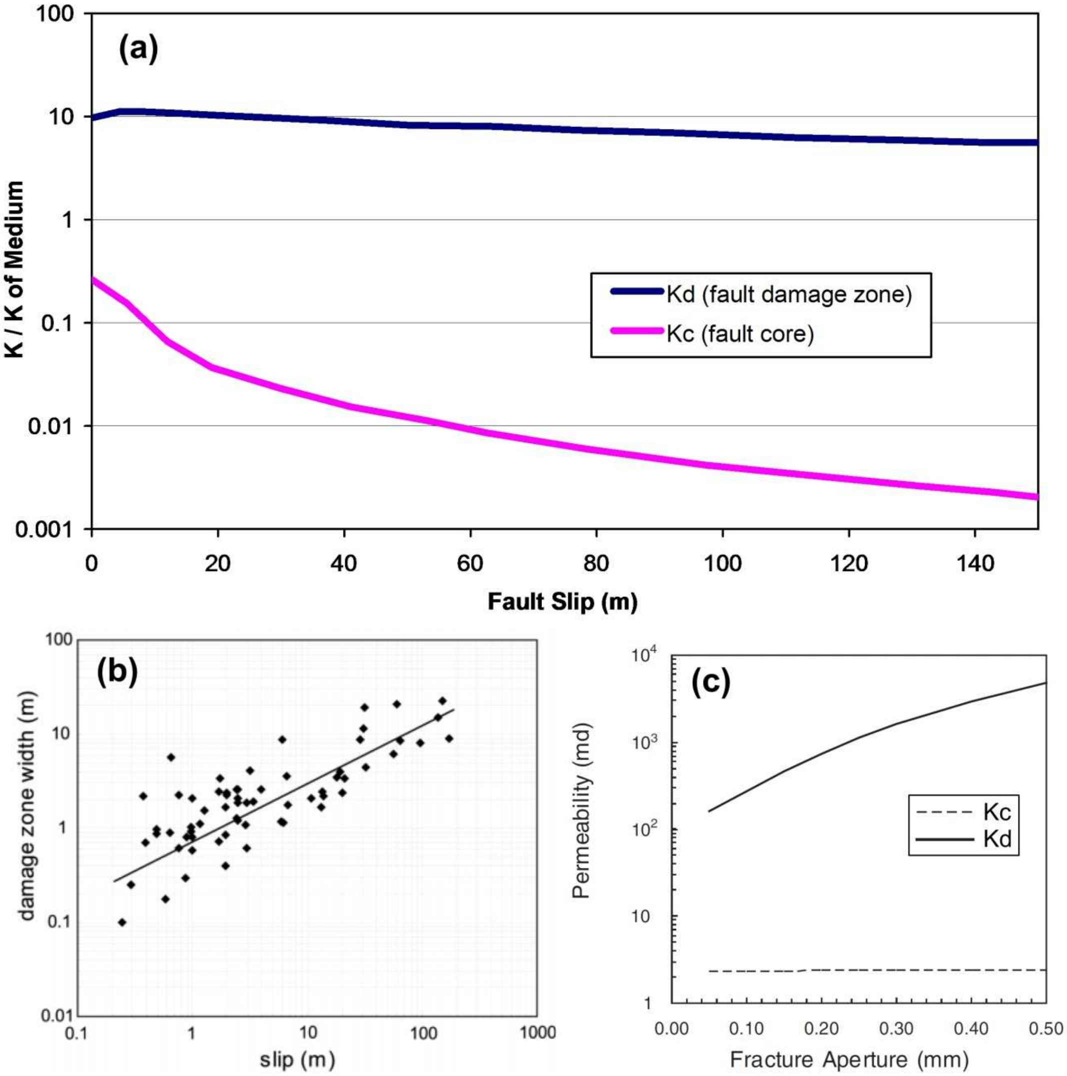
The adopted conceptual model provides estimates of the variation of fault zone width with vertical slip, and the variation of the fault permeability tensor with defect aperture in the damage zone. Figure 24 shows these variations, and the ratio of Kc and Kd to K of the surrounding medium, as a function of fault slip.

The interpreted 70°/250° strike-slip faults in the Bowen Basin appear to show no vertical displacement (as inferred for one lineament, based on Cross-Section A of Figure 3-3 in URS 2012). Published information (see Section 6.3.5 above) suggests Kc and Kd for these faults may be higher than for the 150°/330° faults, due to their large slips.

Fault zone thickness (t) has also been estimated by other authors using field observations of thickness versus fault displacement (D). Two empirical relations are:

- t = D/66 (Hull, 1988)
- t = D/170 (Walsh et al, 1998)

Figure 24: Various relationships derived by Jourde et al (2002) and Flodin et al (2001) to assist with numerical simulation of fault zones. (a) Variation of the fault permeability tensor with fault slip (from Flodin et al, 2001). (b) Variation of the fault damage zone width with slip (after Flodin et al, 2001). (c) Variation of the fault permeability tensor with aperture of defects in the damage zone (after Jourde et al, 2002).



9.2. Paul et al (2009)

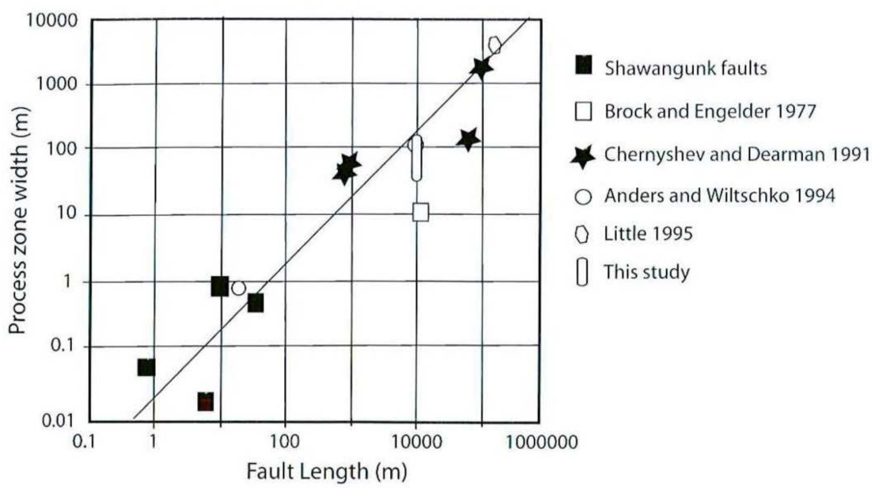
Paul et al (2009) use analytical equations proposed by Freund (1979) and Madariaga (1976) (dynamic-rupture propagation) to define the fault damage zones. These equations use the insitu stress field and primary physical rock properties (such as unconfined compressive strength and S and P wave velocities). The method involves application of energy to a point on a pre-existing fault, then calculating the propagation of slip, and ultimately calculating the width and length of the resulting damage zone along the fault plane by estimating the volume of rock brought to failure by the stress perturbation around the rupture front.

They calibrate a model using observations from the Nojima Fault studies. Their simulations suggest:

- For the CS gas field (refer to section 6.3.2), damage-zone widths of approximately 50m to 140m for east-west faults and 20m to 60 m for north-south faults (consistent with field observations).
- Damage zone width decreases with depth because of increasing elastodynamic stress intensity and because of increasing rock strength with depth.
- Implementation of the method significantly improved calibration of observations. The method is considered to provide a reasonable first-order approximation for permeability characterisation of faults.

The relationship between the width of the fault process zone (the damage zone at the "front" of energy propagation, and approximately proportional to the resulting fault zone) and fault strike length, based on data from several authors, is also provided (Figure 25). This suggests the length of the fault can be used, in the absence of other data, as an approximate indicator of the width of the damage zone.

Figure 25: Fault Process Zone width versus fault strike length (after Paul et al, 2009, modified from Vermilye and Scholz, 1998). Note that "This study" in the key refers to the study of Paul et al. (2009).



9.3. Adopted Conceptual Model for Hydraulic Characteristics of Faults in the Bowen Basin

Earthquake information suggests the Bowen Basin seismic activity preferentially occurs along interpreted 70°/250° strike-slip faults. These int erpreted faults are subparallel to the stress field and are difficult to assess with seismic reflection data. Seismic refraction is usually more effective in identifying these features, if they are subvertical.

Clark et al. (2011) hypothesise that the Bowen Basin faulting predates the Cainozoic, and is largely inactive, based on the lack of neotectonic events in Queensland.

The most comprehensive published information on the location of thrust faults (150°/330°) appears to be the CSIRO (2008) interpretation and the Arrow Interpretation. Analysis of cross-sections in URS (2012) indicates that at a given location, the maximum slip is an average of 80m, but varies substantially. The Sliwa (2011) dataset could not be used to obtain fault slips because the vertical axis is not depth (but may be two-way travel time), and two or more marker horizons were not present on each section (from which the depth scale could be approximated).

For the purpose of fault zone hydraulic characterisation, two factors are used to quantify fault K. These factors were selected based on the data review above, and the data that may be possible to obtain for the Project Area, and comprise the following:

- Variation of slip with depth.
- Variation of K of host rock with depth.

In the absence of site-specific hydraulic test results for faults in the Project area, the conceptual model of Jourde et al (2002) and Flodin et al (2001) is valuable as a tool to reduce uncertainty in assessment results. The model is based on K of the undisturbed medium, which varies according to depth and lithology (see Figure 6). This allows the effect of the insitu stress field to be incorporated (by using K of the medium).

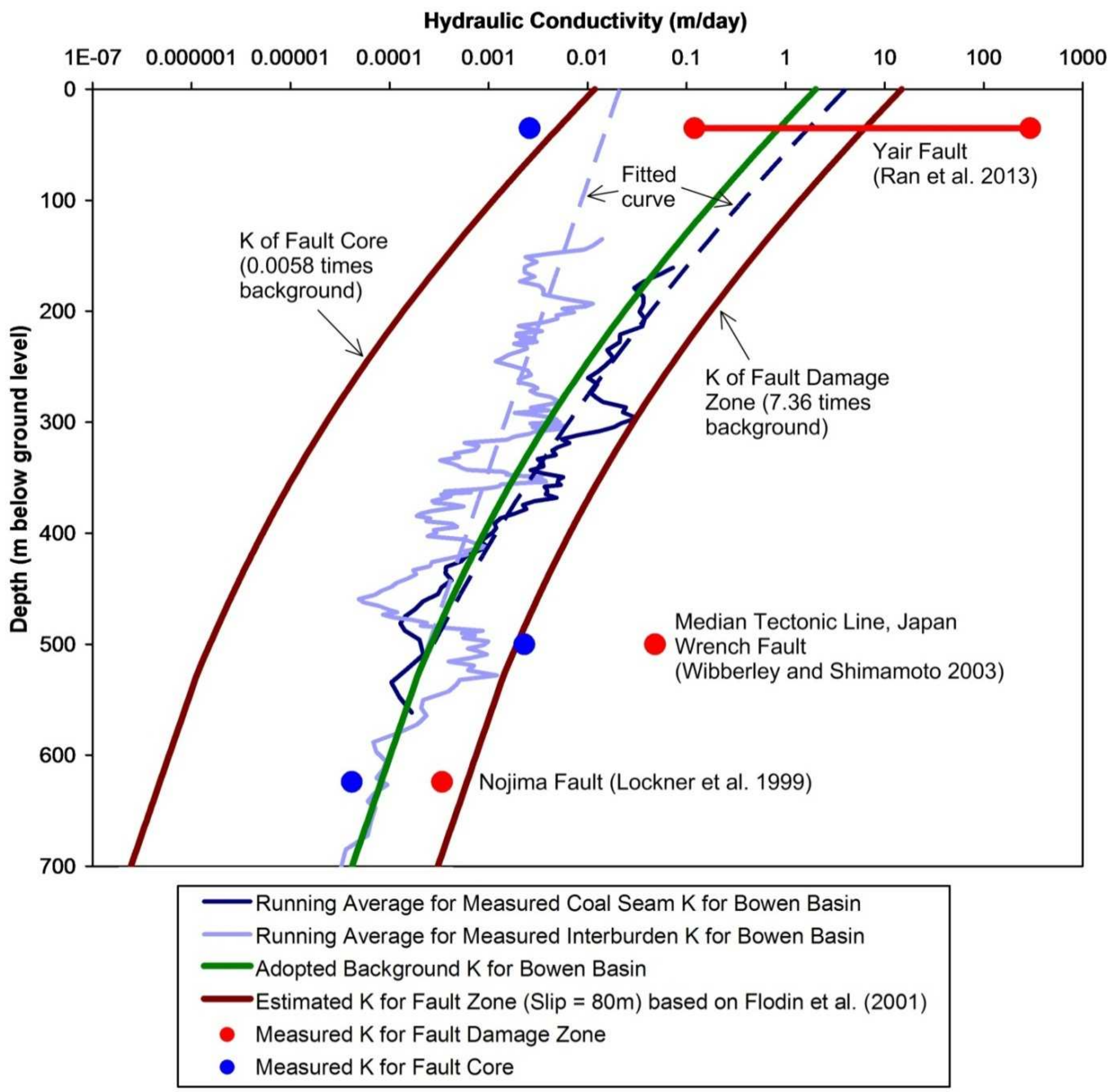
The data review indicates that for the Bowen Basin, the average K of coal is higher than for interburden, and both decrease with depth. To assess the proportion of each lithology with respect to total vertical thickness of the profile, logged information for Arrow bore LW004P was used. The density log for LW004P has been used as an approximate indicator of the ratio of coal to interburden in the profile. Assuming that densities lower that $2gm/cm^3$ indicate coal (however, the fault interval may have logged in this range also), the density log indicates a total interval of 81m of coal to a depth of 450m, or a vertical proportion of 18% of the profile. Between 450m and the base of the bore (895m), a total interval of 6m of coal is interpreted (about 1% of the profile). Using the upper profile proportion as a conservative estimate, the fault core would contain about 20% coal and 80% interburden.

To reduce the fault K characterisation to one of using a single background media K, the background K can be approximated as the average of the lateral hydraulic conductivities of interburden and coal (since both will be present in the fault core and fault damage zone). This is considered conservative for the case where assessment of impact to surface alluvial bodies is required, since lithologies near the alluvial contact are likely to contain more than 50% interburden. Figure 26 shows the data from Figure 6a transformed to a single background value for fault characterisation. The figure also shows Kd and Kc for a slip of 80m (the average maximum slip calculated for faults in the Project area), using the conceptual model formulation of Flodin et al. (2001). Figure 26 also shows field measurements of Kc and Kd from around the world that indicate that the selected conceptual model provides a reasonable preliminary basis for quantitative characterisation in the absence of site-specific data. The MTL (Wibberley and Shimamoto, 2003) is a strike-slip fault and its measurements indicate the likely higher Kc and Kd for these types of faults, due to the magnitude of the strike-slip.

In the absence of any hydraulic test data for the faults within the Project area, the relationships in Figure 26 may provide a reasonable basis for numerical simulation. Fault zone widths can be calculated using the conceptual model. Together, these quantities allow a three-dimensional characterisation of the thrust faults.

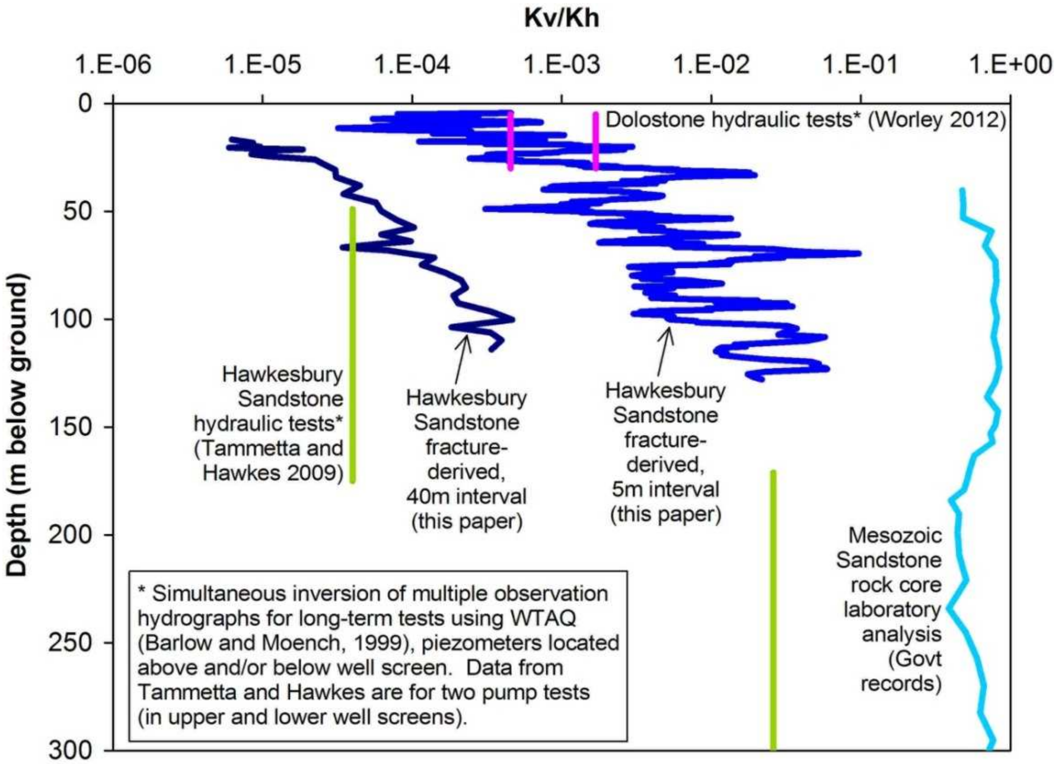
Interpreted 70°/250° strike-slip faults appear to show no vertical displacement (as inferred for one interpreted fault, based on Cross-Section A of Figure 3-3 in URS, 2012). The magnitude of the strike-slip is significantly larger than vertical slips for the 150°/330° faults. Based on seismic events shown in Figure 1, interpreted strike-slip faults may be seismically active at depth.

Figure 26: Measured hydraulic conductivities and those adopted for thrust fault planes, for a slip of 80m, using the conceptual model of Jourde et al (2002) and Flodin et al (2001).



The vertical anisotropy (Kv/Kh) of the medium also has a significant bearing on the conceptual model, since highly anisotropic media will seek out high permeability vertical flow paths in response to depressurisation from above or below. In a detailed study of hydraulic test analysis and analysis of imaged borehole defects, Tammetta (2013) presents results relating to vertical anisotropy of fractured media (Figure 27). For undisturbed media, Kv/Kh increases with depth, and decreases with increasing scale of observation. In the absence of results from vertical interference testing in the northern Bowen Basin, the anisotropy of the Hawkesbury Sandstone at a vertical observation scale of 40m is selected as a reasonable substitute. At 200m depth this distribution gives a Kv/Kh of about 0.004.

Figure 27: Vertical anisotropy of various sedimentary fractured media (after Tammetta, 2013).



9.3.1. Quantitative Conceptualisation

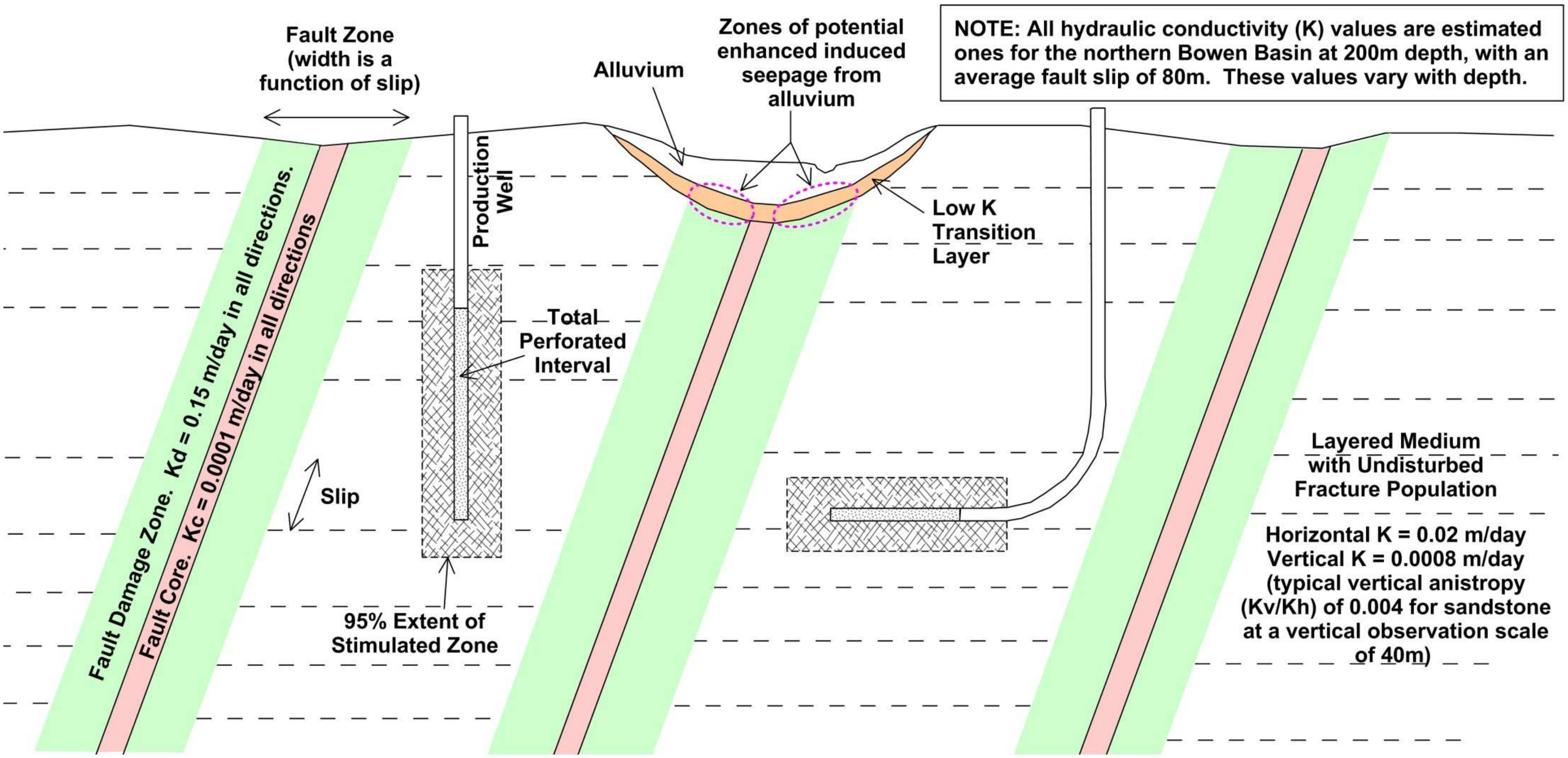
Figure 28 shows an interpreted site-specific conceptual model for fault zone K for the northern Bowen Basin, based on in-situ K measurements from the basin, and information presented in the various published conceptual models for faults at other locations around the world. The quantification of K mainly follows the conceptual model proposed by Jourde et al (2002) and Flodin et al (2001), due to the independent parameters required in their model, and the data that are available for the Bowen Basin for these parameters. The model could apply to faults that have not been subject to sealing through processes such as mineralisation occurring from hydrothermal fluid flow processes. The key elements of the conceptualisation are:

- A low K fault core, with omnidirectional K.
- A high K fault damage zone on either side of the core, with omnidirectional K. The damage zone offers no reduced permeability perpendicular to the fault plane.

Interpreted K values for the Project area as shown in Figure 28 are averages, for an average fault slip of 80m and a depth of 200m. The values vary with depth.

The conceptual model defines a series of subsurface prisms of undisturbed fractured media, bounded by planar sub-vertical faults. The sub-vertical edges of each prism are linked by the fault damage zone which forms a plane of finite thickness, parallel to the fault core, within which K is omnidirectional (that is, K has the same value in any direction within the damage zone, including perpendicular to the plane of the damage zone). The damage zone allows the usual vertical anisotropy of the prism of undisturbed fractured media to be bypassed.

Figure 28: Interpreted potential quantitative conceptual model of hydraulic characteristics of faults in the northern Bowen Basin, using the conceptual model formulation of Flodin et al. (2001) combined with averages of measured hydraulic conductivity of coal and interburden in the Bowen Basin. The conceptual model formulation is used to calculate estimates of Kc and Kd for an average fault slip of 80m and a depth of 200m.

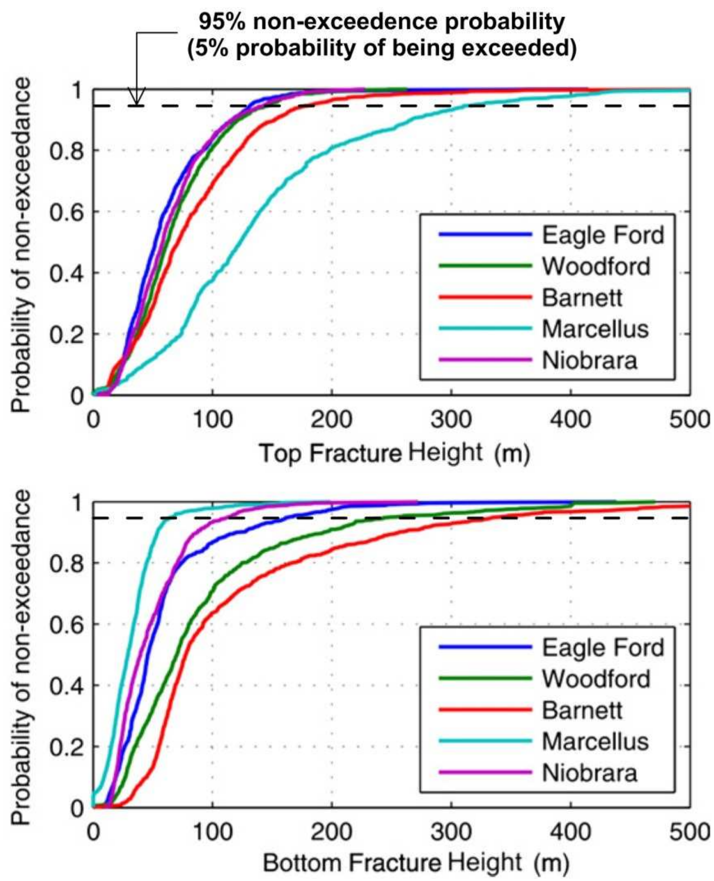


9.3.2. Extent of Fracture Stimulation Zone

The extent of deformation resulting from artificial fracture stimulation will depend on adopted injection pressures, which are themselves selected based on depth and other parameters.

Davies et al (2012) analysed a large database of seismic information related to the vertical extent of stimulated fractures. The inclination of bores from which the stimulation campaigns were carried out is not explicitly stated but is believed to be horizontal. Based on the results of Davies et al (2012), the zone which contains 95% of deformation and strata dilation from stimulation is considered a reasonable volume to use for characterisation of the change in K created by the stimulation process. Beyond 95%, the extent of deformation increases rapidly and is considered an inappropriate pessimistic case. Davies et al (2012) provide results for shales for the vertical extent of deformation, but this serves as a useful guide for Permian coal measures in the Bowen Basin, in the absence of a data base of field observations capable of being used for a probabilistic analysis (Figure 29).

Figure 29: Probabilities of exceedence of vertical stimulated deformation extent for various shales (after Davies et al, 2012).



For the lateral and vertical extents of deformation, a reasonable data base of microseismic monitoring for the Bowen Basin appears to be available. For fracture stimulation, it is considered likely that the extent of microseismic events does not indicate the extent of defect dilation. Envelopes of 95% capture of seismic events would probably need to be extended by some amount to develop a 95% probability envelope of deformation.

There are sparse data for K quantification of the stimulated zone, but results from wells CM004F and CM005FR appear to indicate little change to undisturbed K. Nelson (2003) reports the results of an experimental study on artificial stimulation of gas reservoirs in Cretaceous sandstones of the Piceance Basin of northwestern Colorado. One test indicated an increase in gas production from about 82L/s to about 107L/s following fracture stimulation. A second test indicated an increase from about 19 to about 26L/s. These results indicate a modest increase in gas flow by a factor of about 1.3. Although the increase is small in proportional terms, in absolute terms it represents significantly increased recovery of gas, hence the reason for the continued use of artificial fracture stimulation. The results are not strictly representative of the increase in saturated hydraulic conductivity of the rock medium, firstly because the fluid is gas, and secondly because gas flow is also increased by desorption from increased surface area from new fractures (an increase in fracture surface area may not be simplistically proportional to an increase in hydraulic conductivity).

9.3.3. Proposed Dataset of Faults and Lineaments for Impact Assessment

Drawing 3 shows the adopted database of known or possible discontinuities from which a selection of the structures posing the highest risk can be made. The data base comprises:

- Mapped faults from CSIRO (2008).
- Mapped faults from the Arrow Interpretation.
- 70°/250° strike-slip faults interpreted as part of the current study.

From this data base, a selection of faults based on strike length (Paul et al, 2009) is made, to create a provisional database of structures that have the potential to preferentially allow gas or water migration over a large scale. Drawing 4 shows the selected discontinuities overlaid with the major high K alluvial bodies. The selection also takes into account the potential for interconnection with alluvial bodies. The selection does not take into account the following:

- The slip of individual faults (however this is indirectly accounted for by using the strike length).
- The geological age of the faults.
- The alluvial bodies that are the most highly used for groundwater supply.

The final selection will require an assessment of all these factors.

Shorter, closely spaced discontinuities under or near significant alluvial bodies are retained due to the amplification this affords to the larger-scale K field. Where a CSIRO (2008) fault and an Arrow Interpretation (AI) fault are coincident (that is, they are duplicates), the AI fault is retained. CSIRO (2008) faults are retained wherever they appear to deviate from the corresponding AI fault, or where no AI fault is present.

All interpreted 70°/250° strike-slip faults are included, based on the likelihood of significant slip along strike having occurred to each one. Published information suggests these types of faults have higher Kc and Kd than other faults.

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11. APPENDIX A - FAULT SLIP ANALYSIS

Figure A1: Measurement Points for Fault Throw Analysis.

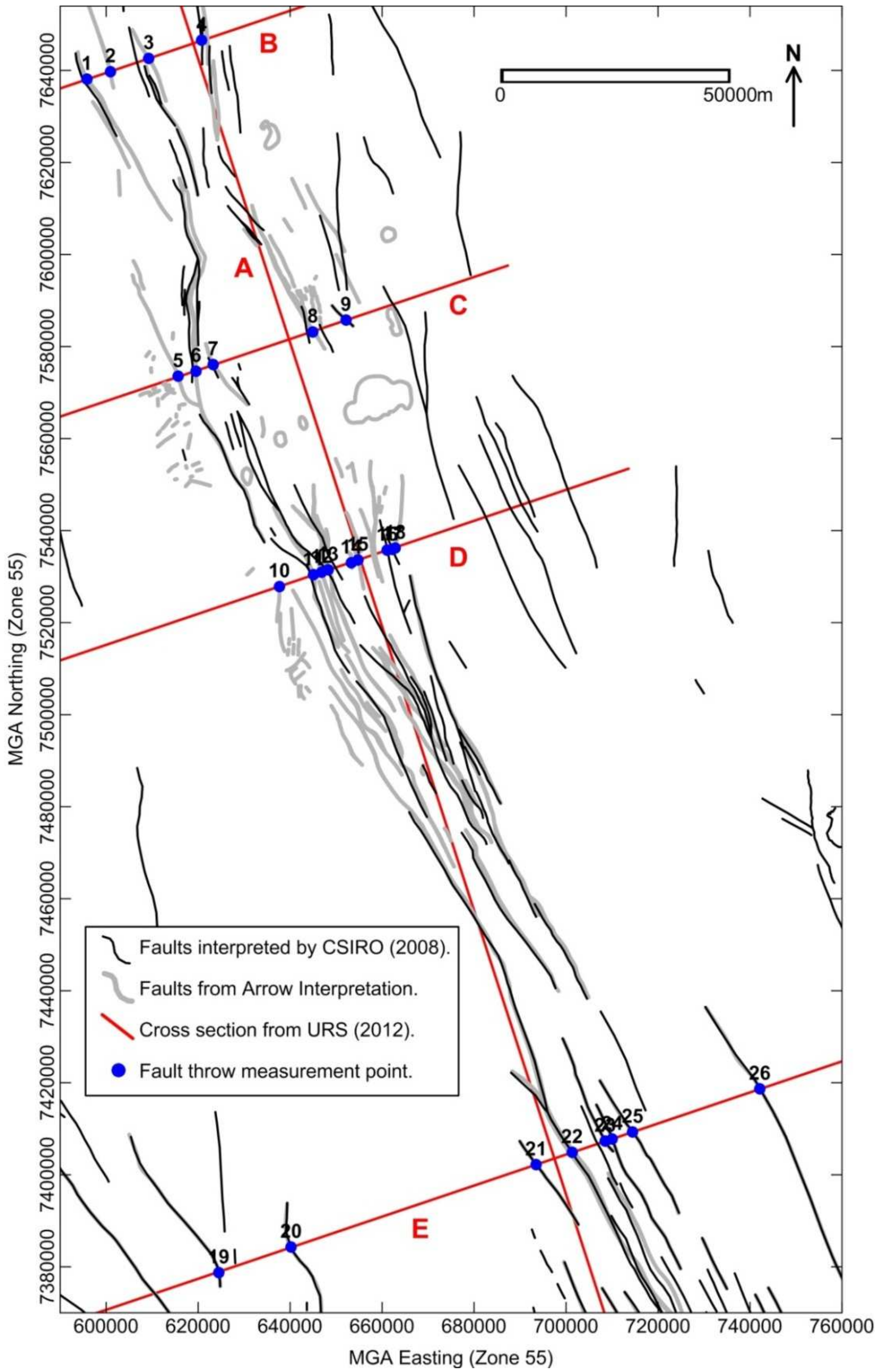
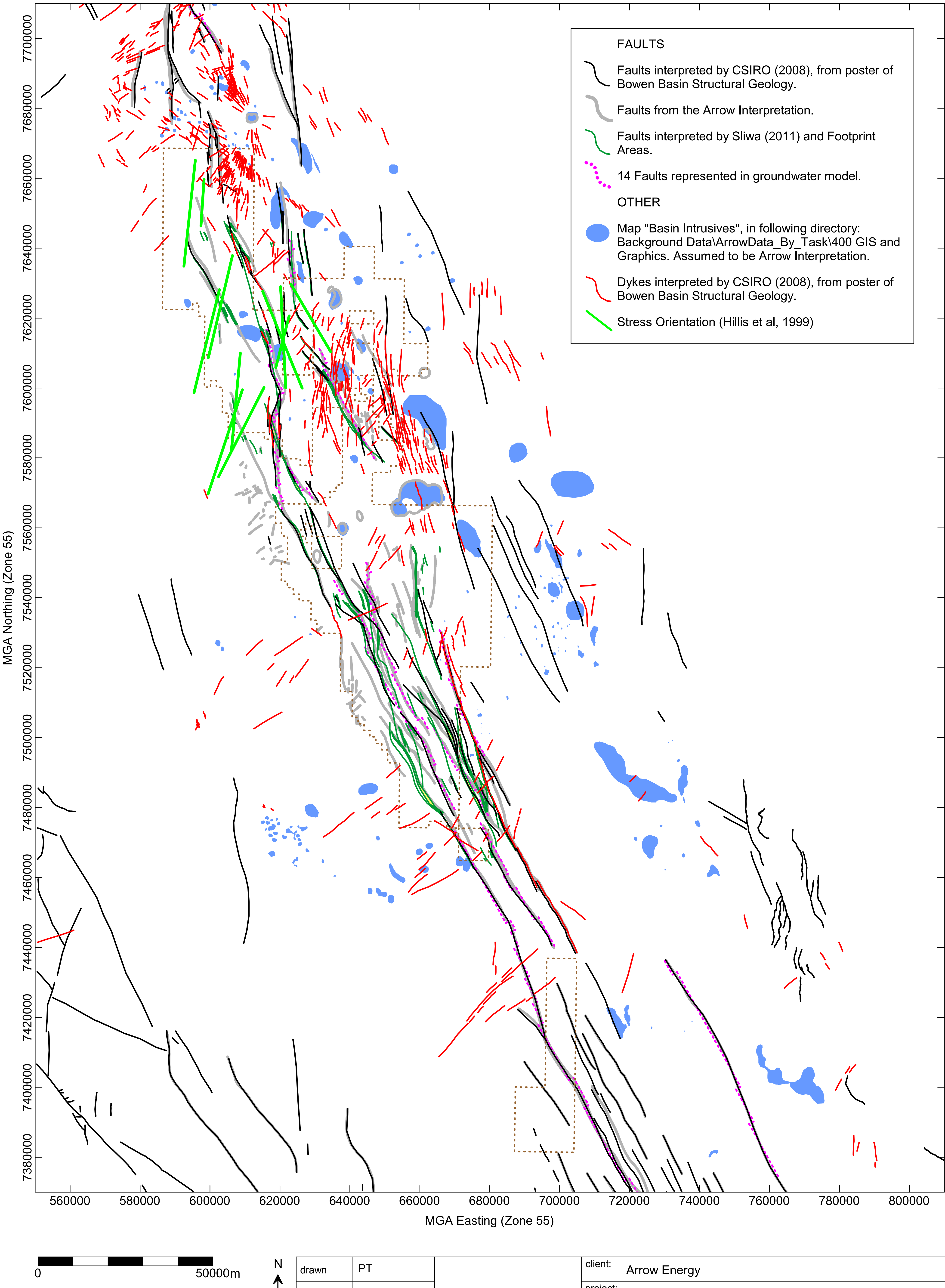


Table A1: Measured Fault Slips

URS (2012) Cross Section	Measurement Point	Easting	Northing	Maximum Slip (m)
B (Figure 3-6 in URS, 2012)	1	595805	7638105	90
	2	600947	7639751	30
	3	609277	7642631	105
	4	620795	7646539	105
C (Figure 3-7 in URS, 2012)	5	615653	7573520	0
	6	619561	7574652	72
	7	623264	7576091	24
	8	644963	7583187	408
	9	652162	7585759	36
D (Figure 3-4 in URS, 2012)	10	637662	7527858	40
	11	645066	7530429	132
	12	646815	7530943	26
	13	648254	7531458	79
	14	653294	7533000	40
	15	654734	7533617	13
	16	661110	7535777	26
	17	662241	7535880	26
	18	662858	7536188	66
E (Figure 3-5 in URS, 2012)	19	624498	7378736	97
	20	640233	7384290	12
	21	693505	7402184	73
	22	701321	7404858	>1090
	23	708520	7407326	145
	24	710063	7407738	24
	25	714485	7409280	24
	26	742150	7418639	194

DRAWINGS



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approved		project:	Bowen Gas project Groundwater Assessment
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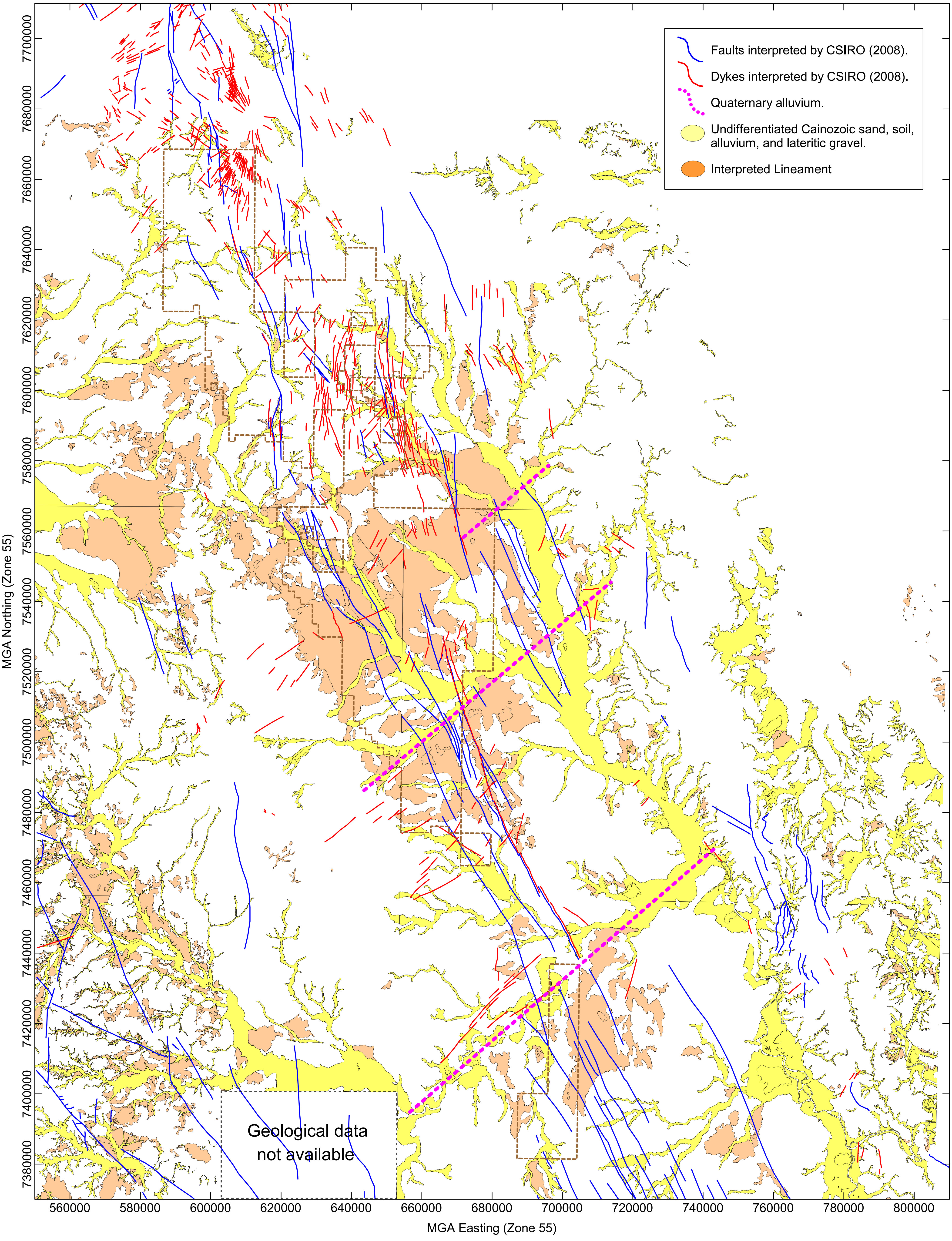
scale	1:1,000,000	project no:	ENAUBRIS107043AC
original size	A3	figure no:	**Drawing 1**

coffey



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approved			project:	Bowen Gas project Groundwater Assessment
date	8 Nov 2013		title:	**Main Alluvial Bodies of the Northern Bowen Basin**
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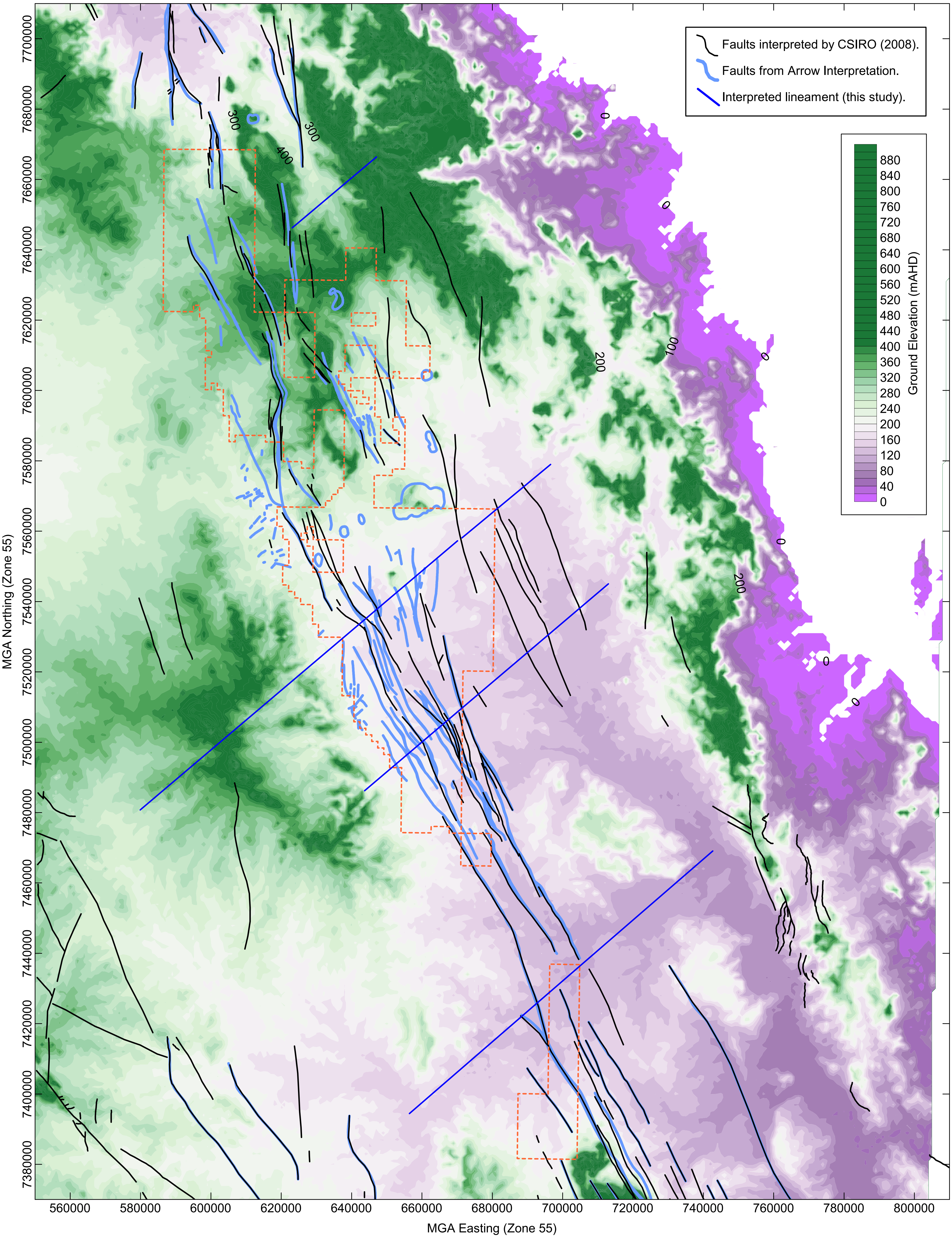

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approved	
date	8 Nov 2013
scale	1:1,000,000
original size	A3

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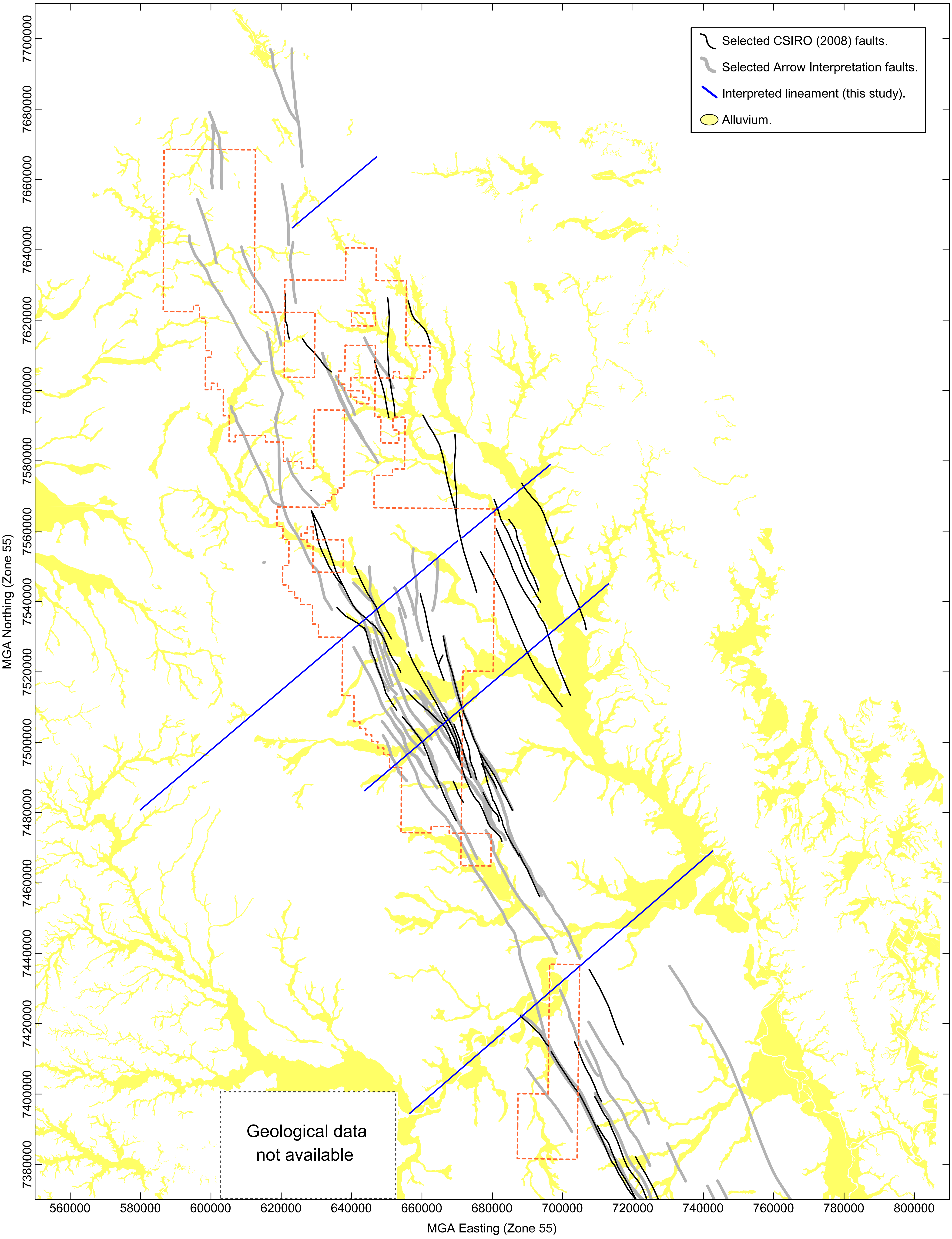
client:	Arrow Energy
project:	Bowen Gas project Groundwater Assessment
title:	**Discontinuity Database (from literature review and interpretations in the current study)**
project no:	ENAUBRIS107043AC
figure no:	**Drawing 3**



drawn	PT	client:	Arrow Energy
approved		project:	Bowen Gas project Groundwater Assessment
date	8 Nov 2013	title:	**Selected Discontinuities**
scale	1:1,000,000	project no:	ENAUBRIS107043AC
original size	A3	figure no:	**Drawing 4**

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Important information about your **Coffey** Report

As a client of Coffey you should know that site subsurface conditions cause more construction problems than any other factor. These notes have been prepared by Coffey to help you interpret and understand the limitations of your report.

Your report is based on project specific criteria

Your report has been developed on the basis of your unique project specific requirements as understood by Coffey and applies only to the site investigated. Project criteria typically include the general nature of the project; its size and configuration; the location of any structures on the site; other site improvements; the presence of underground utilities; and the additional risk imposed by scope-of-service limitations imposed by the client. Your report should not be used if there are any changes to the project without first asking Coffey to assess how factors that changed subsequent to the date of the report affect the report's recommendations. Coffey cannot accept responsibility for problems that may occur due to changed factors if they are not consulted.

Subsurface conditions can change

Subsurface conditions are created by natural processes and the activity of man. For example, water 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 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.

Interpretation of factual data

Site assessment identifies actual subsurface conditions only at those points where samples are taken and when they are taken. Data derived from literature and external data source review, sampling and subsequent laboratory testing are interpreted by geologists, engineers or scientists to provide an opinion about overall site conditions, their likely impact on the proposed development and recommended actions. Actual conditions may differ from those inferred to exist, because no professional, no matter how 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, owners should retain the services of Coffey through the development stage, to identify variances, conduct additional tests if required, and recommend solutions to 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 as the project develops. 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. Your report should not be applied to any project other than that originally specified at the time the report was issued.

Interpretation by other design professionals

Costly problems can occur when other design professionals develop their plans based on misinterpretations of a report. To help avoid misinterpretations, retain Coffey to work with other project design professionals who are affected by the report. Have Coffey explain the report implications to design professionals affected by them and then review plans and specifications produced to see how they incorporate the report findings.

Important information about your **Coffey** Report

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, 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) and laboratory evaluation of field samples. These logs etc. should not under any circumstances be redrawn for inclusion in other documents or separated from the report in any way.

Geoenvironmental concerns are not at issue

Your report is not likely to relate any findings, conclusions, or recommendations about the potential for hazardous materials existing at the site unless specifically required to do so by the client. Specialist equipment, techniques, and personnel are used to perform a geoenvironmental assessment. Contamination can create major health, safety and environmental risks. If you have no information about the potential for your site to be contaminated or create an environmental hazard, you are advised to contact Coffey for information relating to geoenvironmental issues.

Rely on 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 a project, from design to construction. It is common that not all approaches will be necessarily dealt with in your site assessment report due to concepts proposed at that time. As the project progresses through design towards construction,
speak with Coffey to develop alternative approaches to problems that may be of genuine benefit both in time and cost.

Responsibility

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* For further information on this aspect reference should be made to "Guidelines for the Provision of Geotechnical information in Construction Contracts" published by the Institution of Engineers Australia, National headquarters, Canberra, 1987.

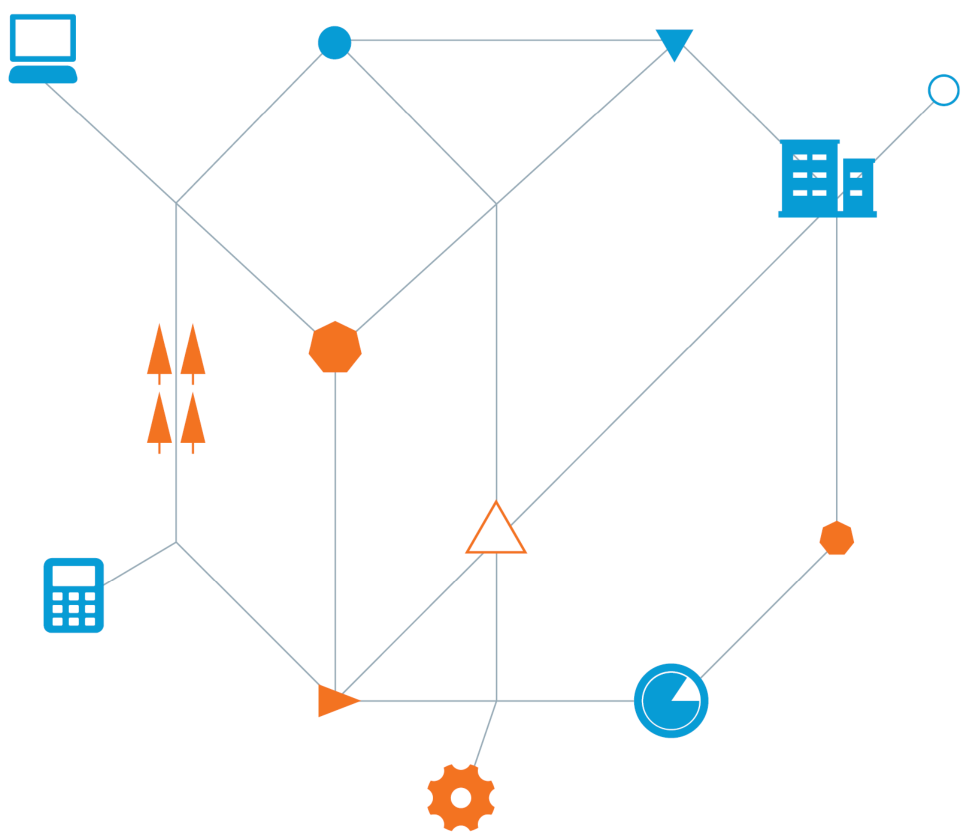
Appendix B
Arrow Energy Bowen Gas Project Baseline Subsidence Monitoring

Supplementary Groundwater Assessment
Arrow Energy Bowen Gas Project
Supplementary Report to the EIS

Baseline Subsidence Monitoring

Arrow Energy
Bowen Gas Project

Report Date: 3 April 2014
Reference: ENAUBRIS10704AA-SA



Simplicity
is complexity's
only adversary

CONTENTS

1 INTRODUCTION

This memo presents a review of the baseline assessment of subsidence carried out at the Moranbah Gas Project site. A baseline subsidence assessment was carried out by Altamira using monitoring compiled from the synthetic aperture radar (InSAR) satellite records over the period December 2006 to January 2011 (Altamira, 2013). The subsidence results have been compared with the results of an Underground Water Impact Report for Petroleum Leases 191, 196, 223 and 224 located to the east of Moranbah.

2 COAL SEAM GAS EXTRACTION (PETROLEUM LEASES 191, 196, 223, 224)

The impacts on groundwater of coal seam gas extraction from Arrow Energy Petroleum Leases 191, 196, 223 and 224 are the subject of an Arrow Energy report (Arrow, 2012).

Petroleum Leases 191, 196, 223 and 224 are located to the east of Moranbah in an area traversed by the Isaac River see Figure 1.

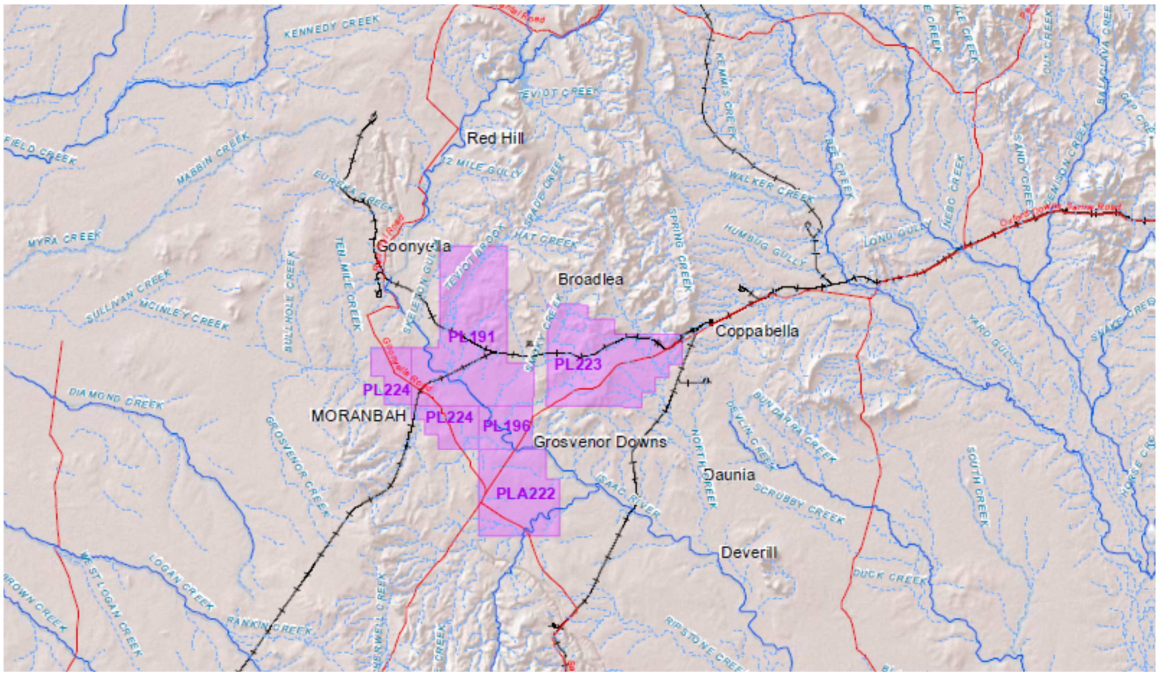


Figure 1: Location of Petroleum Leases 191, 196, 223 and 224

Coal seam gas has been extracted from a network of production wells and a collection system within these petroleum leases. Gas was extracted from the Fort Cooper and Moranbah Coal Measures over the time period of the Altamira baseline subsidence assessment (from 2006 to 2011).

Further coal seam gas extraction is planned to occur to 2040. Groundwater (co-produced water) is extracted as part of the process of coal seam gas extraction and Table 1 summarises the volumes of groundwater extracted from commencement in 2003 to August 2011.

Table 1: Co-Produced Water Associated with Coal Seam Gas Production (2003 to 2011)

Lease	Formation	Groundwater Volume Extracted (ML)
PL191	Fort Cooper Coal Measures and Moranbah Coal Measures (Q Seam)	29
	Moranbah Coal Measures (P, Q and GM Seams)	2,858
PL196	Moranbah Coal Measures (P and GM Seams)	323
	Moranbah Coal Measures (GML Seam)	15
PL223	FG1 Seam	3
PL224	Moranbah Coal Measures (P and GM Seams)	125
Cumulative Total		3,353

Figure 2 illustrates the timing of this groundwater extraction from Petroleum Leases 191, 196 and 224.

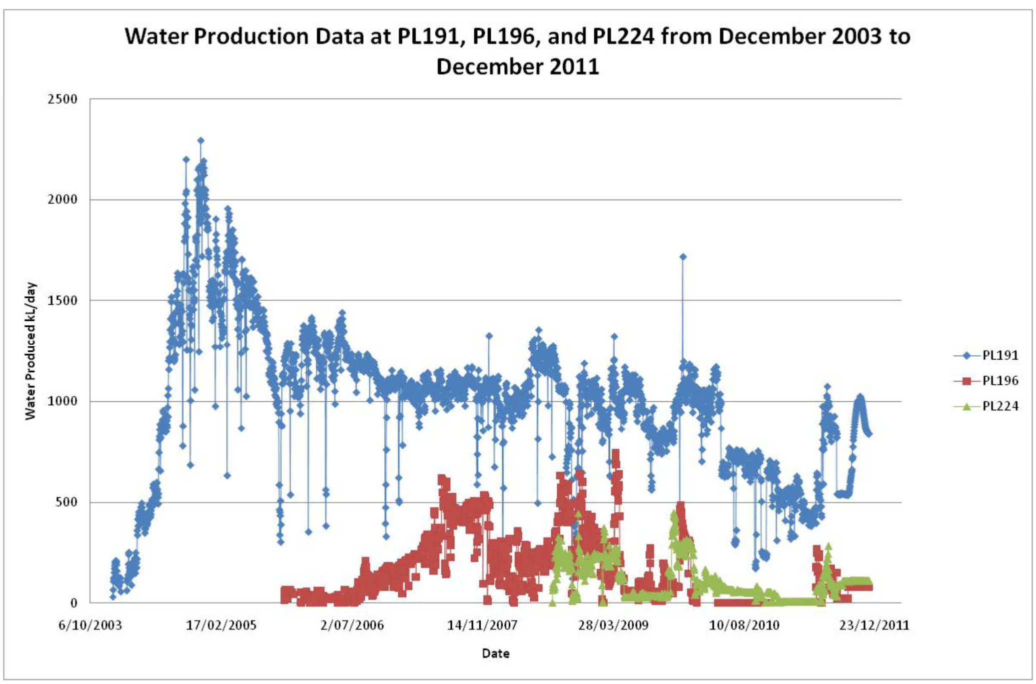


Figure 2: Water Production - Petroleum Leases 191, 196 and 224

Further coal seam gas production to 2040 will result in continuing water production from within the leases. Forecasts for future water production prepared by Arrow are summarised below (Arrow, 2012).

Table 2: Forecast Groundwater Extraction after 2011 from Petroleum Leases 191, 196 and 224

Period	Forecast Groundwater Extraction (ML)
2011 to 2020	9,840
2021 to 2030	5,856
2031 to 2040	2,288

The forecast indicates a gradual reduction in the rate of groundwater production over time.

2.1 Geology

The geological setting is illustrated in Figure 3 (taken from Arrow, 2012).

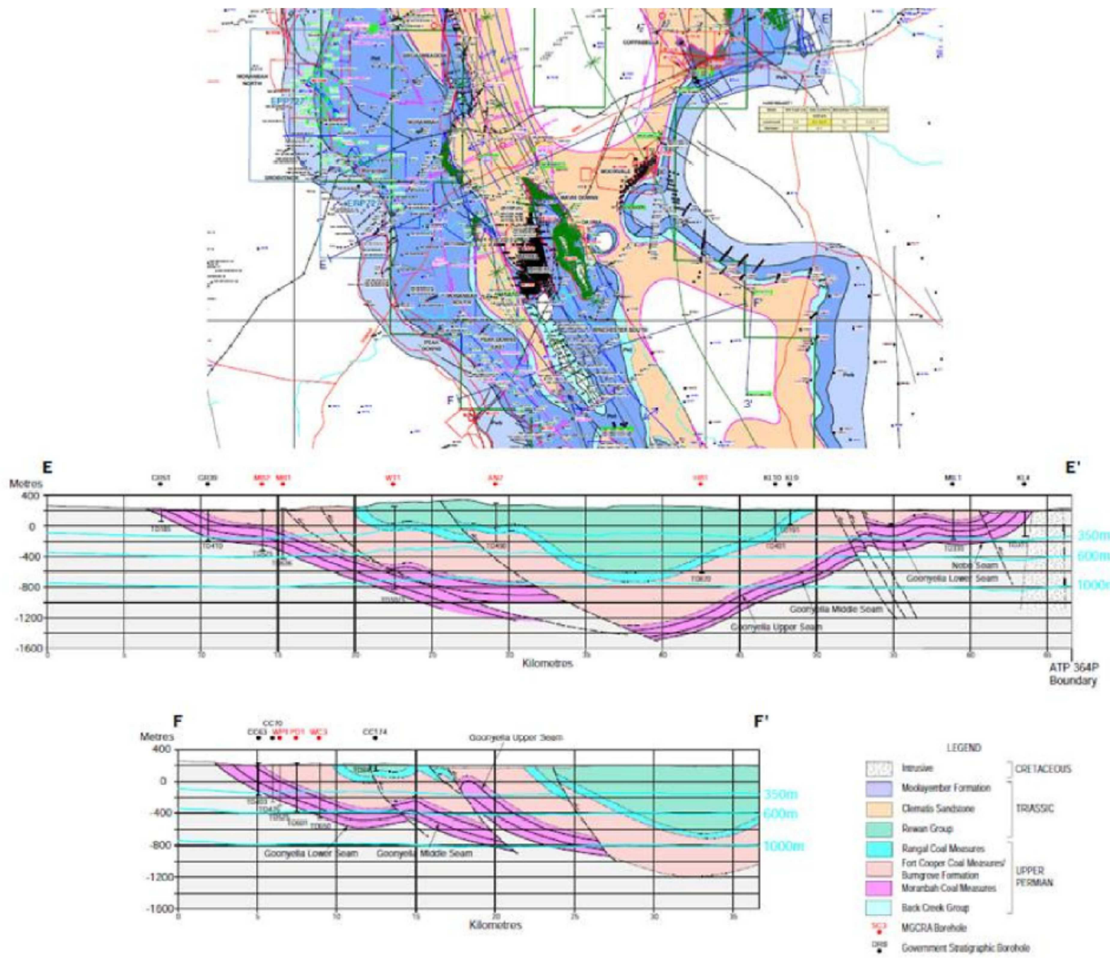


Figure 3: Geological Setting

The interpretation indicates the Moranbah Coal Measures are overlain by the Fort Cooper Coal Measures. Coal seam gas extraction has occurred predominantly from the Moranbah Coal Measures which range in depth up to 1700 m below ground surface. A number of faults are present, typically striking northwest.

2.2 Other Extraction Activities

The Isaac Plains mine commenced operation in the southeast corner of Petroleum Lease 191 and first produced coal in 2007. This mine is an open cut operation. The Goonyella North mine operates to the north of Petroleum Lease 191. It commenced longwall mining operations in 1998. The Grosvenor mine is planned to be an underground coal mine located within Petroleum Lease 191, with first development of coal expected in 2013, and commissioning of the longwall in 2016 (Anglo American 2011).

These coal mining activities will also affect groundwater levels in the area of the coal seam gas operation and will, as a result, contribute to any groundwater related subsidence that could occur. Coal seams mined will be dewatered as a result of the mining process and this will lead to changes in groundwater level in the surrounding area which develop over time. These groundwater level changes result in settlement of the ground surface. Longwall mining operations involve extraction of coal over wide panels (typically some 200 m wide and in excess of 1 km long). This results in collapse of the ground over mined longwall panels. This causes significant surface subsidence directly above and immediately adjacent to the mined area. The vertical subsidence predicted for the Grosvenor mine is anticipated to be 2.7 m.

3 SATELLITE IMAGING METHOD

The subsidence baseline assessment carried out by Altamira (Altamira, 2013) employed data obtained from the advanced land observation satellite (ALOS) satellite launched by the Japanese Aerospace Exploration Agency on January 2006. The satellite contained a phased array type L-band synthetic aperture radar (PALSAR) which allows development of images with resolution of approximately 4.5 m by 5 m. This lateral resolution varies slightly across the area monitored as a result of the changing distance from the satellite path. The vertical resolution of movement is related to the wavelength of the radar signal and it is influenced by a range of factors including the offset of the point of interest from the satellite path, atmospheric conditions and the nature of the ground surface. Settlement results are calculated to the millimetre but the accuracy depends upon the prevailing conditions.

The L-band synthetic radar employed had a wavelength of 236 mm. The wavelength is important as it influences the radar signal capacity to penetrate vegetation. The L-band radar provides a degree of penetration through vegetation so that the results are not adversely affected by growth of grasses and sparse tree cover. The InSAR process involves comparison of the phase difference between pairs of points. Changes in this phase difference from one time to another are interpreted as relative movement between pairs of points. As the process involves comparison of the phase of the returned radar signal movement more than half the wavelength from one satellite pass to the next becomes ambiguous. This factor does not affect the interpretation of the surface movement for the Moranbah study as the movements interpreted between successive satellite passes are much smaller than half the wavelength of the L-band radar used.

Data was obtained by Altamira for two satellite tracks covering Petroleum Leases 191, 196, 223 and 224. Data sets were available for 22 traverses for one of the satellite tracks and 18 traverses for the other track. These data sets provided a reasonably even surface coverage over the period of interpretation.

Altamira processed the satellite data using the same method applied to baseline subsidence monitoring for the Surat and Bowen Basins further to the south. The processing involved identification of phase difference between points within the areas scanned for each data set and applying various corrections to account for the elevation of the points, the velocity of the satellite and atmospheric effects.

Points on the ground suitable for measurement were identified based on amplitude stability of the detected radar response and coherence of the interferograms. Medium resolution interferograms were generated by combining the results of blocks of high resolution points to generate a processing resolution of 35 m by 35 m. Altamira advises that this process reduces noise in the interpreted results but reduces the spatial resolution.

Some areas are unsuited to the use of this method of movement interpretation. For example ploughed fields produce variable response and generally produce a low density of reliable interpretations. Altamira assessed the quality of each interpreted point and did not report those points of low reliability. After processing, Altamira produced a grid of points at approximately 35 m spacing with vertical movement occurring after January 2007, interpreted at a series of times up to January 2011. An average density of 901 points/km^2 was reported for the target area indicating nearly full coverage over the study area.

The results are presented by Altamira in the following way:

- Stability is defined as having vertical movement rates of less than 8 mm/year.
- Areas of uplift are divided into uplift rates of 8 mm/year to 16 mm/year and rates of more than 16 mm/year.
- Areas of subsidence are divided into subsidence rates of 8 mm/year to 16 mm/year and rates of more than 16 mm/year.

These thresholds provide a useful separation of areas where ground movement is small and highlight areas where significant movement is occurring.

4 RESULTS OF BASELINE ASSESSMENT

The results showed the vast bulk of the area monitored was subject to movement of less than 8 mm/year over the monitoring period. Isolated locations with greater rates of movement were identified. Figure 4 (taken from Altamira, 2013) shows the interpreted settlement distribution together with the network of coal seam gas and water gathering network. The gathering network provides a good indication of the areas where coal seam gas is currently produced.

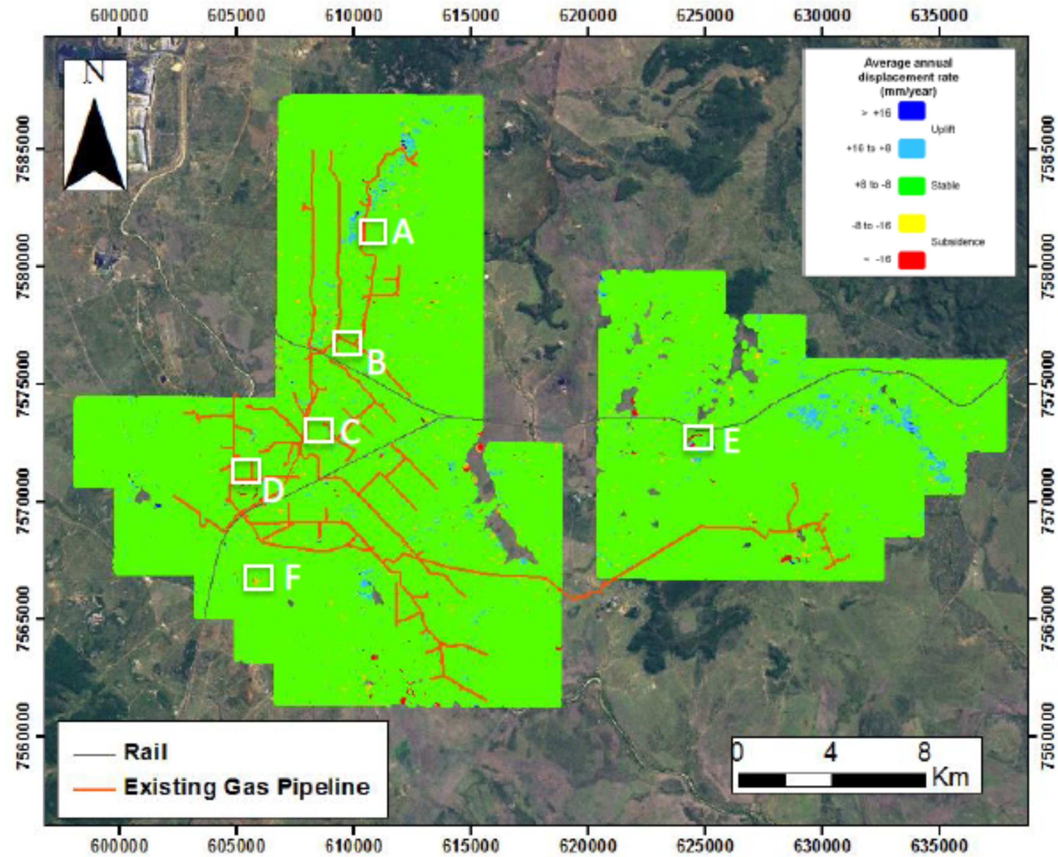


Figure 4: Interpreted Subsidence and Coal Seam Gas and Water Gathering Network

No patterns of movement over the areas subject to gas extraction were apparent in the reported results. Details of selected individual movement locations showing much greater than average movement were presented in the Altamira report (nominated as Areas A to F in Figure 4). These are discussed briefly below:

1) Area A - Upward movements at rates between 8 and 16 mm/yr along Tevoit Brook were interpreted along the alignment of the brook. This is an ephemeral stream. An upward movement of some 60 mm was interpreted from January 2007 to December 2010. Review of rainfall records for Bureau of Meteorology stations near Moranbah reveals that rainfall over the period 2007 to 2010 was significantly greater than for the previous two years. Periods of interpreted upward movement could reasonably be attributed to changes in soil moisture associated with swelling of clay soils.

2) Area B - localised settlement areas near Tevoit Brook associated with areas of bare earth. The reason for the settlement is not clear. It seems to be associated with areas of bare ground in the Google Earth aerial imagery for July 2011 and could possibly be associated with erosion.

3) Area C - Settlement of 60 mm at an isolated location at a production well site over the period January 2007 to December 2010. Adjacent locations showed of 40 mm over the same period. The cause of the settlement is not clear.

4) Area D - Localised upward movement of 50 mm is interpreted at a site which appears to be a gas processing site over the period January 2007 to December 2010. The reason for the upward movement is not clear. The area involved is approximately one hectare and contains what appears (in aerial imagery) to be gas handling facilities. It follows a similar pattern to that interpreted as discussed in Point 1) above and may be related to swelling of clay soil in an area which has been cleared of vegetation.

5) Area E - Settlement of 130 mm is interpreted on a circular embankment apparently constructed for a rail loop. The design details and time of construction of the embankment are not available. A settlement of 130 mm over a four year period following construction of a fill embankment is not unexpected. The timing and magnitude of settlement of such facilities depends on the height and construction process and the geotechnical properties of the foundation soils.

6) Area F – Settlement of up to 70 mm is interpreted at the embankment for a water storage pond near the racecourse. The interpreted movement is greatest at the eastern corner of the water storage. Review of the Google Earth aerial imagery reveals that the surrounding ground falls to the east so that the largest interpreted settlement is associated with greatest embankment height.

Review of the above details shows that the subsidence assessment by Altamira is reasonable and is consistent with site surface features.

4.1 Further Interpretation of Subsidence Baseline Results

The interpretation by Altamira indicates that subsidence associated with coal seam gas extraction over the period 2007 to 2011 had not produced impacts greater than 8 mm/year. Further analysis of data provided by Altamira was carried out by Coffey to assess whether any widely distributed low magnitude subsidence effects were present.

The database of results provided by Altamira was processed to provide average ground movement over 500 m by 500 m blocks over the period 2007 to 2011. The purpose of this averaging process is to highlight small ground movement occurring over wide areas. This was carried out to seek possible changes associated with widespread changes in groundwater level which are anticipated to have occurred at depth as a result of coal seam gas extraction.

The results of this processing are presented in Figure 5 showing where interpreted ground movement averaged in this way exceeded 10 mm over the four year period (an average rate of 2.5 mm/yr). It is apparent that over the bulk of the area interpreted ground movement over the four year period is less than 10 mm (subsidence or uplift).

A diagonal zone of upward movement is interpreted over the four year monitoring period in the north of Petroleum Lease 191, along the alignment of Teviot Brook (note: refer to Figure 1 for Petroleum Lease locations). This is considered likely to be associated with swelling of soil associated with above average rainfall over the period as discussed in Section 4 above.

Minor subsidence (between 10 mm and 20 mm) is interpreted to have occurred at approximately 5% of locations within the area studied. Comparison with the gas pipeline network shown in Figure 4 reveals a higher frequency of areas with subsidence interpreted to be in the range 10 to 20 mm over the baseline period in Petroleum Lease 223. Given that only 3 ML of groundwater was produced associated with coal seam gas extraction over the period it is considered unlikely that this movement is related to coal seam gas production. It is possible that the interpreted minor subsidence could be related to minor works such as desiccation of cleared areas. Review of imagery from Google Earth

(September 2007) reveals the commencement of open cut mining operations in this area which is considered a more likely cause of the minor subsidence interpreted.

There is a higher frequency of areas with average downward vertical movement in the range 10 mm to 20 mm along the western margin of Petroleum Lease 191. This is approximately correlated with the gas pipeline network and coal seam gas extraction in this area with a comparatively high concentration of areas of 10 mm or more of subsidence in the area of greatest concentration of gas collection pipes in the southern part of Petroleum Lease 191.

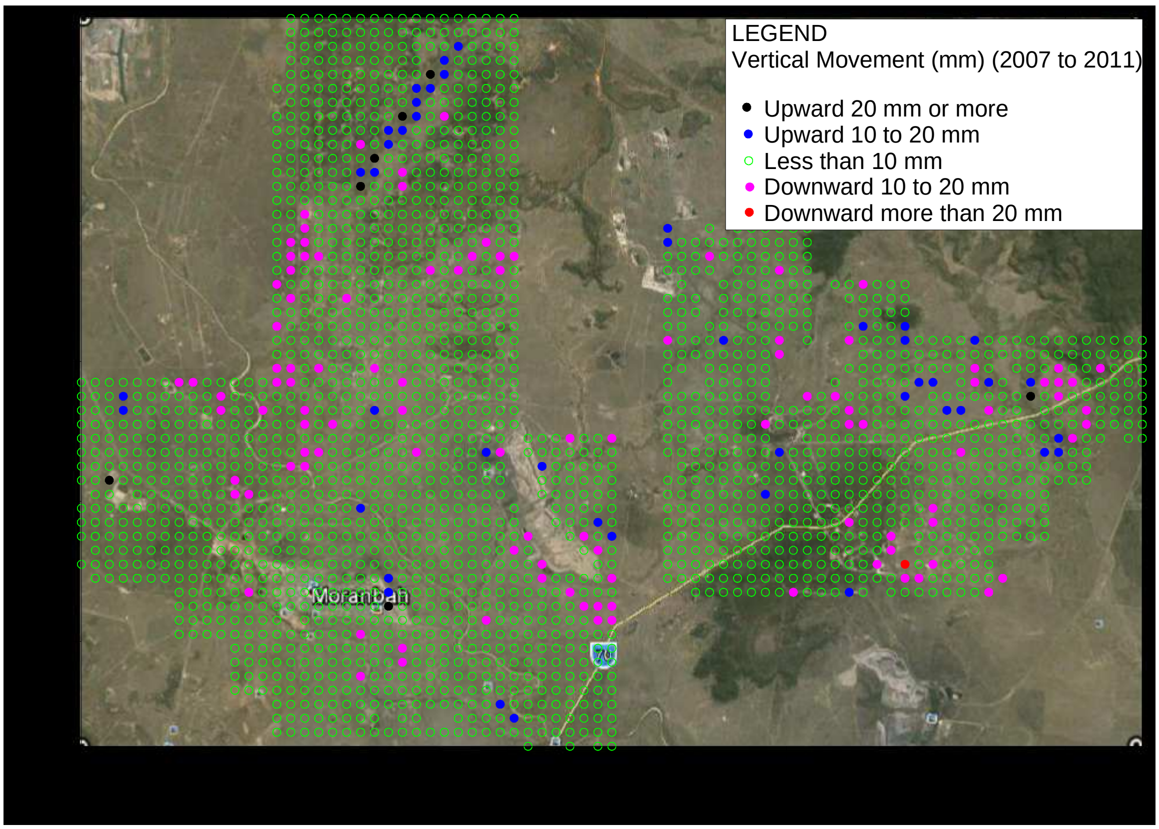


Figure 5: Interpreted Subsidence – Moranbah Gas Project area

5 PREDICTION OF SUBSIDENCE DUE TO CSG EXTRACTION

Subsidence associated with coal seam gas extraction can occur from two processes:

- Shrinkage of the coal seam due to removal of gas; and
- Compression of the target coal seam and overlying/underlying formations due to reduced groundwater pressure.

The second of the above processes occurs as a result of lowering of the groundwater pressure within coal and overlying/underlying formations due to coal seam gas extraction. This change in groundwater pressure causes increase vertical stress on the fabric of the coal and rock leading to compression. The accumulation of compression over the entire ground profile is seen as settlement at the ground surface.

An assessment of measured groundwater levels across Petroleum Leases 191, 196, 223 and 224 is reported by Arrow (2012). It shows groundwater level in the alluvial aquifer in the range 190 mAHD to 230 mAHD (falling to the southeast across the site consistent with the topography). Groundwater levels measured in the tertiary basalt and sand aquifer within these petroleum leases range from 220 mAHD to 290 mAHD. Groundwater levels within the Permian coal measure rock across the same area ranged from 70 mAHD to 250 mAHD. This suggests a reduction of up to 150 m in the Permian coal measures. For the purposes of assessment, a reduction of 100 m was adopted as this is more consistent with the apparent average head reduction within Petroleum Lease 191 in the areas where the water collection network was most dense.

Monitoring results obtained from Department Natural Resources and Mines in the surrounding area showed alluvial groundwater levels remaining within a narrow band apparently influenced by seasonal factors. Analysis presented by Arrow (2012) indicates that groundwater level within the alluvial system in the petroleum leases will not change significantly in response to coal seam gas extraction.

5.1 Coal Shrinkage

The properties governing the contraction of coal due to gas removal from seams in the Moranbah Coal Measures are not available. Robertson (2005) reported a strain of 0.001 for a gas pressure change of 500 kPa (equivalent to pressure under 50 m of water) in a bituminous coal seam. It would be preferable to use data obtained from testing of the coal seams affected but in the absence of such test results the literature value nominated was employed. While it is unclear if this value would relate the coal in the target seams at Moranbah it does give an indication of potential shrinkage due to reduction in gas content. Arrow (2012) indicates that the target seams in the Petroleum Leases 191, 196 and 224 have the following approximate thicknesses:

P Seam – combined thickness of three main plies: 5 m

GM Seam : 5 m

GML Seam : 6.5 m.

In Petroleum Lease 191 gas is predominantly extracted from the P and GM Seams which have an approximate combined thickness of 10m. Assuming partial pressure in methane reduces by half the groundwater pressure in the areas of Petroleum Lease 191 (i.e. a gas pressure reduction of 500 kPa) giving a shrinkage strain of 0.001, this would result in a contribution of 10 mm to surface subsidence (0.001 x 10 m = 10 mm). It must be recognised that this assessment is uncertain due to uncertainties in the properties of the coal and in the assessment of gas pressure reduction. Recognising this uncertainty a range of 5 mm to 15 mm may be possible.

5.2 Compression of the ground profile due to groundwater level changes

Assuming that the piezometric level in the Permian coal measures was comparable to the levels interpreted in the tertiary horizon, the results suggest a drawdown of 100 m over a significant area in Petroleum Lease 191. The compression modulus (a measure of the compressive stiffness of the rock) of the Permian coal measure rocks is not available. The sandstone interburden is expected to be significantly stiffer than the coal seams. For the purposes of assessment the following values were adopted:

Modulus of sandstone 10 GPa

Modulus of coal seams 3 GPa

Assuming an average drawdown of 100 m (corresponding to a 1000 kPa pressure reduction) in the Moranbah Coal Measures (which Arrow, 2012 indicate as ranging in thickness from 250 m to 300 m) a settlement of 30 mm is assessed associated with compression due to reduction in groundwater level allowing 15 m aggregate thickness of coal seam and 250 m thickness of sandstone (250m x 1000 kPa / 10 GPa + 15 m x 1000kPa / 3 GPa = 30 mm). This assessment contains uncertainties in relation to the vertical extent of groundwater level changes and in the mechanical properties of the coal and the affected sandstone units. Consequently the assessment should not be considered an absolute value but an indication of the amount of subsidence. A realistic range might be 10 mm to 60 mm recognising these uncertainties.

5.3 Aggregate Subsidence Assessment

Combining the two components of subsidence associated with coal seam gas extraction assessed above yields a subsidence assessment of 40 mm, approximately 30 mm due to coal shrinkage and 10 mm due to compression of the ground profile. Aggregate settlement in the range 15 mm to 75 mm is considered reasonable taking account of uncertainties in the extent of groundwater level changes and in the properties of the accompanying sandstone)

The above settlement assessments are uncertain due to the lack of data available in relation to the detailed groundwater pressure changes, the compressive modulus of the coal and the Permian coal measure rocks and the strain response of the coal following extraction of methane. Comparison with the results of interpretation of the Altamira work (which indicates subsidence of less than 20 mm in the area of greatest coal seam gas extraction) indicates that the above assessment of subsidence based on groundwater response is above the subsidence which has occurred. This is likely a result of the conservative choices in the coal and rock stiffness properties for the subsidence assessment.

Continuing coal seam gas extraction in the area will result in greater and more widespread reduction in groundwater level within the target coal seams and the geological profile above and below the seams. This will result in further settlement over time perhaps doubling in magnitude to range from 20 mm to 40 mm if the average groundwater drawdown in the Moranbah Coal Measure rocks were to increase to 200 m.

6 IMPACTS OF COAL SEAM GAS RELATED SUBSIDENCE

The subsidence interpreted from satellite monitoring indicates minor ground movements comparable in scale to those occurring from natural processes.

The magnitude of settlement associated with coal seam gas extraction is substantially less than that arising for longwall coal mining which results in subsidence of a significant proportion of the extracted coal thickness. Subsidence from this mechanism is typically well in excess of 1 m. Longwall coal mining also results in lowering of groundwater levels in the area surrounding the longwall mine and this would lead to settlement similar to that discussed as applying to during coal seam gas extraction. The surface settlement associated with this groundwater lowering is at least an order of magnitude less than that associated with ground collapse over longwall workings.

The magnitude of surface settlement associated with coal seam gas extraction at the petroleum leases is small and comparable with that occurring from natural and common construction processes. For example, rise in ground level of some 60mm was interpreted to have occurred near Tevoit Brook considered likely to be a result of swelling of soil during a period of higher than average rainfall. This would be expected to be reversed during extended periods of low rainfall.

7 REFERENCES

Arrow Energy (2012) Underground Water Impact Report – For Petroleum Leases 191, 196, 223, 224.

Anglo American (2011) Grosvenor Fact Sheet – December 2011.

Robertson, E.P. (2005) Measurement and modelling of sorption-induced strain data. PhD Dissertation, Colorado School of Mines.

Altamira Information (2013) InSAR historical study of the Moranbah Gas Project – October 2013.

Important information about your **Coffey** Report

As a client of Coffey you should know that site subsurface conditions cause more construction problems than any other factor. These notes have been prepared by Coffey to help you interpret and understand the limitations of your report.

Your report is based on project specific criteria

Your report has been developed on the basis of your unique project specific requirements as understood by Coffey and applies only to the site investigated. Project criteria typically include the general nature of the project; its size and configuration; the location of any structures on the site; other site improvements; the presence of underground utilities; and the additional risk imposed by scope-of-service limitations imposed by the client. Your report should not be used if there are any changes to the project without first asking Coffey to assess how factors that changed subsequent to the date of the report affect the report's recommendations. Coffey cannot accept responsibility for problems that may occur due to changed factors if they are not consulted.

Subsurface conditions can change

Subsurface conditions are created by natural processes and the activity of man. For example, water 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 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.

Interpretation of factual data

Site assessment identifies actual subsurface conditions only at those points where samples are taken and when they are taken. Data derived from literature and external data source review, sampling and subsequent laboratory testing are interpreted by geologists, engineers or scientists to provide an opinion about overall site conditions, their likely impact on the proposed development and recommended actions. Actual conditions may differ from those inferred to exist, because no professional, no matter how 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, owners should retain the services of Coffey through the development stage, to identify variances, conduct additional tests if required, and recommend solutions to 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 as the project develops. 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. Your report should not be applied to any project other than that originally specified at the time the report was issued.

Interpretation by other design professionals

Costly problems can occur when other design professionals develop their plans based on misinterpretations of a report. To help avoid misinterpretations, retain Coffey to work with other project design professionals who are affected by the report. Have Coffey explain the report implications to design professionals affected by them and then review plans and specifications produced to see how they incorporate the report findings.

coffey

Important information about your **Coffey** Report

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, 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) and laboratory evaluation of field samples. These logs etc. should not under any circumstances be redrawn for inclusion in other documents or separated from the report in any way.

Geoenvironmental concerns are not at issue

Your report is not likely to relate any findings, conclusions, or recommendations about the potential for hazardous materials existing at the site unless specifically required to do so by the client. Specialist equipment, techniques, and personnel are used to perform a geoenvironmental assessment. Contamination can create major health, safety and environmental risks. If you have no information about the potential for your site to be contaminated or create an environmental hazard, you are advised to contact Coffey for information relating to geoenvironmental issues.

Rely on 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 a project, from design to construction. It is common that not all approaches will be necessarily dealt with in your site assessment report due to concepts proposed at that time. As the project progresses through design towards construction,
speak with Coffey to develop alternative approaches to problems that may be of genuine benefit both in time and cost.

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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 the 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.

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Appendix C
Arrow Energy Bowen Gas Project
A Study of the Simulation of Faults as Preferential Pathways for Groundwater Flow in the Bowen Basin

Supplementary Groundwater Assessment
Arrow Energy Bowen Gas Project
Supplementary Report to the EIS

Document Number: 004-000-AA-7180-00032

Environment

Modelling Study

A study of the Simulation of faults as preferential pathways for groundwater flow in the Bowen Basin

Revision: 03

Date: 12/03/2014

Document Status: Final

Security Classification: Public

Document Administration

Document Information

Title	A study of the Simulation of faults as preferential pathways for groundwater flow in the Bowen Basin
Summary	This document describes a study undertaken to simulate the potential for faulting within the Bowen Basin to act as conduits or barriers to groundwater flow
Document Number	004-000-AA-7180-00032
Revision	02
Revision Date	12/03/2014
Discipline	Environment (V)
Document Type	Modelling Study
Document Status	Final
Security Classification	Public

Revision History

Revision	Revision Date	Document Status	Reviewer	Author
03	12/03/2014	Final	Simon Gossmann	Kavita Prasad
02	13/12/2013	Draft	Simon Gossmann	Kavita Prasad
01	29/11/2013	Draft	St.John Herbert	Kavita Prasad

Acceptance and release

Prepared by:

Kavita Prasad

Checked by:

St.John Herbert

Approved by:

Simon Gossmann

Contents

List of Tables and Figures

1 Introduction

The simulation of groundwater flow in structurally complex geological settings may need to account for fault characteristics. Depending on the geological setting and their hydraulic properties, faults may serve as pathways or barriers to groundwater flow. This technical note presents a synthetic study investigating two questions relevant to Arrow's proposed Coal Seam Gas (CSG) project in the Bowen Basin:

1. The behaviour of groundwater in response to CSG production near "closed" faults (barrier to groundwater flow)
2. The potential for CSG production to influence the amount of groundwater flow along "open" faults (pathway to flow)

This study provides an assessment of these two scenarios based on a numerical groundwater modelling exercise.

1.1 Background

A regional groundwater model was developed by Ausenco Norwest as part of the Bowen Gas Project (BGP) Environmental Impact Statement (EIS) (URS, 2012). The model objective was to predict and delineate areas within aquifers affected by Arrow's CSG operations. At that time in the model domain, the nature of the faults and their impact on the hydrogeologic flow system were not known or supported by the available data set and were not included in the initial model base case simulation except as discontinuities of units. However, additional simulations were run to assess model sensitivity to the faults, given a set of defining parameters for the major faults as either pathways or barriers to flow. This was undertaken using the wall or horizontal flow boundary (HFB) package. The HFBs were assigned to the layers representing consolidated geology, layers 3 to 18. A review of results at the end of production and 50 years after show little difference in drawdown between the base case scenario with HFBs and without HFBs.

Since the completion of the EIS, a regional study has been undertaken for the Supplementary Report to the Environmental Impact Statement (SREIS), investigating major fault structures within the Basin. Reference should be made to the groundwater technical report presented in the SREIS for a detailed assessment on the hydraulic behaviour of faults. A review of all available data indicates that faults in the Bowen Basin are generally of low permeability both parallel to and normal to the fault planes. In support of this, work undertaken by Hillis and Reynolds (2002) suggest a regional NE-SW trend for maximum horizontal stress, which is perpendicular or close to perpendicular for all major faults that cross cut formations within the Basin. Based on the above study, the current compressive stress regime would suggest that major faults in the basin are sealed and will not be a preferential pathway for either gas or water migration, which is consistent with field evidence. In reality, it is expected that the majority of faults in the Bowen Basin behave as barriers to groundwater flow. The base case presented in the EIS is consistent with this principle.

Nonetheless, for completeness an assessment of the opposite scenario where faults (or other conduits such as weathered igneous dykes) behave as pathways to groundwater flow form the basis for this study. If the hydraulic properties of structural and igneous features in the Basin are higher than the surrounding formations, then it can be hypothesised that these zones represent preferential pathways for flow, and may play a role in aquifer recharge and discharge. It can be assumed that such features would influence the movement of groundwater in response to CSG production.

1.2 Hypothesis

The aim of this study is to test the following hypotheses:

1. Closed faults or conduits will act as barriers to groundwater flow along and across faults near a CSG production well.
2. CSG production from a well in close proximity to an open fault or conduit will result in increased flow along the fault plane or conduit towards the pumping zone resulting in aquifer interconnectivity.

Figures 1-1 and 1-2 provide a conceptual representation of these two hypotheses. Figure 1-1 shows the fault/conduit acting as a barrier to flow as indicated by the above studies and presented in the SREIS chapter as the probable scenario. Figure 1-2 shows the fault/conduit acting as a pathway to flow.

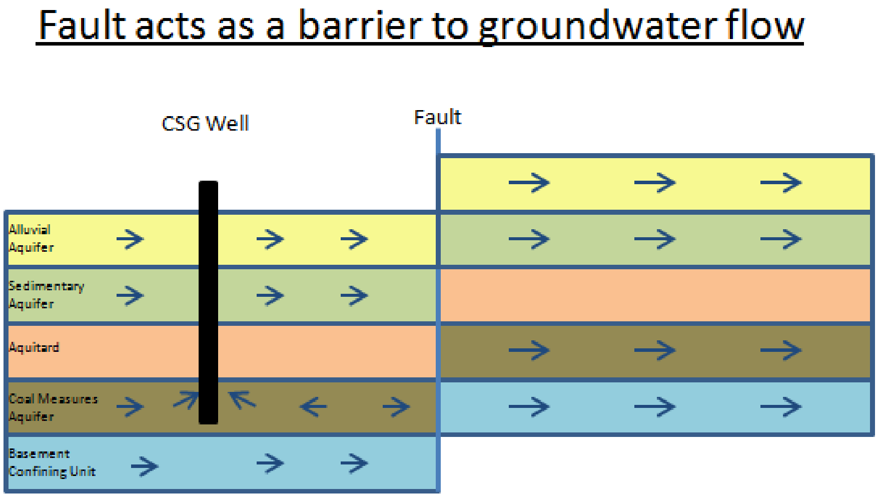

Figure 1-1: Schematic showing groundwater movement (compartmentalisation) in response to CSG production near a "closed" fault (barrier to groundwater flow, Hypothesis 1))

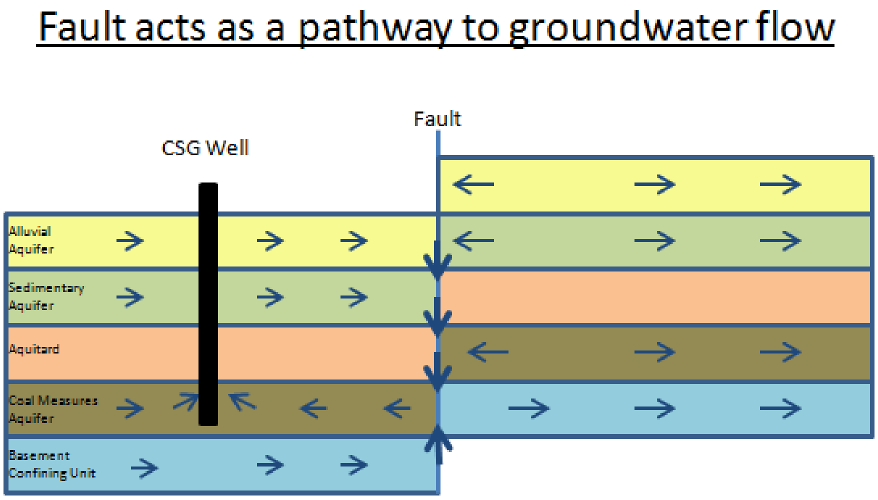

Figure 1-2: Schematic showing groundwater movement in response to CSG production near an "open" fault (pathway to groundwater flow, Hypothesis 2)

2 Methodology

The regional groundwater model developed for the BGP EIS encompassed an area of 66,330 square kilometres and has a 1.5 kilometre grid spacing, hence being too coarse for the detail required in this study. In order to investigate the hypotheses presented in Section 1.2, Telescopic Mesh Refinement (TMR) has been used to create a more refined model (the local groundwater model) within the subregion of the BGP regional model. Figure 2-1 identifies the area within which the local groundwater model has been exported. The local groundwater model domain exists within the proposed BGP CSG well field and encompasses a major fault represented as a HFB in the regional model.

The code employed for the local groundwater model remains the same as the regional groundwater model, MODFLOW SURFACT within the Groundwater Vistas (GV) user interface. Reference should be made to Appendix M of the BGP EIS which details the design, construction and calibration of the regional groundwater model. The TMR data was imported into a 10 km x 10 km domain (from row 1 to 100 and column 1 to 100) to define the extents of the local groundwater model. The local groundwater model grids consist of 180,000 active cells. By utilising TMR, the study was able to efficiently refine the model domain from being 66,330 square kilometres and 1.5 km x 1.5 km grids in the regional groundwater model, to having 100 square kilometres and 100 m x 100 m grids in order to better represent the faults on a local scale; whilst maintaining consistency with the parent model.

The following sections describe in detail the methodology employed to test the hypotheses, including:

- What parameters and scenarios were used to assess the hypotheses;
- How the faults were represented in the local groundwater model to assess the hypotheses;
- How the production wells simulated in the model were refined to assess the hypotheses;
- The model outputs used to assess the hypotheses.

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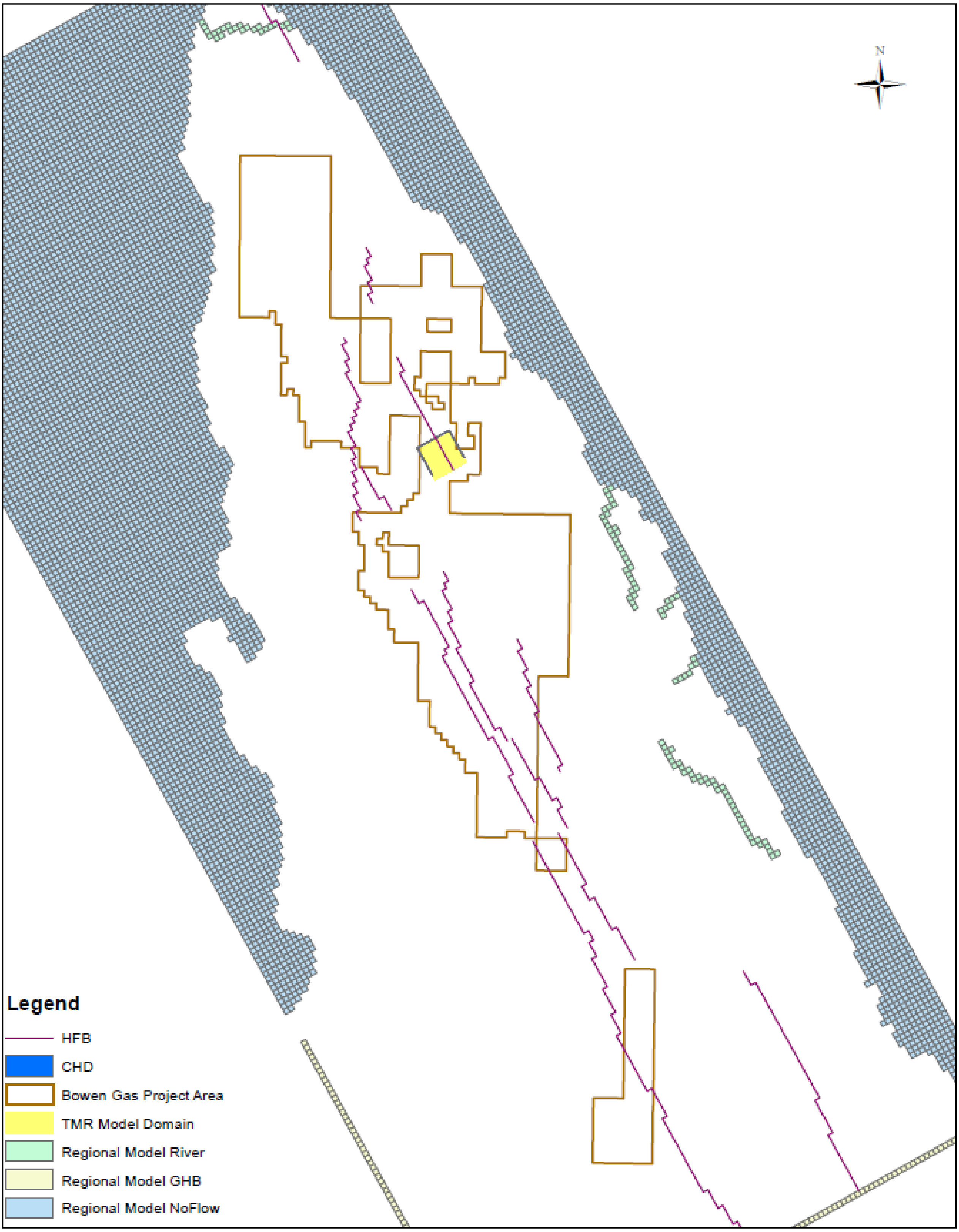

Figure 2-1 - TMR area within the regional BGP Groundwater Model

Source: Arrow Energy Limited

0 15 30 60 Kilometers

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2.1 Model Parameters

All structural and parameterisation data for the local groundwater model mimics that of the area extracted from the regional groundwater model. Reference should be made to Appendix M of the BGP EIS which details the regional groundwater model aquifer parameters adopted. Edge boundary conditions were automatically assigned to replicate the internal boundaries in each cell of the new local groundwater model that lie within the boundary cell of the regional groundwater model. For transient models, the edge boundary conditions are limited to constant heads. This is because the constant head (time-varying specified head) package (CHD) in MODFLOW is the only package capable of varying the boundary head within a stress period for TMR. Note that the CHD heads are the heads imported from the parent model for each time period at the boundary of the TMR model.

Two representative model hypotheses have been simulated as shown in Table 3-1.

Table 2-1: Modelled Scenarios

Hypothesis	Fault and conduit Vertical Hydraulic Conductivity (m/d)	Assumption
1	1×10^{-9}	Fault or conduit represents a no-connection barrier to flow (Hypothesis 1)
2	1	Fault or conduit represents vertical pathway to flow (Hypothesis 2)

2.2 Fault Representation

Faults that were represented in the local groundwater model included the existing regional fault (vertical fault) which was exported over from the parent model, as well as an additional sub-vertical conduit. The methods of representing these features in the local groundwater model are discussed in more detail below.

2.2.1 Vertical Fault

The vertical fault represented in the local groundwater model has been exported from the regional parent model which simulated faults using HFBs. In order to simulate vertical flow along the fault, hydraulic conductivity zones were applied to the column next to the HFB which were in line with the conductivity values represented by the HFB. This assumes that the width of the fault zone is 100 m which is considered to be a conservative approach. The vertical extent of the simulated fault in the model is from Layer 3 to 18.

In order to test hypothesis 1, that closed faults will act as barriers to groundwater flow, the hydraulic conductivity values for the HFB and the hydraulic conductivity zones in the column next to the HFBs were set as 1×10^{-9} m/day.

In order to test hypothesis 2, that CSG production will result in increased flow along the fault plane, the hydraulic conductivity values for the HFB and the hydraulic conductivity zones in the column next to the HFBs were set as 1 m/day.

The position of the vertical fault in the local groundwater model is shown in Figure 2-2.

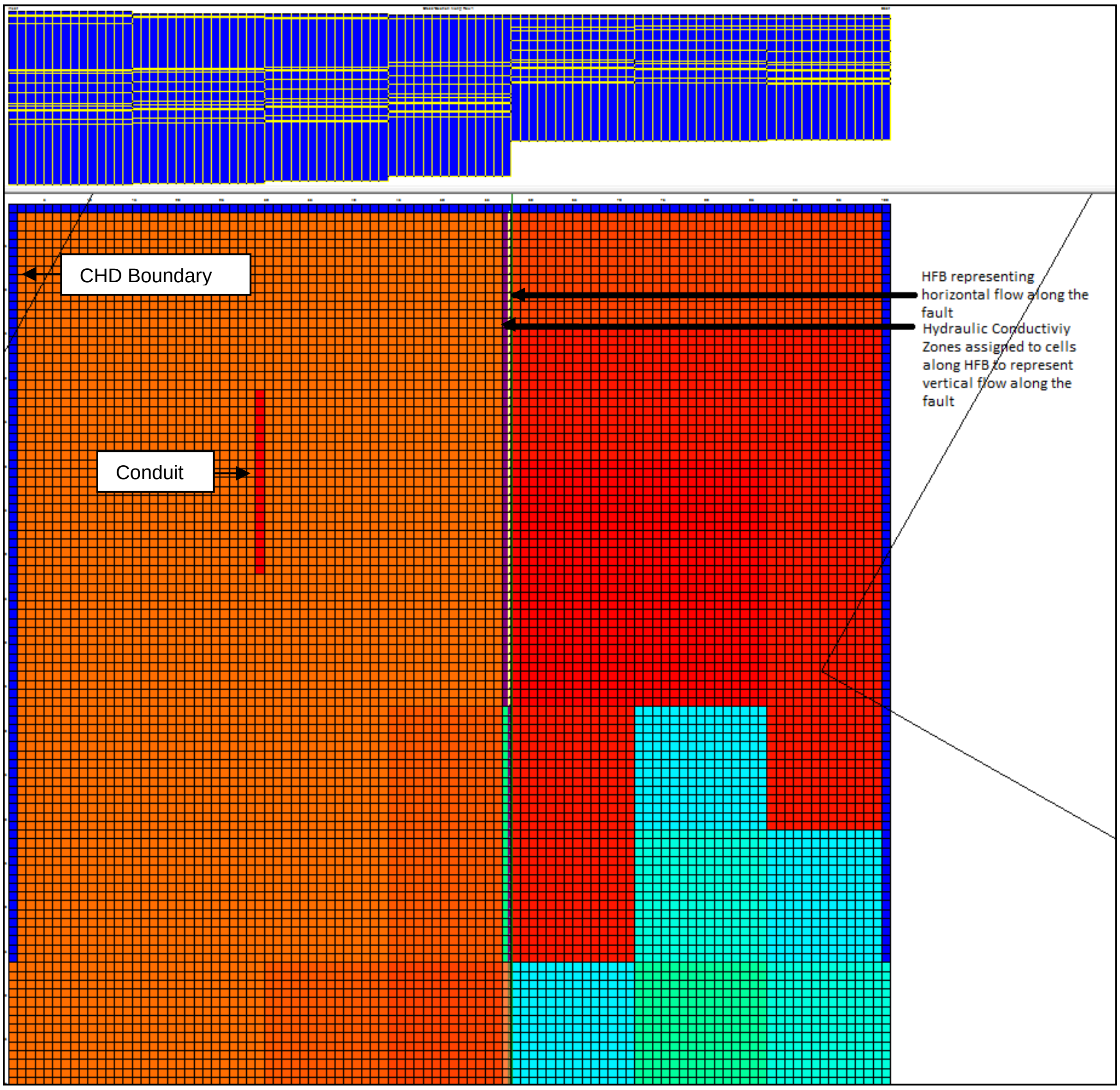

Figure 2-2: Location of the fault represented in the local groundwater model

2.2.2 Sub-vertical Conduit

A hypothetical sub-vertical conduit (possible intrusion or fault) was also simulated in the local groundwater model. Figure 2-3 shows the position of the conduit in the local groundwater model which is assumed to be 2 km in length. Vertical flow along this conduit was represented by assigning hydraulic conductivity zones to cells representing the feature. By doing so, the width of the conduit zone is assumed to be 100 m which is considered to be a conservative approach. Whilst the vertical extent of the conduit is from Layer 3 to 18, the hydraulic conductivity zones were offset (by one cell) in each layer as shown in Figure 2-3.

In order to test hypothesis 1, that closed conduits will act as barriers to groundwater flow, the hydraulic conductivity values for the hydraulic conductivity zones representing the conduit were set as 1 x 10^{-9} m/day.

In order to test hypothesis 2, that CSG production will result in increased flow along the conduit, the hydraulic conductivity values for the hydraulic conductivity zones representing the conduit were set as 1 m/day.

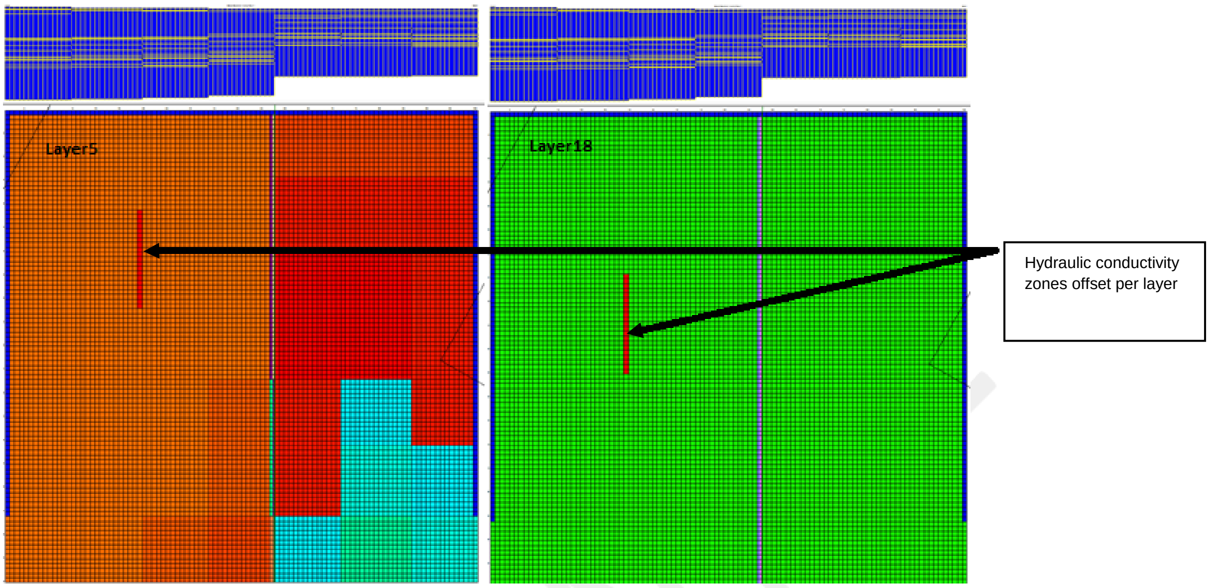

Figure 2-3: Location of simulated sub-vertical fault zone in the local groundwater model

2.3 Production Wells

The number of production wells and associated water production rates simulated in the local groundwater model has been reduced by 90% from that simulated in the regional groundwater model. This was undertaken to resolve model convergence issues that are likely to be associated with one or in part both of two effects.

Firstly, as the local groundwater model is an extract from a larger model with a larger field development plan of wells, some of the wells in the local groundwater model were at or close to boundaries of the TMR model domain which could contribute to numerical instability.

Secondly, the requirement for the local groundwater model to be re-parameterised. This can be due to several issues including effect of pumping rates on finer model grid.

Whilst the placement of wells is yet to be finalised for the BGP field development plan, the outcomes of this study nevertheless provides a synthetic scenario which aims to provide an initial assessment of the likely effects and significance of flow along permeable faults in the model.

The locations of the production wells and target layer are shown in Figure 2-4. Based on this, the wells closest to the fault and conduit feature are located in layer 5 of the local groundwater model, which represents CSG production from the Rangal Coal Measures.

As such, In order to test hypothesis 1, that closed faults or conduits will act as barriers to groundwater flow, the effects of production from specific wells in layer 5 was assessed near the fault and conduit.

In order to test hypothesis 2, that CSG production will result in increased flow along the fault or conduit, the effects of production from specific wells in layer 5 was assessed near the fault and conduit. In addition to this, the model was run without production wells in layer 5. This will provide a comparison between the amount of flow along the fault and conduit in layer 5 with and without production wells.

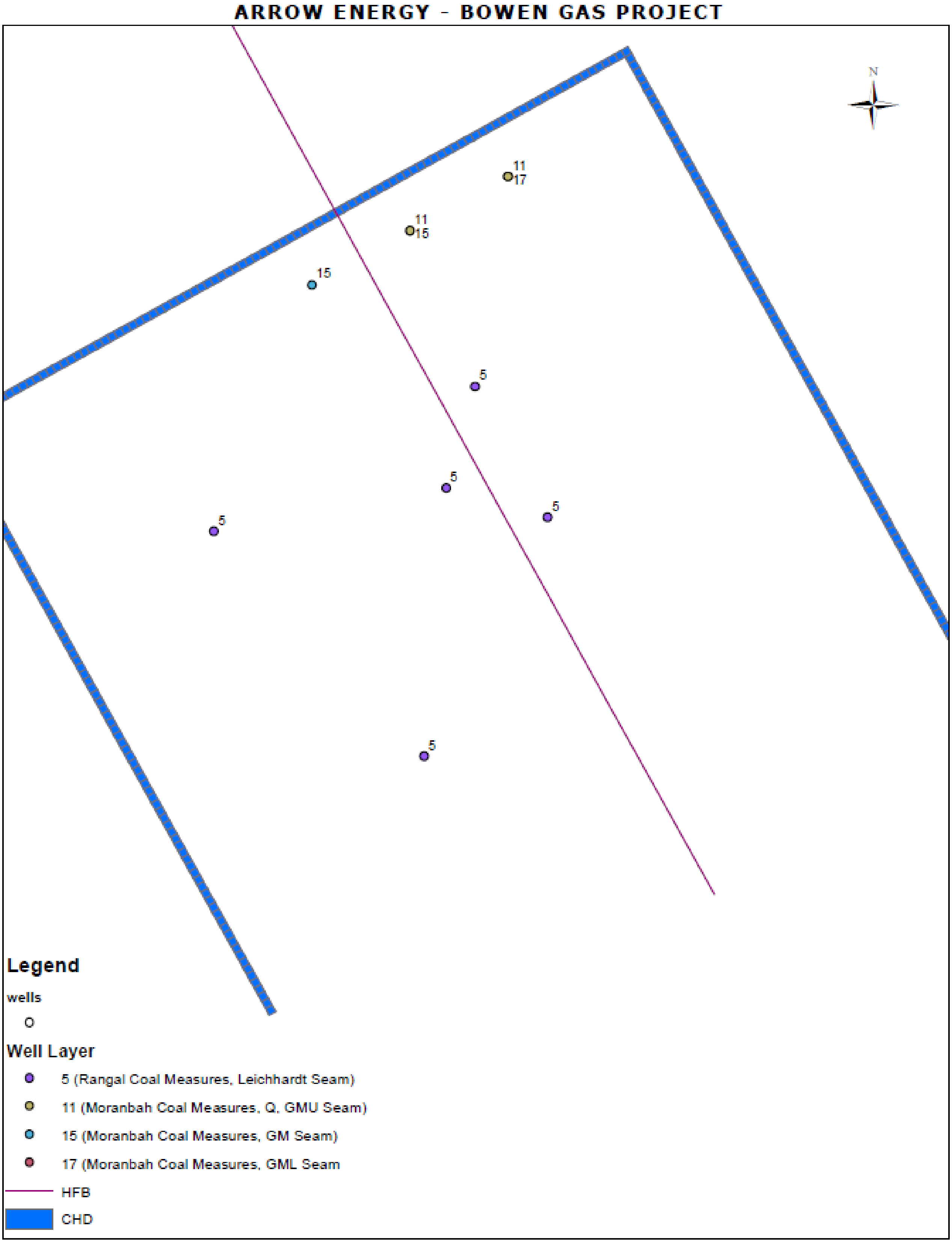

Figure 2-4 **Location of the production wells in the local groundwater model**

Source: Arrow Energy Limited

0 0.5 1 2 Kilometers

arrow energy go further

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2.4 Model Outputs

Key model outputs to test hypothesis 1 and 2 include:

- Interlayer Flux for Layer 5;
- Drawdown Contours; and
- Velocity Vectors.

2.4.1 Vertical Fault

Model hypothesis 1 tests that closed faults will act as barriers to groundwater flow. Drawdown outputs for this scenario were reviewed to show if the fault limits the migration of drawdown impacts horizontally across the fault and vertically along the fault and into other layers. Hydrostratigraphic Units (HSUs) were assigned to the column representing the fault in order to extract flux data specific to the fault plane from the model. Vertical movement of groundwater from the fault into and out from layer 5, the layer with a nearby CSG production well, can be calculated to indicate the amount of flux along the fault plane. Very low flux values (compared to production rates) would support Hypothesis 1 i.e. limited to negligible movement of groundwater along the fault plane during CSG production.

Model hypothesis 2 tests that CSG production would result in increased flow along open faults. Drawdown outputs for this scenario were reviewed to show if the fault plays a role in the migration of drawdown impacts horizontally and in particular vertically into other aquifers. A review of drawdown near a CSG production well between hypothesis 1 and 2 is used to quantify this. Hydrostratigraphic Units (HSUs) were assigned to the column representing the fault in order to extract flux data specific to the fault plane from the model. Vertical movement of groundwater from the fault into and out from layer 5, the layer with a nearby CSG production well, was calculated to indicate the amount of flux along the fault plane. Flux data was compared between the production and no production cases to assess if CSG production would result in increased flow along the fault. An increase in flux values for the production case in comparison to the no production case would support Hypothesis 2 i.e. production of a CSG well near an open fault would result in increased flow along the fault into the produced formation.

2.4.2 Sub-vertical Conduit

Model hypothesis 1 tests that closed conduits will act as barriers to groundwater flow. A model cross-section along the CSG well and conduit zone with velocity vectors showing the direction of groundwater flow provides a representation of groundwater movement. Velocity vectors in the conduit zone reflect only horizontal flow would support Hypothesis 1.

Model hypothesis 2 test that CSG production would result in increased flow along open conduits. A model cross-section along the CSG well and conduit zone with velocity vectors showing the direction of groundwater flow provides a representation of groundwater movement. A comparison is made between the production and no production cases to assess if flow along the conduit only occurs if there is CSG production. Velocity vectors in the conduit zone would represent vertical flow indicating inter-aquifer flow along the conduit would indicate support of hypothesis 2.

3 Results

Each well was simulated for a production period of 15 years which is the production life for the wells in this area of the model and results have been presented at the end of 9125 days. Results for the vertical fault and sub-vertical conduit are presented in the following sections.

3.1 Vertical Fault

The drawdown and interlayer flux results for testing hypothesis 1 and 2 at the end of well life are presented in detail below, however, the results that support Hypotheses 1 and 2 are:

- Hypothesis 1: the fault limits the migration of drawdown impacts horizontally and vertically along the fault and into other layers. There is limited movement of groundwater along the fault plane during CSG production.
- Hypothesis 2: the fault plays a role in slightly enhancing the migration of drawdown impacts horizontally and vertically into other aquifers. Production from a CSG well near the fault results in a slight increase in flow along the fault into the produced formation.

3.1.1 Hypothesis 1 – Barrier to Groundwater Flow

Drawdown in the local groundwater model domain resulting from CSG production was predicted. The key results are presented as contour maps showing the extent of the 5 m drawdown contour. Figure 3-1 shows model results in Layers 4 to 8, in response to a production well in Layer 5 which is located near the fault simulated as a barrier to groundwater flow. The figure also shows groundwater velocity vectors which identify the direction of groundwater flow.

Based on these results, the extent of drawdown is tightly constrained around the production well in layer 5 and impacts based on the 5 m drawdown contour remain within the Rangal Coal Measures. This indicates that the fault does not significantly contribute to the propagation of impact. Observations of flow direction on each side of the closed fault suggest a compartmentalisation of groundwater due to the fault acting as a barrier to flow. These results are in support of Hypothesis 1, that the fault limits the migration of drawdown impacts.

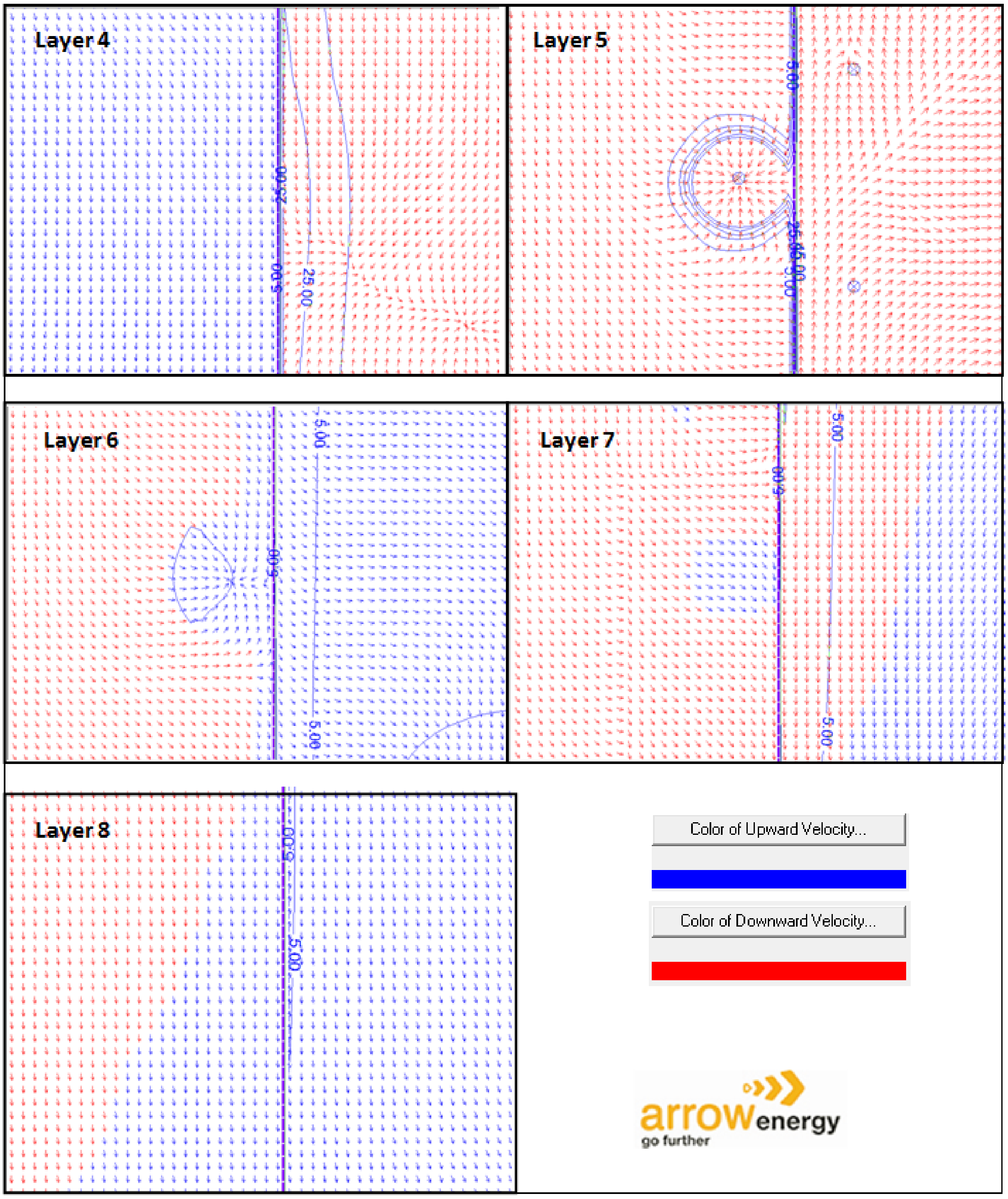

Figure 3-1: Velocity vectors showing the influence to groundwater drawdown near the fault existing as a barrier to groundwater flow from pumping in layer 5 at 9125 days.

Groundwater fluxes for the fault zone in layer 5 were extracted to assess flows along the closed fault. Figure 3-2 below shows the total flux from the fault zone to layer 5 over the life of the well in comparison to the well production rate. The amount of flux is low ranging from 0.0111 to 0.0147 m^3/day. Whilst a slight increase in flux of 0.0036 m^3/day is noted over the production period, this is considered to be insignificant, particularly in comparison to the modelled production rates of up to 57 m^3/day. These results are in support of Hypothesis 1, that the fault limits the migration of drawdown impacts.

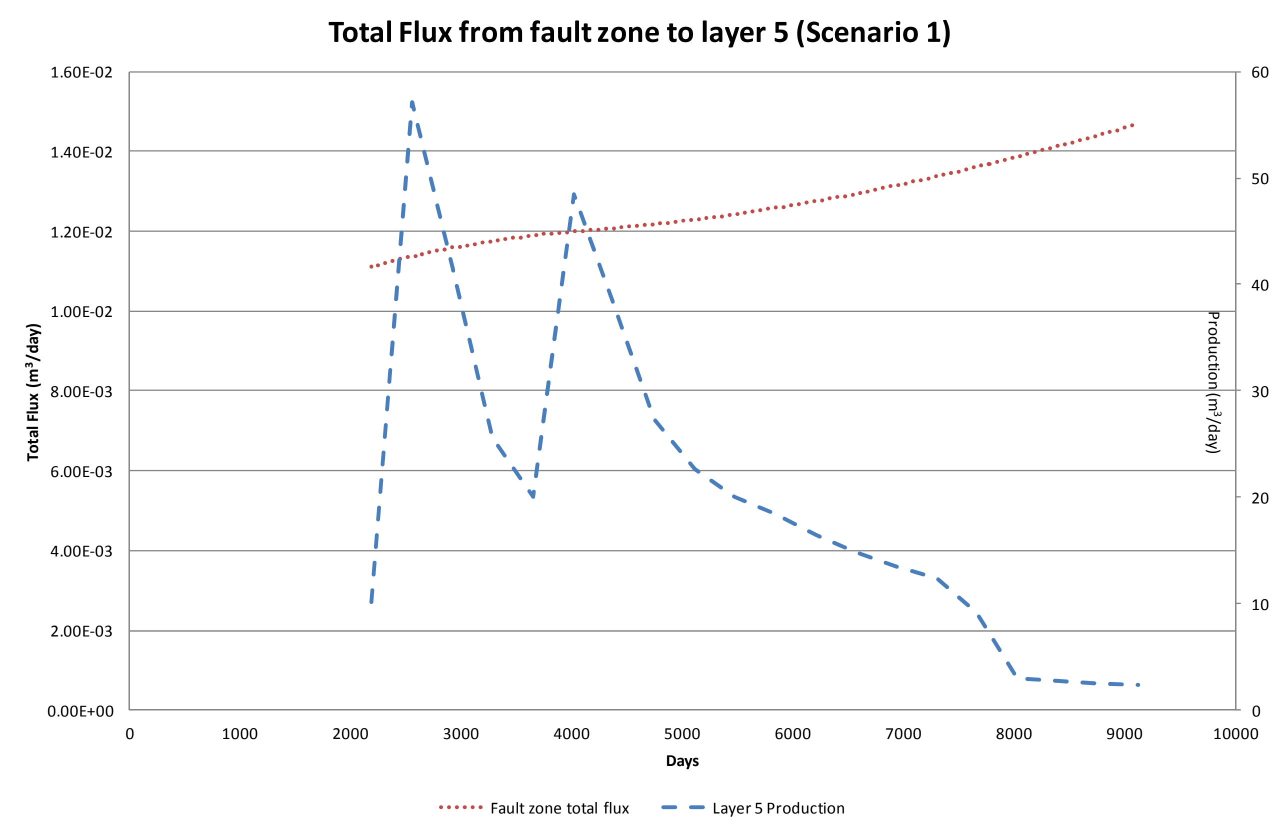

Figure 3-2: Total flux along the fault zone for Layer 5 (Scenario 1).

3.1.2 Hypothesis 2 – Pathway to groundwater flow

Drawdown in the local groundwater model domain resulting from CSG production was predicted. The key results are presented as contour maps showing the extent of the 5 m drawdown contour. Figure 3-3 shows model results in Layers 4 to 8, in response to a production well in Layer 5 which is located near the fault which has been simulated as a pathway to groundwater flow. The groundwater velocity vectors depicted in this figure show the direction of groundwater flow at the end of well life (9125 days).

Based on these results, the extent of drawdown around the production well in layer 5 is slightly larger than that noted for Scenario 1. Impacts based on the 5 m drawdown contour remain within the Rangal Coal Measures. Observations of flow suggest that the fault does not impede flow across the fault zone, given the differences between the high hydraulic conductivity of the fault zone and low hydraulic conductivity of the surrounding aquifers, the fault acts as a preferential vertical pathway for flow. These results are in support of Hypothesis 2, that the fault plays a role in the migration of drawdown impacts.

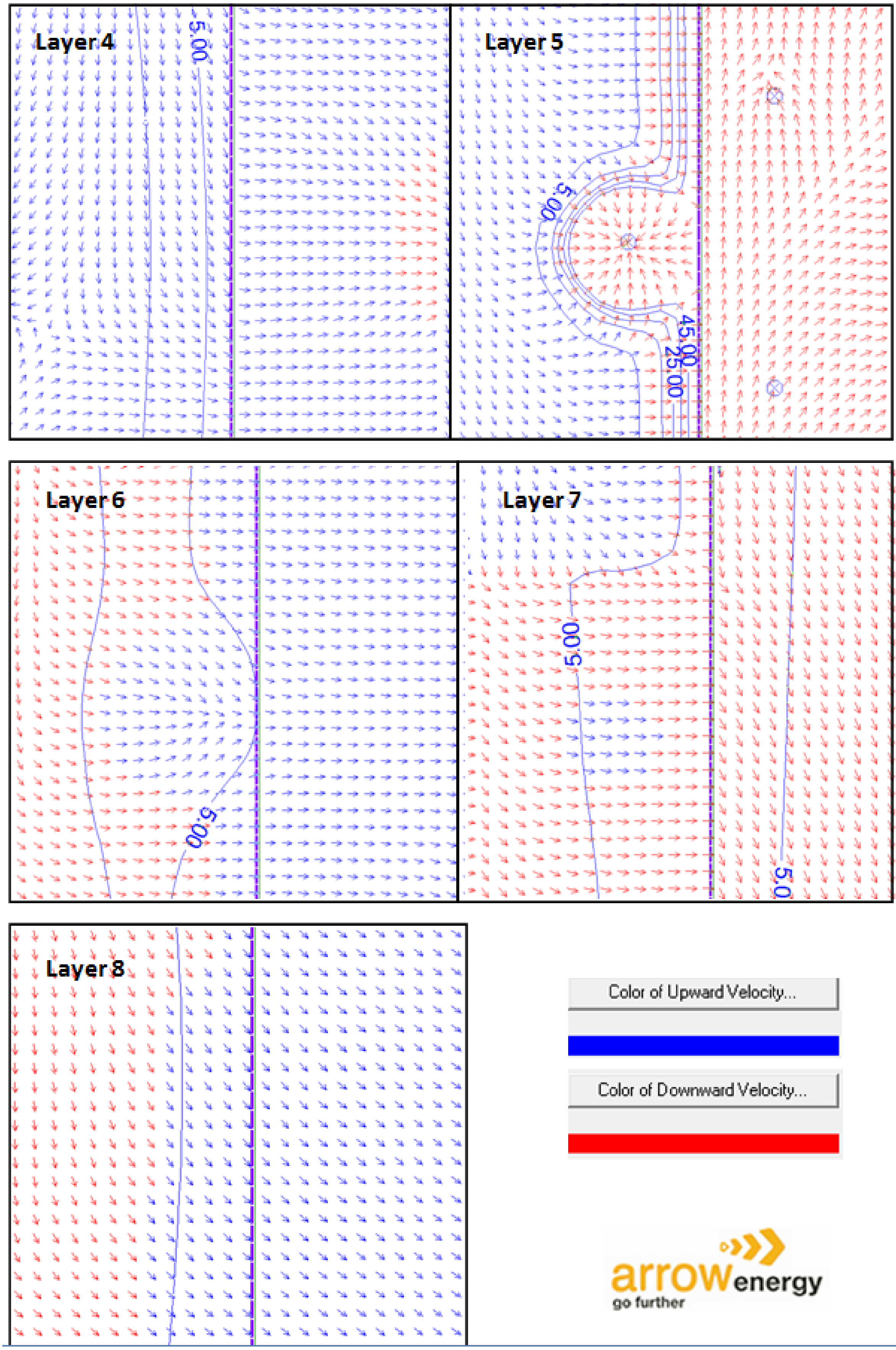

Figure 3-3: Velocity vectors showing the influence to groundwater drawdown near the fault existing as a pathway to groundwater flow from pumping in layer 5 at 9125 days.

Groundwater fluxes for the fault zone in layer 5 were extracted to assess flows along the open fault. Figure 3-4 below shows the total flux from the fault zone to layer 5 over the life of the well in comparison to the well production rate. The amount of flux is low ranging from 0.0088 to 0.0465 m^3/day. Whilst an increase in flux of 0.038 m^3/day is noted over the production period, this is considered to be minor, particularly in comparison to the production rates of up to 57 m^3/day. However it is four times greater than the closed scenario indicating a substantial difference in flow is possible between the hypotheses. These results are in support of Hypothesis 2, that the fault plays a role in the migration of drawdown impacts.

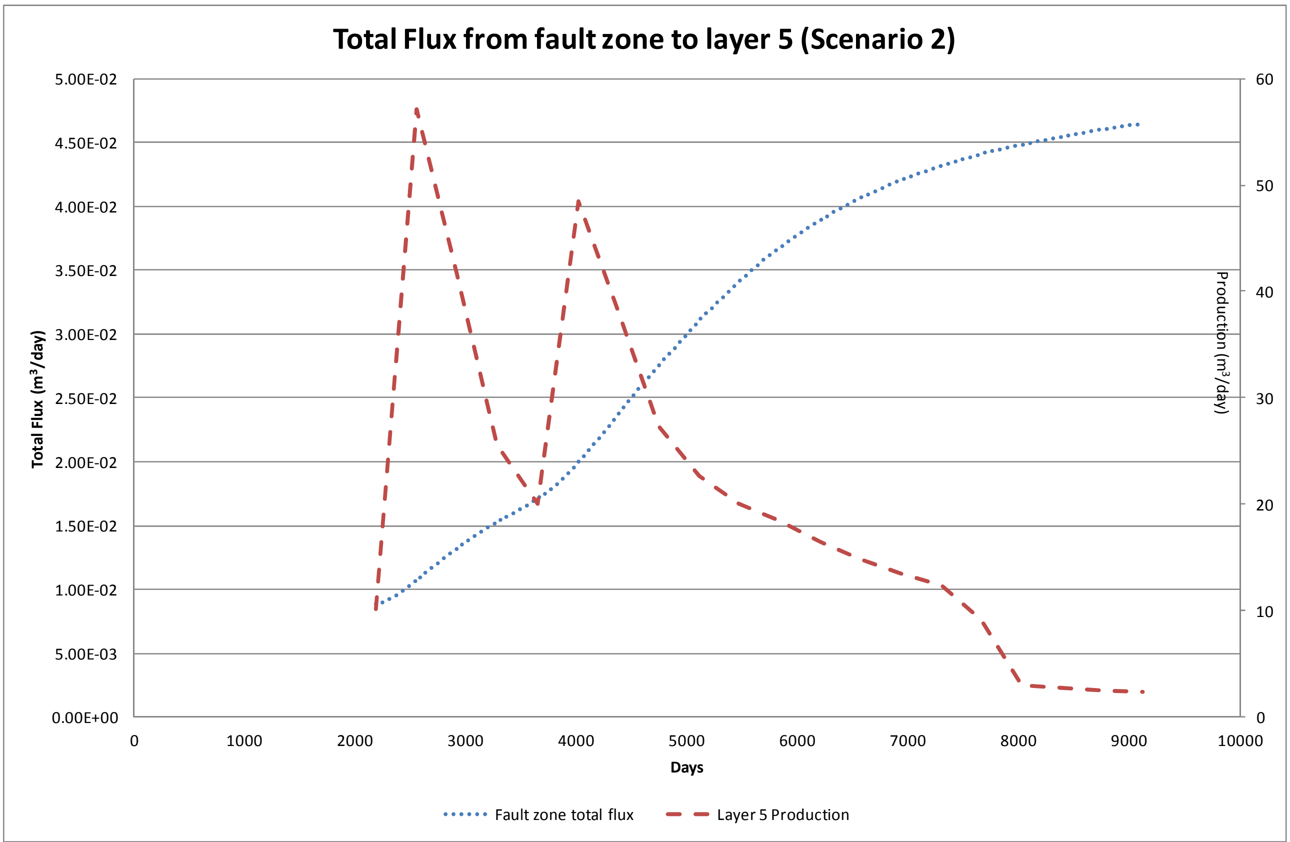

Figure 3-4: Total flux along the fault zone for Layer 5 (Scenario 2).

Model hypothesis 2 was also simulated with no CSG production in layer 5. A comparison of the total flux along the fault zone between the production and no production cases provided an indication of net increase in flow along the fault zone for layer 5. It should be noted that production was still simulated in layers 11, 15 and 17 of the groundwater model. The resultant layer 5 fluxes have been compared to the scenario 2 (with production) fluxes (Figure 3-5).

Little difference is observed between the flows to layer 5 from the fault zone for the no production and production cases. The flows from the fault to layer 5 for the production case, is greater than the flows from the fault to layer 5 for the no production case. At the end of production, which represents the greatest amount of total flux, the total flux for the production case is 0.0465 m^3/day, whereas the no production case is 0.0435 m^3/day. This is only an increase in flow by 0.003 m^3/day in this case. This suggests that CSG production may result in only slightly higher flows along the fault to layer 5 (the production zone). This may be because the regional pressures and gradients affecting the fault dominate movement of water along the fault. Whilst these results are in support of Hypothesis 2, they suggest that the fault plays only a minor role in the migration of drawdown impacts.

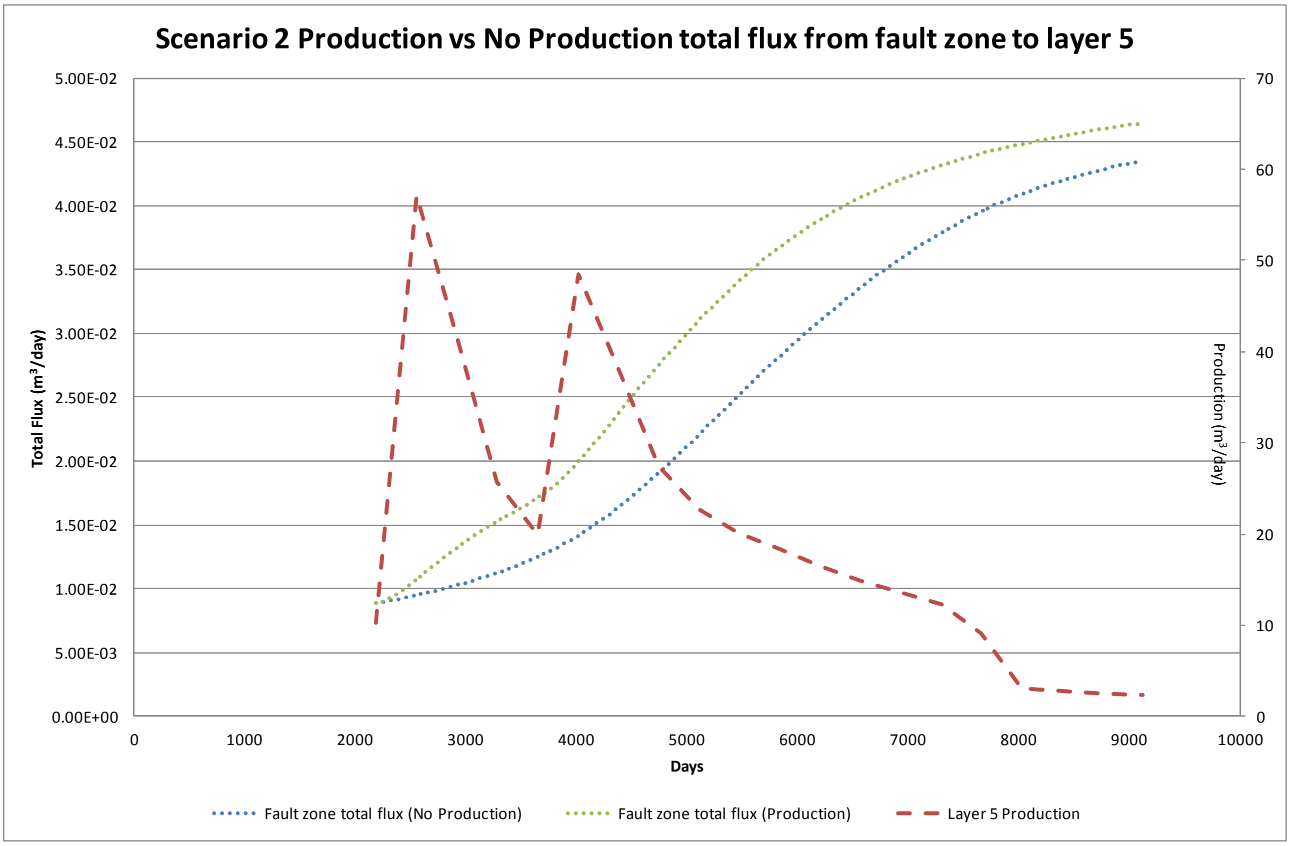

Figure 3-5: Groundwater flux along the fault zone for Scenario 2 where production has been simulated and has not simulated for layer 5 in the model.

3.1.3 Comparative Total Flux (Upscaling)

Given that the water production rates and well numbers were reduced by 90%, the inter-layer fluxes have been increased by 90% for comparative purposes. This is shown in Figure 3-6 below in order to demonstrate what the actual fluxes could be relative to full field development plan rates of production. In this case, the fluxes can be expected to be 90% higher than that modelled. The flux at the end of production for scenario 2, which results in the most flux is 0.418 m^3/day. Compared to the maximum production rate of 514 m^3/day, flux along the fault zone is still considered to be low.

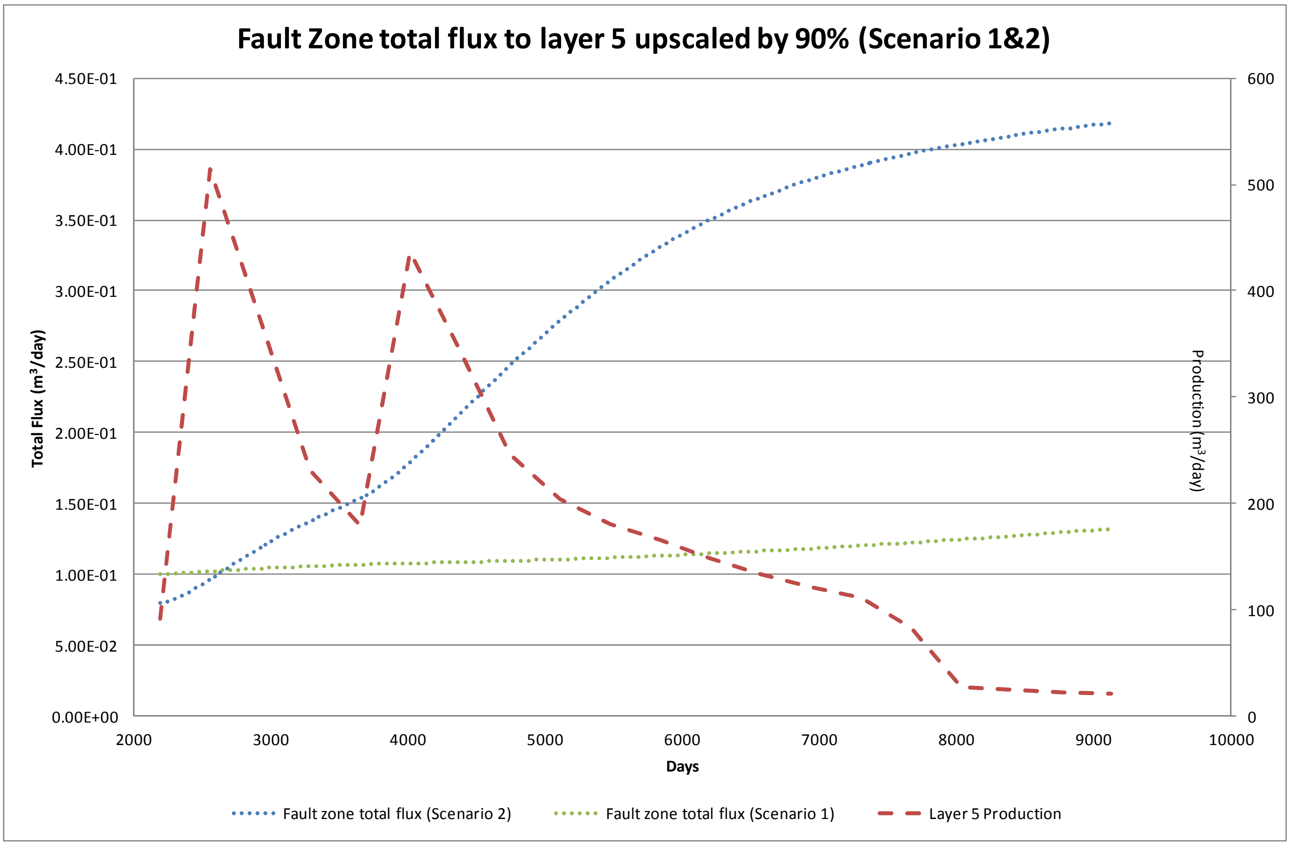

Figure 3-6: A 90% increase of production rates in layer 5 as well as total flux along fault zone to layer 5 for comparison.

3.2 Sub-vertical Conduit

Cross-sections of the sub-vertical conduit showing the velocity vectors for Hypothesis 1 and 2 at the end of well life are presented below.

These results are in support of Hypothesis 1 and 2:

- Hypothesis 1: There is no vertical flow (inter-aquifer flow) along the closed conduit in response to CSG production.
- Hypothesis 2: CSG production near the open conduit results in vertical flow along the conduit indicating inter-aquifer flow.

3.2.1 Hypothesis 1 – Barrier to Groundwater Flow

Figure 3-7 shows a cross-sectional view of the conduit zone simulated as a barrier to groundwater flow near the CSG production well. The groundwater velocity vectors depicted in this figure show the direction of groundwater flow at the end of well life (9125 days). Note that there is no horizontal flow boundary along the simulated conduit.

The direction of flow is observed to be horizontal across the layer consistent with regional flow gradients. Where the production well exists, flow is horizontal and vertical in the immediate vicinity of the well in response to the reduction in pressure as a result of CSG production. Vertical flow along the conduit is not observed, suggesting that inter-aquifer flow does not occur along the conduit in this scenario. This is in support of Hypothesis 1, that there is no vertical flow (inter-aquifer flow) along the closed conduit in response to CSG production.

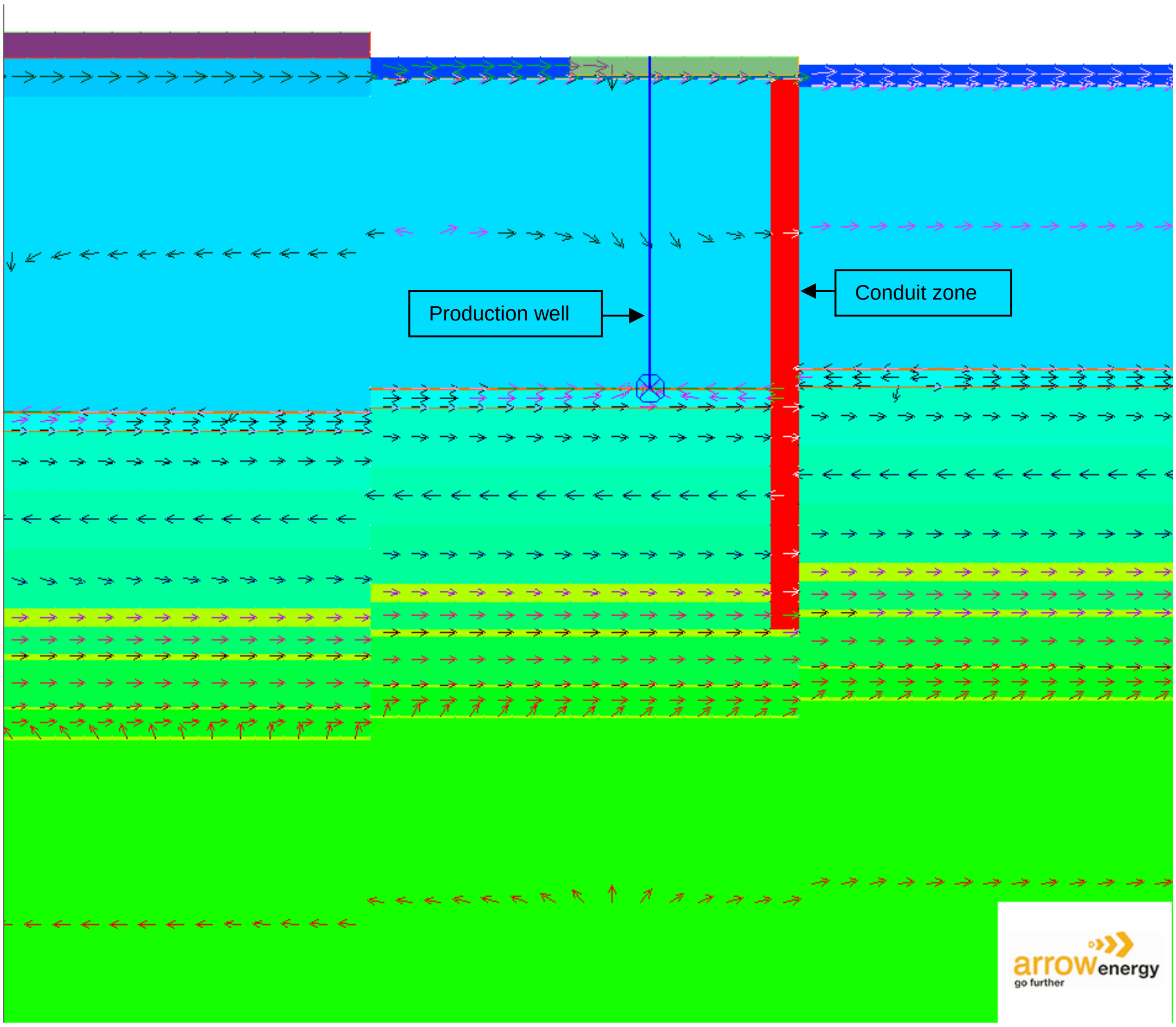

Figure 3-7: Cross section showing velocity vectors indicating no vertical movement of groundwater between layers along the conduit zone at 9125 days.

3.2.2 Hypothesis 2 – Pathway to groundwater flow

Figure 3-8 shows a cross-sectional view of the conduit zone simulated as a pathway to groundwater flow near the CSG production well. The groundwater velocity vectors depicted in this figure show the direction of groundwater flow at the end of well life. Note that there is no horizontal flow boundary along the simulated conduit zone.

Observations of velocity vectors along the conduit zone shows vertical flow suggesting inter-aquifer flow along the conduit. Where the production well exists, flow is horizontal and vertical in the immediate vicinity of the well in response to the reduction in pressure as a result of CSG production. This is in support of Hypothesis 2, that CSG production near the open conduit results in vertical flow along the conduit indicating inter-aquifer flow.

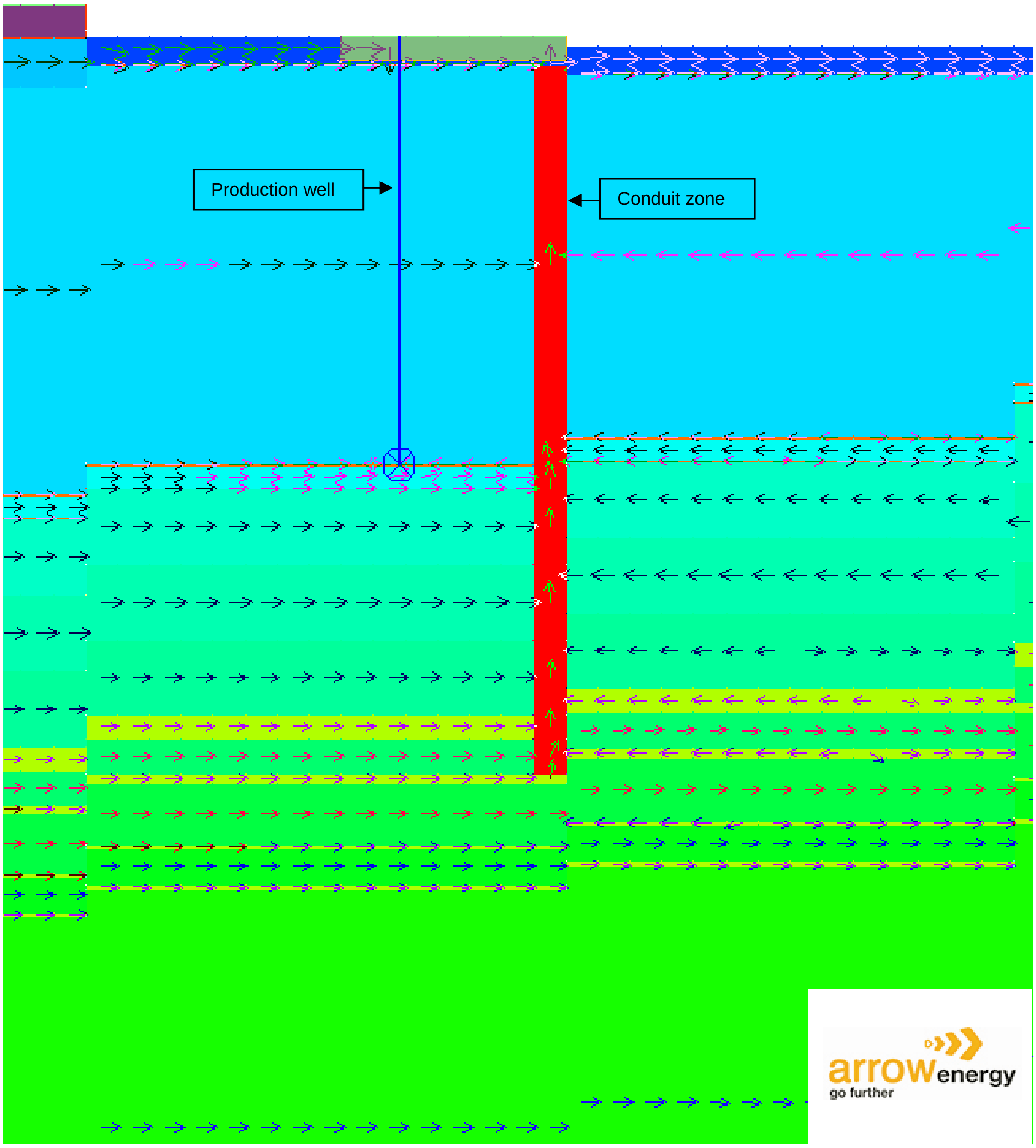

Figure 3-8: Cross section showing velocity vectors indicating vertical movement of groundwater between layers along the conduit zone at 9125 days.

Figure 3-9 below shows a cross-sectional view of the conduit zone simulated as a pathway to groundwater flow with no CSG production in Layer 5. Note that there is no horizontal flow boundary along the simulated conduit zone.

Observations of velocity vectors along the conduit zone in the no production case shows vertical flow along the conduit. This suggests that the open conduit acts as a preferential pathway for flow in the absence of a nearby CSG well. The total flux from the conduit to layer 5 at 9125 days is 0.00391 m^3/day and -0.0877 m^3/day (negative flux represents flow from the layer to the conduit) for production case and no production case respectively. This suggests that there is an increase in flux along the conduit of 0.09 m^3/day in this case. This is in support of Hypothesis 2, that CSG production near the open conduit results in vertical flow along the conduit indicating inter-aquifer flow.

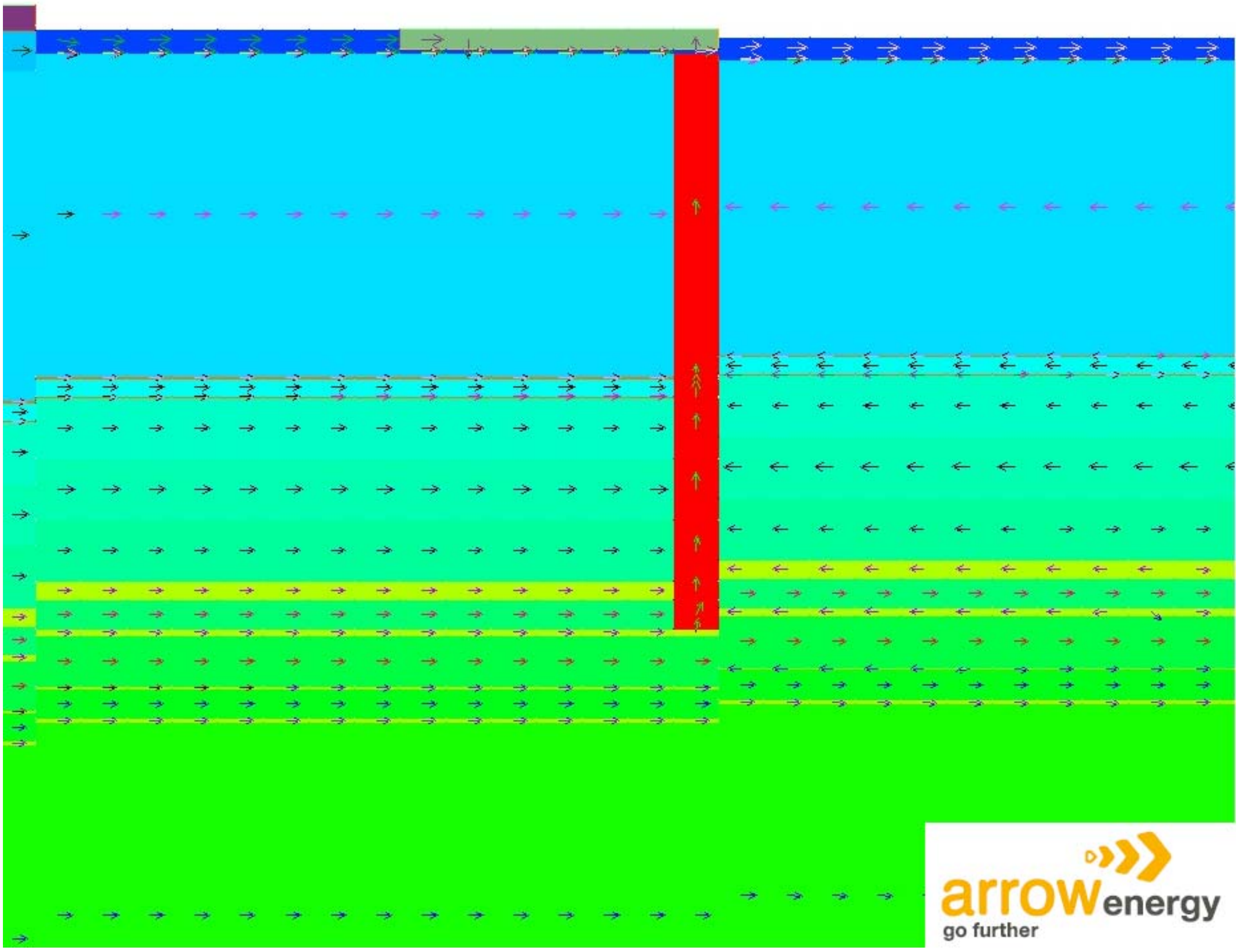

Figure 3-9: Cross section showing velocity vectors indicating vertical movement of groundwater between layers along the conduit zone at 9125 days without production in Layer 5.

4 Conclusion

Available data within the Bowen Basin indicates that faults are generally of low permeability both parallel to and normal to the fault planes. The current compressive stress regime of the Basin suggests that major faults in the basin are sealed and will not be a preferential pathway for either gas or water migration, which is consistent with field evidence. In reality, it is expected that the majority of faults in the Bowen Basin behave as barriers to groundwater flow. The base case presented in the EIS is consistent with this principle. The results of this study are also in support of this, that closed faults or conduits will act as barriers to groundwater flow along and across faults near a CSG production well (Hypothesis 1). Key findings supporting this are:

- Drawdown impacts are constrained to the target aquifer and do not propagate into the overlying or underlying aquifers
- Flow direction on each side of the closed fault suggest a compartmentalisation of groundwater due to the fault acting as a barrier to groundwater flow
- Groundwater flux for the fault is low ranging from 0.0111 to 0.0147 m3/day in comparison to modelled production rates of up to 57 m3/day
- Velocity vectors do not show vertical movement of water along the fault zone

Whilst the above results represent the most likely scenario, an assessment of the opposite scenario where faults (or other conduits such as weathered igneous dykes) behave as pathways to groundwater flow was undertaken for completeness. If the hydraulic properties of structural and igneous features in the Basin are higher than the surrounding formations, then it can be hypothesised that these zones represent preferential pathways for flow, and may play a role in aquifer recharge and discharge. It can be assumed that such features would influence the movement of groundwater in response to CSG production. Results from this study which support this are:

- Drawdown and flow direction on each side of the fault suggest that the fault acts as a preferential vertical pathway for flow given its higher hydraulic conductivity in relation to the low hydraulic conductivity of the surrounding aquifers
- Groundwater flux for the fault is low ranging from 0.088 to 0.0465 m3/day in comparison to modelled production rates of up to 57 m3/day. However, being up to four times greater flux in comparison the Hypothesis 1 suggests a substantial difference in flow is possible between the hypotheses.
- Velocity vectors show vertical movement of water along the fault zone

Whilst these results are in support of Hypothesis 2, the study suggests that the fault plays only a minor role in the migration of drawdown impacts i.e. impacts are low. This was demonstrated in the study by the following result:

- Total flux along the fault zone for a case representing no production is 0.0435 m3/day, which is an increase in total flux of only 0.003 m3/day from the production case

Based on the above findings, the outcomes of this study maintain that faulting in the Basin behave has barriers to groundwater flow along and across faults near a CSG production well. In the event that a fault zone represents an existing preferential pathway for flow, the fault will only play a minor role in the migration of drawdown impacts associated with CSG production.

References

- URS (2012) Arrow Energy Bowen Gas Project Environmental Impact Statement
- Hillis and Reynolds (2002) In situ stress field of Australia, Geological Society of Australia Special Publication 22, pages 43-52.

Appendix D
Arrow Energy Bowen Gas Project
Bowen Basin EIS Groundwater Model Review

Supplementary Groundwater Assessment
Arrow Energy Bowen Gas Project
Supplementary Report to the EIS

Arrow Energy Pty Ltd

Bowen Basin EIS Groundwater Model Review

CDM Smith

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Bowen Basin EIS Groundwater Model Review

8 October 2013

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Appendices

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REV0	08/19/2013	Lloyd Townley	Lloyd Townley	08/10/2013	Draft

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Project Number:	PGW130025

Executive Summary

Arrow Energy Pty Ltd (Arrow) is proposing to expand coal seam gas operations (CSG) in the Bowen Basin with the Bowen Gas Project (BGP). They have prepared a voluntary Environmental Impact Statement (EIS) for the Queensland Department of Environment and Heritage Protection to cover the project's scope, potential impacts and mitigation strategies. As part of the EIS, a numerical groundwater flow model was prepared by Ausenco-Norwest (Ausenco) to predict the impact of the proposed CSG operations on deep and shallow aquifers in the North Bowen Basin (NBB) regional area. CDM Smith has reviewed the final released EIS with reference to the Australian Groundwater Modelling Guidelines (2012).

Three documents were reviewed with reference to the NBB model prepared by Ausenco, covering the groundwater section of the EIS, an appendix on groundwater and geology, and a multi-part appendix on the groundwater model itself.

CDM Smith's review finds that the NBB model created by Ausenco-Norwest for Arrow's BGP is a well-designed and well-executed numerical groundwater model. The conceptualisation of the groundwater flow regime is complete. The model employs good software to represent structural geometry, discretisation and parameterisation appropriately for a regional scale model. Calibration to steady state groundwater measurements from before 1980 is well-considered and the model achieves a good fit. Limited availability of regional groundwater measurements affected by coal seam gas production causes the model to have a confidence level classification of Class 1, whereas otherwise the model contains many features of a higher confidence level.

Model predictions are appropriately designed, and presented to meet the model and project objectives. Sensitivity analysis considers the most uncertain parameters and generally indicates that the base case simulation is conservative in predicting the largest likely impacts. The reliability of model predictions is discussed in terms of the limitations of single-phase groundwater flow methodology and the regional scale of the model. A formal uncertainty analysis has not been performed. These restrictions are appropriate for a Class 1 model, and the predictions can be considered reasonable within the modelling assumptions and numerical methodology.

CDM Smith finds that the NBB model developed by Ausenco for Arrow's BGP conforms to best industry practice, is fit for purpose, and fulfils the appropriate portions of the Australian Groundwater Modelling Guidelines.

Section 1 Introduction and Scope

Arrow Energy Pty Ltd (Arrow) is proposing to expand coal seam gas (CSG) operations in the Bowen Basin with the Bowen Gas Project (BGP). They have prepared a voluntary Environmental Impact Statement (EIS) for the Queensland Department of Environment and Heritage Protection (DEHP) to cover the project's scope, potential impacts and mitigation strategies.

As part of the EIS, a numerical groundwater flow model was prepared by Ausenco-Norwest (Ausenco) to predict the impact of the proposed CSG operations on deep and shallow aquifers in the North Bowen Basin (NBB) regional area. The objective of modelling was to predict and delineate areas within aquifers affected by the BGP operations where groundwater drawdown exceeds the threshold criteria set by the DEHP. Ausenco also prepared several reports on the groundwater modelling methodology, which were included in the EIS as Appendix M.

NTEC Environmental Technology (NTEC) reviewed the Ausenco model and the draft EIS appendix in 2012, with reference to the then draft Australian Groundwater Modelling Guidelines[1] (Guidelines). CDM Smith Australia Pty Ltd (CDM Smith) acquired NTEC in February 2013. Arrow has requested a report summarising the previous review stages, with reference to the final released EIS. CDM Smith's review may be publically released by Arrow as part of a Supplementary EIS (SEIS). As the previous reviews were prepared to assist the groundwater modelling team in preparing the NBB model, this report provides commentary in a more general framework, with less emphasis on technical terminology and more consideration of the suitability of the final model.

1.1 Modelling and reviewing guidelines

Our expert knowledge of groundwater modelling and the now-released Guidelines of 2012 provided a basis for the review. It is important to note that these Guidelines are not standards but they do provide a framework for discussing best practice groundwater models.

The guidelines emphasise that models should be "fit for purpose," and fulfil the objectives of both the groundwater modelling and the overall project. Three types of reviews are suggested:

- A model appraisal by a non-technical reviewer to evaluate the model results;
- An in-depth peer review by experienced hydrogeologists and modellers; and
- A post-audit as a critical re-examination of the model when new data become available or the model objectives change.

This report represents an in-depth peer review of the reports described below. Model files were not examined, nor were any additional model runs performed.

The Guidelines also suggest a staged approach to reviewing, with a review occurring after each reporting stage. They provide guidance on seven main aspects of the modelling process relevant to this review, such as Planning, Conceptualisation, Reporting, etc. Within each phase, "Guiding

[1] Barnett, B., Townley, L.R., Post, V., Evans, R.E., Hunt, R.J., Peeters, L., Richardson, S., Werner, A.D., Knapton, A., Boronkay, A. (2012) Australian Groundwater Modelling Guidelines, Waterlines Report, National Water Commission, Canberra Australia, 191 pp.

Principles" provide an overarching intention for that stage of the modelling process. These seven aspects are addressed in detail in Section 2 with reference to the Ausenco model.

1.2 Review procedure

This report summarises several stages of work which NTEC and CDM Smith performed in review of the NBB model and the Bowen Gas Project EIS. The groundwater section of the EIS, and Ausenco's Appendices were compared to the draft reports received by NTEC during the initial review process. In this way, CDM Smith could confirm that changes suggested by NTEC were incorporated into the final submission, and the final documents were cross-checked against the now-released Australian Groundwater Modelling Guidelines.

As part of the initial review, considerable personal interaction occurred between Arrow, Ausenco and NTEC employees. Dr Lynn Reid of NTEC participated in several phone consultations with Dr Konrad Quast of Ausenco in July and August 2012, and visited the Brisbane-based modelling team in August 2012. NTEC also prepared three draft memoranda on the design and construction, the calibration, and the predictions of the NBB model. This review updates those findings to include the final EIS submission.

1.3 Documents reviewed

Several final EIS documents were reviewed for information on the groundwater model. In the list that follows, a phrase in brackets following the title is later used in the Discussion in Section 2. The following documents were reviewed:

1. Arrow Energy, Chapter 14 Groundwater. Part of Arrow Bowen Gas Project Environmental Impact Statement [Chapter 14].
2. Arrow Energy, Appendix L, Groundwater and Geology Technical Report [Appendix L]. Of particular relevance within this report are:
    a. Section 4.10 Conceptual Hydrogeological Model
    b. Section 7 Groundwater Model
    c. Section 8 Potential Impacts
3. Arrow Energy, Appendix M, Groundwater Model Technical Report [Appendix M]. This appendix contained several subreports:
    a. Ausenco-Norwest, Groundwater Model, Northern Bowen Basin Regional Model Impact Predictions, Queensland, Australia, for Arrow Energy Pty Ltd., October 10, 2012 (main body of report)
    b. Ausenco-Norwest, Technical Note Model Code Selection, Northern Bowen Basin Regional Model, Queensland Australia, for Arrow Energy Pty Ltd., May 1, 2012 (Appendix A)
    c. Ausenco-Norwest, Technical Note -- Geologic Model and Groundwater Model Importation, Northern Bowen Basin Regional Model, Queensland Australia, for Arrow Energy Pty Ltd., May 1, 2012 (Appendix B).
    d. Ausenco-Norwest, Technical Note: Groundwater Model Parameterisation and Calibration, Northern Bowen Basin Regional Model, Queensland, Australia, for Arrow Energy Pty Ltd., September 7, 2012 (Appendix C) [Appendix M Calibration]

e. Appendix D: Modelled Groundwater Drawdowns [Appendix M Results]

As discussed above, draft versions of portions of 3a, and all of 3c and 3d were also reviewed by NTEC Environmental Technology in June through September, 2012.

Section 2 Discussion

The structure of the EIS includes general information in the main body of the report, with technical appendices covering geology, groundwater, and the NBB model itself. As information relevant to the groundwater regime and numerical model is spread across several sections and sometimes included in multiple sections, the following discussion follows the ordering of the Australian Groundwater Modelling Guidelines and does not reflect the order presented in the BGP EIS.

2.1 Planning

Project planning is a key step in determining why a model is being built, what the model can achieve, and what information is needed to succeed. The Guiding Principles primarily relate to defining clear model objectives, determining an appropriate confidence-level classification, and revisiting the objectives regularly to ensure the modelling effort remains on track and produces useful results. The EIS report and the groundwater model are consistent with the suggestions and intent of the Australian Groundwater Modelling Guidelines, even though the information provided is presented in a distributed form, in the EIS and its Appendices.

In the context of this project, the NBB model objectives are clearly stated: to determine locations within unconfined and confined aquifers where predicted drawdown exceeds threshold levels established by the DEHP. The modelling objectives are also tied in to the assigned Class 1 confidence-level classification. A Class 1 model is suitable for predicting long-term impacts of proposed developments in low-value aquifers.

This lowest level of confidence classification is necessary for the NBB model primarily because of inadequate historical transient groundwater monitoring data. Higher levels of classification would require groundwater head measurements over a significant period of time in the affected and nearby aquifers, with spatial distribution in several locations of the model domain. In addition, the prediction period of over 100 years is more than 10 times as long as the available transient calibration data record of 8 years. In line with, and appropriate for, the Class 1 classification, the model does not pretend to be able to predict highly accurate groundwater responses to proposed activities across the entire Bowen Basin domain.

The NBB model objectives are related to the overall project objective of characterising the groundwater resources and hydrogeological environment of the Bowen Basin adjacent to the BGP. The project objectives are integral to the much broader EIS objective of investigating all environmental impacts of the BGP. Because the BGP project objectives are so broad, they do not directly address the modelling; however, the model is an essential tool for predicting long-term aspects of the proposed BGP. That said, the Guidelines would prefer that the model objectives directly address the project objectives, and vice versa.

2.2 Conceptualisation

Conceptualisation is the process of describing the groundwater system, based on interpreted geological and hydrological data and understanding of the physical stresses which drive the system. The conceptual model should be able to be used as a guide to development of a numerical model, in that it contains all essential features of the groundwater system. A numerical model need not completely reflect the conceptual model, in that further simplification may be necessary for computational reasons (Barnet et al., 2012).

The conceptualisation of the NBB area is good, and is primarily presented in Appendix L. A significant literature review has been completed which also covers previous numerical models. The aquifer system is adequately described, especially the hydrostratigraphy which references the DEHP classification system. The project team has presented piezometric surface maps of the major aquifers to help visualise the groundwater regime.

Because the BGP covers a number of disconnected tenures, the NBB region encompassing the entire project is necessarily quite large. Despite the extent, there are very few bores to provide groundwater measurements or temporal hydrographs, which limits the conceptualisation and eventual calibration of the numerical model.

The river system has been extensively investigated with the aim of understanding losing and gaining reaches and groundwater/surface-water interactions. The data quality of both groundwater bore and surface water flows is discussed.

The conceptualisation does discuss how this physical understanding will be represented in the numerical model. Some discussion of alternative conceptualisation of the effects of major faulting is presented.

2.3 Design and construction

The Guidelines provide six guiding principles on model construction. They alternate between stressing two points. The first desirable is adherence to the planning and conceptualisation phases, as well as developing a model of sufficient refinement in time and space to meet those objectives. Secondly, practical implementation of a model which should be as simple as possible in design, spatial and temporal discretization, and computer execution time to address the objectives.

The NBB model is well designed, and contains features not usually found in a Class 1 confidence-level classification. The discretisation has 1,500 m resolution horizontally and one layer per hydrostratigraphic unit vertically. While the cell size is considered somewhat large, given the extent of the NBB domain, the discretisation is appropriate. A horizontally rotated and vertically deformed grid enables better representation of faulting and stratigraphy, which is necessarily coarse given the grid size. The representation of the surface aquifers is appropriate, given the coarse discretisation. Temporal discretisation to monthly time periods is more than adequate, especially given the sparse hydrograph data.

The geologic model appears to be supported by multiple streams of evidence. Ten spatially distributed hydrologic properties were assigned: the horizontal and vertical hydraulic conductivity and any horizontal anisotropy; specific storage and specific yield; total and effective porosity; groundwater recharge as a percentage of precipitation; and the rate and extinction depth of evapotranspiration. Coal permeability was extensively detailed from Arrow's coring. The remaining hydraulic properties were assumed constant over the model domain.

The boundary conditions are consistent with the conceptual model and confidence-level classification. As the model domain is quite large, horizontal boundary conditions should not have an undue effect on predictions in the centre of the domain in the BGP. The description of the calculation of evapotranspiration is clear, and the methodology thorough and well-documented from independent sources. Net recharge is assigned based on zones defined by surficial geology.

Initial conditions for the predictive model are based on a steady state simulation. The model has adequate convergence criteria, and MODFLOW-SURFACT provides good solvers.

The choice of software is thoroughly justified, and the solution methodology and convergence criteria are appropriate. Although the model contains only single-phase flow of groundwater and neglects liberation of coal seam gas by depressurisation, the influence of two phase flow is likely to be small on the regional scale.

The model is appropriate for its chosen use. Some aspects of the conceptual model, such as the representation of faults and igneous intrusions, are necessarily simplified in this regional scale model. However, if future use of the model requires precise predictions in shallow aquifers, the model construction will need to be improved to capture the interrelationship between aquifers used by nearby stakeholders, such as farming and surface coal mining, and the deeper basin structure.

2.4 Calibration

Calibration is the process of adjusting model parameters and boundary conditions until simulated model results reflect measured field values. Sensitivity analysis investigates whether changing parameters makes a significant difference to model outcomes, both in historical simulations and future predictions. The Guidelines focus on understanding that parameters are always uncertain, and measurement values, quantity and quality and hydrogeological experience should guide calibration and sensitivity analysis. In particular, one Guiding Principle is that the calibration process should be designed to produce a model that works best for future predictions, rather than just to provide historical data matching.

Calibration of the model is briefly described in Appendix L and Appendix M, with exhaustive detail provided in the Appendix M Calibration. Appendix L, Section 7.4, provides a nice summary of the calibration procedure. The calibration procedure involved a manual adjustment of model parameters based on residual mismatch between observation and modelled results, calibration sensitivities, and the guidance of reasonable parameter value ranges.

The sensitivity results are deferred until Section 2.5.1, as they are based on predictive models.

2.4.1 Steady state calibration

The steady state reflects conditions experienced in the NBB pre-1980. This early date predates significant developments which impact groundwater, including surface coal mining.

The first step in calibration is to obtain a database of measurements, with some indication of the reliability of the data. The NBB model uses groundwater head data, quantitative stream baseflow, and qualitative spring elevations and groundwater flow directions at boundaries to calibrate the model in steady state. Quality control criteria are clearly laid out for selecting historical groundwater head measurements before 1980 from Queensland State Government sources. Multiple standing water level measurements in time at 482 bores were averaged to provide steady-state measurements, which also provided an estimate in the standard deviation of the permissible mismatch between observed and modelled heads. Five reaches of rivers within the model domain were used to quantitatively compare baseflow estimates. This use of river baseflows, or surface-water / groundwater flux estimates for calibration targets, is particularly commendable and beyond what is usually considered in a Class 1 model.

Although the uncertainty in temporal averaging was not used to weight the head measurement residuals, the steady state calibration of 3% scaled root mean square (SRMS) in groundwater heads can be considered good, with no obvious spatial or head-dependent trends in the errors. Calibration results were well-presented both graphically and descriptively. The gaining river reaches had modelled baseflows within ranges estimated by independent methods. Similarly, qualitative matches with existing springs were modelled; this result is also quite good given the large scale of the model domain and subsequent coarse vertical discretization.

Discussion of the model mass balance in the steady state calibration in Appendix M Calibration provides support for an accurate solution, and is very helpful for understanding the magnitude and interplay of hydrogeologic forces in the steady state model initial conditions. For example, the use of GHB boundary conditions in the conceptual model did not unduly influence numerical results. The steady state calibration and the mass balance are used as evidence that the alternative conceptual model of including regional faults as horizontal flow barriers was not justified from a calibration point of view.

2.4.2 Transient calibration

Transient calibration targets were derived from coal seam gas (CSG) production data from Arrow's nearby Moranbah Gas Project (MGP) over 8 years from 2003 to 2012. The pressure heads from CSG monitoring points were used to further calibrate hydraulic conductivity and specific storage. These updated parameters were re-used in the steady-state model to define a consistent starting condition for transient predictions. Although the modelled heads did not match the heads derived from transient CSG production, they did have the same trends.

The mismatch is to be expected as the production rates and pressures were derived from CSG wells which produce both water and gas as a result of pumping. This two-phase flow involves relative permeabilities to water and gas flow which are a function of water saturation in the aquifer. The single-phase MODFLOW-SURFACT model cannot represent this complex interplay. Moreover, the regional scale of the NBB model cannot reflect the small-scale effects of CSG generation measured in the production bores. The final model parameters correctly reflect ranges which are appropriate for basin-scale hydraulics rather than detailed gas/water flow near pumping CSG bores. For this reason, Ausenco refers to the transient calibration procedure as "verification" rather than "calibration." However, verification implies that independent data have been used to confirm model predictions, which is not the case with the calibration procedure described in the NBB model. Nonetheless, transient groundwater data are insufficient to perform a verification of the model.

2.5 Prediction and sensitivity

A numerical model is often used for predictive purposes, to "look into the future" to obtain the outputs required to meet the project objectives. The Guidelines suggest Guiding Principles for predictive modelling which again emphasize that modelling is an uncertain art, and that models should be carefully checked before results are accepted.

For the NBB model, the objectives are to determine the impact of the BGP CSG production on regional groundwater heads. The predictions from the NBB model are described in Section 14.7, Appendix L, sec 7.5, and extensively in section 7 of Appendix M, and Appendix D of Appendix M (Appendix M Results). Two scenarios were used for predictive simulations; in both cases, initial heads are assumed to be the pre-1980 steady state groundwater levels.

- A base case including only BGP CSG water production rates. Prediction begins in 2017 with 55 years of CSG production until 2072, and ends after an additional 50 years of groundwater system recovery prediction until 2122. The base case also included a sensitivity study on how faults may influence regional groundwater levels.
- A cumulative case including BGP CSG water production, and additional water production from the Arrow MGP and significant water production rates assumed from regional bores entitled to withdraw groundwater by Queensland (WERD). Historical water use from the MGP and WERD is simulated from 2003 to 2011, then projected BGP, MGP, and WERD production rates are simulated from 2012 to 2072, with groundwater recovery again predicted until 2122.

The locations and pumping rates of CSG water production used in the predictive model were carefully considered based on operational rules. The WERD rates were applied at the maximum allocated rate, although operational experience suggested that many groundwater users pump at an average rate of only 20% of allocation. The WERD rates, and therefore cumulative water production from regional users, are higher than likely to be used and significantly overshadow the projected CSG water production in the cumulative case.

Predicted drawdowns exceeding 2 or 5 metres are mapped in the coal seam and shallow aquifers at the end of CSG production as well as 50 years post-development for the base case prediction. These fundamental objectives are shown in Section 14, Appendix L, and Appendix M. The trigger thresholds of drawdown are further described in the text. The cumulative case drawdown predictions exceeding the trigger thresholds are also mapped and described in Appendix M.

Although the modelling objectives are met with the detailed mapping of aquifer impacts, additional information about the model results could have been included to provide better understanding of the dynamics of the groundwater system under the stress of CSG production. Water balance inputs and outputs to the potentially affected aquifers could have been quantified. Determining the source of the extracted water e.g. storage or influx from interburden aquitards, would help to check long-term conceptual behaviour of the aquifer system and ensure model realism. Time series of predicted drawdown at selected deep and shallow aquifer locations would allow validation of the modelling with future monitoring and enable aquifer users to understand the likely impacts of the project over time.

2.5.1 Sensitivity

The draft model reports discussed sensitivity analysis which was performed by comparing SRMS against multipliers applied to hydraulic conductivity, recharge rates, and evapotranspiration rates. The final EIS does not discuss this procedure during the calibration process, except to note that sensitivity analysis was utilised while manually adjusting model parameters.

The predictive simulations have three sensitivity scenarios to investigate the impact of vertical conductivity and specific storage on the horizontal and vertical propagation of groundwater drawdown. Sensitivity scenarios are well-chosen, and the discussion concerning the choice of sensitivity parameters versus calibrated values is clear and appropriate.

Because the sensitivity simulations were not calibrated against observations, only qualitative behaviour of the modelled system can be described. For two sensitivity simulations, the base case simulation is shown to be conservative, in that it produces larger or equivalent drawdown extents than the sensitivity simulations. The other sensitivity scenario demonstrates increased drawdown, but is not significantly different than the base case in shallow aquifers.

2.6 Uncertainty

Uncertainty analysis is suggested by the Guidelines because all models are approximations to reality. As the modelling process is governed by the project and model objectives, uncertainty estimates should also be framed in respect to those aims. Uncertainty increases when small-scale systems significantly influence the model results, and decrease when relative measures of impact are utilised, such as the difference between a base-case scenario and one with CSG pumping stresses. The Guidelines again are pragmatic, and recognize that uncertainty analysis can take considerable amounts of effort and time to accomplish.

The groundwater sections and appendices of the EIS discuss uncertainty in the hydraulic parameter data ranges and the numerical model. Three sources of uncertainty are proposed:

- Uncertainty in model conceptualisation and the simplifications required for numerical implementation
- Field measurements
- Spatial variability of rock properties which is not included in the constant parameters per layer in the model.

The structural uncertainty of the influence of faulting was addressed in the modelling process. Differing scenarios were modelled which included and excluded the regional scale faults. As significant differences were not found in predicted groundwater levels, the faults were not included in the final predictive scenarios. However, Appendix L correctly states that the other sources of predictive uncertainty were not assessed.

In line with the low Class 1 confidence-level classification of the NBB model, there are not overwhelming reasons to perform significant uncertainty analysis at this stage in the BGP project. The model is understood to be a regional scale model which cannot predict in fine detail. Arrow proposes to perform additional monitoring of groundwater levels and measure hydrostratigraphic properties with field testing. These data will be used to update the model in the future, which will likely increase the confidence-level classification and reduce uncertainty.

2.7 Reporting

The Guidelines suggest a staged approach to modelling, and also a staged approach to reporting. The guiding principles emphasize that reporting should be targeted to the audience, and presented as much as possible with clear graphical visualisations.

Reporting on the NBB model has been performed sequentially throughout the development of the model. Draft reports were produced by Ausenco and reviewed by NTEC at three stages of the modelling work:

- To describe the geologic model, hydrostratigraphic units conceptualisation, and gridding and model domain in Groundwater Vistas. A final version of this report is included as an appendix to Appendix M.

- To describe the parameterisation and calibration of the model. A final version of this report is also included as an appendix to Appendix M.

- To describe the predicted impacts of CSG production. A final version of this report is also included as an appendix to Appendix M.

An additional interim report on the choice of the modelling software is also included as an appendix to Appendix M.

The final reporting on the NBB model and the hydrogeologic characterisation of the BGP is contained in multiple reports: a more general discussion in Sections 13 and 14 of the EIS, more data and conceptualisation in Appendix L, and the detailed discussion of the numerical model in Appendix M and the attached interim reports.

In summary, the reporting for the NBB model is exhaustively documented. The reporting in Section 14 is appropriately aimed to a more general audience, and the figures are well designed and clear. The detailed discussions in Appendix M provide clear rationale and methodology for the numerical model.

Section 3 Conclusions

The Australian Groundwater Modelling Guidelines provide two checklists to help with reviewing a groundwater model. Table 9-1 of the Guidelines provides an overarching checklist to determine the suitability of a model, and is presented below. Appendix A of this report provides the detailed checklist derived from Table 9-2.

3.1 Suitability of the NBB model

The general checklist is addressed below, with the numbers derived from the order of Table 9-1 of the Guidelines.

1. *Are the model objectives and model confidence level classification clearly stated?* Yes, the NBB model plainly details the model objectives and confidence level classification. The objectives and classification are referred to throughout the document.

2. *Are the objectives satisfied?* Yes, the NBB model provides clearly delineated maps of locations where CSG production will significantly impact groundwater levels.

3. *Is the conceptual model consistent with objectives and confidence level classification*? Yes, the conceptual model is thorough and exceeds the Class 1 classification level.

4. *Is the conceptual model based on all available data, presented clearly and reviewed by an appropriate reviewer?* Yes, available data is inspected for the conceptual model. The conceptual model is well described. NTEC Environmental Technology provided a review of the conceptual model in 2012.

5. *Does the model design conform to best practice?* Yes, the model design is suitable for a regional scale model.

6. *Is the model calibration satisfactory?* Within the limitations of the available data, the model calibration is acceptable.

7. *Are the calibrated parameter values and estimated fluxes plausible?* Yes, parameters and flux outputs are plausible and well presented.

8. *Do the model predictions conform to best practice?* Yes, predictions and reporting are of a high standard.

9. *Is the uncertainty associated with the predictions reported?* Not directly. Data measurement uncertainty is presented and sensitivity to the fault scenarios are analysed. Prediction uncertainty is not quantitatively provided, however a Class 1 model is assumed to be less accurate than models with higher confidence-level classifications.

10. *Is the model fit for purpose?* Yes, the North Bowen Basin model prepared by Ausenco for Arrow's Bowen Gas Project is fit for the purpose of estimating groundwater impacts created by CSG pumping.

3.2 Conclusions

The NBB model created by Ausenco-Norwest for Arrow's Bowen Gas Project is a well-designed and well-executed numerical groundwater model. The conceptualisation of the groundwater flow regime includes information from multiple sources and represents the important stresses affecting groundwater flow in the region. Ausenco has chosen good software, and constructed the model to take into account complex structural geometry. The model discretisation is appropriate for a regional scale model. Parameterisation of hydraulic properties takes advantage of detailed information where available, and elsewhere considers properties to be constant by layer.

Calibration to steady-state groundwater measurements from before 1980 is well-considered and the model achieves a good fit to these measurements. Measurements are less extensive after this point in time, and there is little or no direct measurement of regional groundwater levels affected by coal seam gas production. This lack of data availability causes the model to have a confidence level classification of Class 1, whereas otherwise the model contains many features of a higher confidence-level.

Model predictions are appropriately designed and presented in maps which meet the model and project objectives to understand where CSG production impacts groundwater drawdown in excess of DEHP trigger guidelines. Sensitivity analysis considers the most uncertain parameters and generally indicates that the base case simulation is a conservative one in predicting the largest likely impacts.

The reliability of the model predictions is discussed in terms of the limitations of single-phase groundwater flow methodology and the regional scale of the model, including unmodelled local variations in properties. Local features such as coal mines are not included, nor are the influences of possible future climate change. A formal uncertainty analysis has not been performed. These restrictions are appropriate for a Class 1 model, and the predictions can be considered reasonable within the modelling assumptions and numerical methodology.

Appendix A – Peer Review Checklist

Table A-1: Checklist 9.2 from the Australian Groundwater Modelling Guidelines (Barnett et al., 2012).

Review Questions	Yes or No	Comments
OVERALL	TRUE	
1. Planning	**TRUE**	
1.1 Are the project objectives stated?	TRUE	Groundwater impact assessment
1.2 Are the model objectives stated?	TRUE	Clear objectives relating to UWIR thresholds and groundwater modelling guidelines.
1.3 Is it clear how the model will contribute to meeting the project objectives?	PARTIAL	No, not really for overall EIS, which is very vague. For groundwater impact assessment, Yes it is clear that modelling will be required to meet them.
1.4 Is a groundwater model the best option to address the project and model objectives?	TRUE	Yes for model objectives. Likely for project objectives.
1.5 Is the target model confidence-level classification stated and justified?	TRUE	Class 1 or better – is excluded from Class 2 by insufficient calibration data.
1.6 Are the planned limitations and exclusions of the model stated?	TRUE	Well-stated in relation to two-phase flow.
2. Conceptualisation	**TRUE**	Most of conceptualization is in Appendix L rather than Appendix M.
2.1 Has a literature review been completed, including examination of prior investigations?	TRUE	Yes, for geology, groundwater, and modelling. Table 2-2 in Appendix L is extensive.
2.2 Is the aquifer system adequately described?	TRUE	
2.2.1 hydrostratigraphy including aquifer type (porous, fractured rock ...)	TRUE	Well described in Appendix L
2.2.2 lateral extent, boundaries and significant internal features such as faults and regional folds	TRUE	Lateral extent is large to cover the disconnected leases.
2.2.3 aquifer geometry including layer elevations and thicknesses	TRUE	Both geologic and hydrogeologic descriptions. Separated by ages.
2.2.4 confined or unconfined flow and the variation of these conditions in space and time?	TRUE	Described for each aquifer age.
2.3 Have data on groundwater stresses been collected and analysed?	TRUE	
2.3.1 recharge from rainfall, irrigation, floods, lakes	TRUE	No direct measurements in this study but other studies cited and described.
2.3.2 river or lake stage heights	TRUE	Semi-arid climate; levels described in Appendix M.
2.3.3 groundwater usage (pumping, returns etc)	TRUE	Bore yields and comparison to rainfall shown
2.3.4 evapotranspiration	TRUE	Described conceptually and with use of 'excess water'
2.3.5 other?	TRUE	Springs
2.4 Have groundwater level observations been collected and analysed?	TRUE	
2.4.1 selection of representative bore hydrographs	TRUE	For different ages of aquifers
2.4.2 comparison of hydrographs	TRUE	Also within/without model area
2.4.3 effect of stresses on hydrographs	TRUE	Seasonality, but insufficient sampling frequency to draw conclusions

Review Questions	Yes or No	Comments
2.4.4 watertable maps/piezometric surfaces?	TRUE	Yes, in different aquifers, with inferred flow directions clearly shown
2.4.5 If relevant, are density and barometric effects taken into account in the interpretation of groundwater head and flow data?	TRUE	Convert pressure into heads
2.5 Have flow observations been collected and analysed?	TRUE	
2.5.1 baseflow in rivers	TRUE	Good inclusion in reports
2.5.2 discharge in springs	0.5	No springs in area, but some to southeast
2.5.3 location of diffuse discharge areas?	TRUE	Few wetlands in semi-arid region
2.6 Is the measurement error or data uncertainty reported?	TRUE	
2.6.1 measurement error for directly measured quantities (e.g. piezometric level, concentration, flows)	TRUE	True within bores, discussed with regard to flows
2.6.2 spatial variability/heterogeneity of parameters	TRUE	Discussion of precipitation, evapotranspiration, vertical permeability
2.6.3 interpolation algorithm(s) and uncertainty of gridded data?	TRUE	Some discussion about geological modelling; emphasis on vertical variability of permeability in coal seams
2.7 Have consistent data units and geometric datum been used?	FALSE	Some units non-standard: e.g. cumecs, chainage, millidarcies
2.8 Is there a clear description of the conceptual model?	TRUE	In Appendix L
2.8.1 Is there a graphical representation of the conceptual model?	TRUE	Cross sections
2.8.2 Is the conceptual model based on all available, relevant data?	TRUE	
2.9 Is the conceptual model consistent with the model objectives and target model confidence level classification?	TRUE	
2.9.1 Are the relevant processes identified?	TRUE	Model classification is limited only by data, not processes
2.9.2 Is justification provided for omission or simplification of processes?	TRUE	Data limitations discussed; some related to size of project
2.10 Have alternative conceptual models been investigated?	FALSE	Although there is some discussion in sensitivity analysis, especially with relation to faulting
3. Design and construction	**TRUE**	
3.1 Is the design consistent with the conceptual model?	TRUE	
3.2 Is the choice of numerical method and software appropriate (Table 4-2)?	TRUE	Long description in Appendix M
3.2.1 Are the numerical and discretisation methods appropriate?	TRUE	Finite difference is useful for water balance
3.2.2 Is the software reputable?	TRUE	State-of-the-art finite difference
3.2.3 Is the software included in the archive or are references to the software provided?	TRUE	Commercial code
3.3 Are the spatial domain and discretisation appropriate?	TRUE	
3.3.1 1D/2D/3D	TRUE	3D
3.3.2 lateral extent	TRUE	Large extent to cover all properties and basin-scale structures
3.3.3 layer geometry?	TRUE	18 layers
3.3.4 Is the horizontal discretisation appropriate for the objectives, problem setting, conceptual model and target confidence level classification?	TRUE	1,500m grid; cannot make finer in sub-regions given finite difference limitations
3.3.5 Is the vertical discretisation appropriate? Are aquitards divided in multiple layers to model time lags of propagation of responses in the vertical direction?	PARTIAL	Deformed grid is good choice but no additional discretisation in vertical direction

Review Questions	Yes or No	Comments
3.4 Are the temporal domain and discretisation appropriate?	TRUE	
3.4.1 steady state or transient	TRUE	Both steady state (for initial conditions) and transient
3.4.2 stress periods	TRUE	30 days
3.4.3 time steps?	N/A	Not discussed other than use of SURFACT's adaptive time stepping
3.5 Are the boundary conditions plausible and sufficiently unrestrictive?	TRUE	Good description in Appendix C of Appendix M
3.5.1 Is the implementation of boundary conditions consistent with the conceptual model?	TRUE	
3.5.2 Are the boundary conditions chosen to have a minimal impact on key model outcomes? How is this ascertained?	PARTIAL	Boundary edges based on geological model, which may not be hydrogeologically determined. Yes for a discussion of GHBs in the Surat Basin
3.5.3 Is the calculation of diffuse recharge consistent with model objectives and confidence level?	TRUE	Spatially distributed based on rainfall patterns
3.5.4 Are lateral boundaries time-invariant?	TRUE	
3.6 Are the initial conditions appropriate?	TRUE	
3.6.1 Are the initial heads based on interpolation or on groundwater modelling?	TRUE	Steady state model pre-1980 provides initial conditions for transient
3.6.2 Is the effect of initial conditions on key model outcomes assessed?	FALSE	But model outcomes subtract CSG versus nominal case
3.6.3 How is the initial concentration of solutes obtained (when relevant)?	N/A	Groundwater flow only
3.7 Is the numerical solution of the model adequate?	FALSE	
3.7.1 Solution method/solver	TRUE	SURFACT provides good solvers
3.7.2 Convergence criteria	TRUE	0.001 metres for steady state, 0.1 m for transient
3.7.3 Numerical precision	FALSE	No discussion
4. Calibration and sensitivity	**TRUE**	
4.1 Are all available types of observations used for calibration?	TRUE	
4.1.1 Groundwater head data	TRUE	482 bores in steady state; trends for transient
4.1.2 Flux observations	TRUE	Input/output on boundaries and gaining/losing reaches of rivers
4.1.3 Other: environmental tracers, gradients, age, temperature, concentrations etc.	TRUE	Springs and discharge elevations
4.2 Does the calibration methodology conform to best practice?	TRUE	Good steady state calibration results
4.2.1 Parameterisation	TRUE	Parameterisation is appropriate for large scale; in some vertical variability there is great detail
4.2.2 Objective function	FALSE	Not discussed, assumed least-squares from SURFACT
4.2.3 Identifiability of parameters	TRUE	More steady-state data than parameters, although storage is poorly identified as there is little transient groundwater data
4.2.4 Which methodology is used for model calibration?	FALSE	Trial and error assumed as no automatic mentioned
4.3 Is a sensitivity of key model outcomes assessed against?	TRUE	
4.3.1 Parameters	TRUE	Sensitivity analysis during calibration process and for Kv, Ss
4.3.2 Boundary conditions	TRUE	Horizontal flow barriers are considered
4.3.3 Initial conditions	FALSE	Steady state taken as initial conditions for transient
4.3.4 Stresses	TRUE	Uses cumulative pumping/impacts versus single scenarios

Review Questions	Yes or No	Comments
4.4 Have the calibration results been adequately reported?	TRUE	
4.4.1 Are there graphs showing modelled and observed hydrographs at an appropriate scale?	TRUE	Yes, also good maps
4.4.2 Is it clear whether observed or assumed vertical head gradients have been replicated by the model?	FALSE	Discussed in conceptualisation and in calibration summaries, but not in modelling results
4.4.3 Are calibration statistics reported and illustrated in a reasonable manner?	TRUE	Reported, graphs of steady state in appendix
4.5 Are multiple methods of plotting calibration results used to highlight goodness of fit robustly? Is the model sufficiently calibrated?	TRUE	Residual charts in three formats as well
4.5.1 spatially	TRUE	Hydrographs on maps
4.5.2 temporally	TRUE	Transient model is called a "verification"
4.6 Are the calibrated parameters plausible?	TRUE	Yes, generally lie within literature ranges
4.7 Are the water volumes and fluxes in the water balance realistic?	TRUE	Yes, very little effect from GHBs.
4.8 Has the model been verified?	FALSE	Verification of steady-state calibration involved adjusting storage parameters in the transient procedure. Not a true verification procedure of the transient model with independent data, but then again there is little transient data.
5. Prediction	**TRUE**	
5.1 Are the model predictions designed in a manner that meets the model objectives?	TRUE	Yes, maps clearly show thresholds
5.2 Is predictive uncertainty acknowledged and addressed?	FALSE	Acknowledged but not addressed
5.3 Are the assumed climatic stresses appropriate?	FALSE	Not considered, but reasonable assumption for Class 1 model
5.4 Is a null scenario defined?	TRUE	Yes, "Base Case" scenario
5.5 Are the scenarios defined in accordance with the model objectives and confidence level classification?	TRUE	Considers pumping and sensitivity scenarios
5.5.1 Are the pumping stresses similar in magnitude to those of the calibrated model? If not, is there reference to the associated reduction in model confidence?	TRUE	Class 1 refers to pumping stresses
5.5.2 Are well losses accounted for when estimating maximum pumping rates per well?	TRUE	Effects of large grid cells and single-phase flow are noted
5.5.3 Is the temporal scale of the predictions commensurate with the calibrated model? If not, is there reference to the associated reduction in model confidence?	TRUE	Class 1 refers to lack of calibration data in time
5.5.4 Are the assumed stresses and timescale appropriate for the stated objectives?	TRUE	
5.6 Do the prediction results meet the stated objectives?	TRUE	Predictions framed in terms of UWIR thresholds
5.7 Are the components of the predicted mass balance realistic?	TRUE	
5.7.1 Are the pumping rates assigned in the input files equal to the modelled pumping rates?	N/A	Cannot be determined in a model review
5.7.2 Does predicted seepage to or from a river exceed measured or expected river flow?	TRUE	Reported values are consistent with model
5.7.3 Are there any anomalous boundary fluxes due to superposition of head dependent sinks (e.g. evapotranspiration) on head-dependent boundary cells (Type 1 or 3 boundary conditions)?	FALSE	No anomalous fluxes obvious
5.7.4 Is diffuse recharge from rainfall smaller than rainfall?	TRUE	Recharge and ET are basically balanced

Review Questions	Yes or No	Comments
5.7.5 Are model storage changes dominated by anomalous head increases in isolated cells that receive recharge?	FALSE	No obvious problems
5.8 Has particle tracking been considered as an alternative to solute transport modelling?	N/A	No solute transport modelling
6. Uncertainty	**FALSE**	Not considered except descriptively
6.1 Is some qualitative or quantitative measure of uncertainty associated with the prediction reported together with the prediction?	FALSE	Effects of uncertainty are not considered part of the analysis
6.2 Is the model with minimum prediction-error variance chosen for each prediction?	TRUE	
6.3 Are the sources of uncertainty discussed?	TRUE	Yes, discussions throughout albeit non-quantitative
6.3.1 measurement of uncertainty of observations and parameters	TRUE	
6.3.2 structural or model uncertainty	TRUE	Effect of dykes considered
6.4 Is the approach to estimation of uncertainty described and appropriate?	FALSE	Not considered
6.5 Are there useful depictions of uncertainty?	FALSE	Not considered
7. Solute transport	**N/A**	Described conceptually but not modelled
8. Surface water–groundwater interaction	**TRUE**	
8.1 Is the conceptualisation of surface water–groundwater interaction in accordance with the model objectives?	TRUE	Suitable for Class 1
8.2 Is the implementation of surface water–groundwater interaction appropriate?	TRUE	Yes, or better than is needed
8.3 Is the groundwater model coupled with a surface water model?	FALSE	
8.3.1 Is the adopted approach appropriate?	TRUE	Yes, physical scale is too large for detailed surface water model
8.3.2 Have appropriate time steps and stress periods been adopted?	N/A	
8.3.3 Are the interface fluxes consistent between the groundwater and surface water models?	TRUE	Model predicts gaining/losing stream sections

Appendix B – Disclaimer and Limitations

This report has been prepared by CDM Smith Australia Pty Ltd (CDM Smith) for the sole benefit of Arrow Energy Pty Ltd for the sole purpose of providing review on the groundwater numerical model of the Bowen Basin.

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If further information becomes available, or additional assumptions need to be made, CDM Smith reserves its right to amend this report.

Appendix E
Arrow Energy Bowen Gas Project Parameter and Predictive Error/Uncertainty Assessment, Northern Bowen Basin Regional Groundwater Model, Queensland, Australia

Supplementary Groundwater Assessment
Arrow Energy Bowen Gas Project
Supplementary Report to the EIS

PARAMETER AND PREDICTIVE ERROR/UNCERTAINTY ASSESSMENT NORTHERN BOWEN BASIN REGIONAL GROUNDWATER MODEL QUEENSLAND, AUSTRALIA

Submitted to:
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EXECUTIVE SUMMARY

Groundwater drawdown related to Arrow Energy Pty Ltd's Bowen Gas Project coal seam gas production was modelled by Norwest Corporation using MODFLOW-SURFACT^{TM} and the Groundwater Vistas 6 interface in support of the Bowen Gas Project Environmental Impact Statement. Following the completion of initial model predictions for the Environmental Impact Statement, Norwest Corporation began an assessment of model parameter predictive error/ uncertainty and data worth in order to better understand the model limitations and to identify data gaps. This report presents the initial assessment findings, and results from Null Space Monte Carlo (NSMC) and Pareto front analyses. Recommendations to improve the model confidence level classification and the robustness of the model predictions are provided.

The Parameter Estimation (PEST) software package and the associated GENLINPRED utility were used to assess the steady-state BGP EIS model and provide an updated calibrated parameter set. The assessment was implemented with respect to the existing BGP EIS model, which does not incorporate pilot points. Therefore, PEST was used with the existing defined parameter zones and reaches and not with pilot points. The results indicate groups of parameters which can be predicted based on existing observations, and points to data gaps that if filled can result in reducing predictive error.

The initial findings indicate that the model parameters associated with alluvium and Tertiary basin infill in the upper two model layers is associated with the least amount of predictive error/uncertainty and supported by the data worth of river reach fluxes. The parameters having the greatest predictive error/uncertainty are the majority of the vertical hydraulic conductivities and horizontal hydraulic conductivities in the deeper model layers representing Permian formations and are areas of focus for future data collection.

Parameters determined to have a high degree of predictive uncertainty from the initial PEST simulations and GENLINPRED analysis were not used in NSMC and Pareto front analysis. The results of the NSMC and Pareto front analyses indicate that the BGP EIS base case is overall conservative in estimates of predicted drawdown associated with BGP production, and the probability of 2 meters or more drawdown within the shallow alluvial and Tertiary unconfined aquifers of the Bowen Basin resulting from BGP production is low. The BGP EIS base case results are conservative in that the drawdown extent and magnitude are at the higher end of predictions supported by the NSMC analysis and the majority of NSMC cases produced lower predicted drawdown areal extents and maximums at the end of CSG production.

1 INTRODUCTION

Norwest developed the Northern Bowen Basin (NBB) groundwater flow model in support of the Bowen Gas Project (BGP) Environmental Impact Statement (EIS) for Arrow Energy Pty Ltd (Arrow). The groundwater flow model is referenced from this point forward as the BGP model. The current version of the BGP model[1] is based on the data and basin knowledge existing at the time of its development, which enabled construction of a model fit for purpose at a Class 1 confidence level as defined in the 2012 Australian groundwater modelling guidelines (Barnett et al. 2012)[2].

As new data become available through additional coal seam gas (CSG) and monitor well drilling and testing, and subsequent data interpretation, the BGP model can be updated to include the most up-to-date information, making it a more robust simulator providing greater confidence in predictions, therefore increasing the confidence level classification. Achieving a higher level of confidence based on the 2012 groundwater modelling guidelines will make the model predictions more defensible to regulatory authorities and stakeholders and applicable at a more local scale.

The parameter predictive error/uncertainty and data worth in the BGP steady-state model were partially assessed using PEST and associated utilities to show the model's capabilities and to point out areas of the model with additional data needs. This helps focus on areas of new data gathering. This analysis will also demonstrate that error/uncertainty analysis of both parameters and predictions have been undertaken as part of the EIS process.

1.1 EIS BGP Model Background

A brief description of the model is provided here. The BGP EIS and supplemental model report provide a detailed review of the conceptual hydrogeologic conceptual model and numerical model development.

The BGP groundwater flow model was developed in MODFLOW-SURFACT™ using the Groundwater Vistas 6 (GV) interface.

The model has 18 layers on a constant 1,500 m by 1,500 m grid cell size. This was an optimized resolution, based on the regional nature of the EIS, the typical horizontal production well length, limitations on the available information, and to effectively manage simulation time so as to produce acceptable results within a reasonable time frame.

[1] Ausenco - Norwest. 2012. *Groundwater Model, Northern Bowen Basin Regional Model Impact Predictions, Queensland, Australia.* Submitted to Arrow Energy, 10 October, 2012.

[2] Barnett, B., L.R. Townley, V. Post, R.E. Evans, R.J. Hunt, L. Peeters, S. Richardson, A.D. Werner, A. Knapton, and A. Boronkay. 2012. *Australian groundwater modelling guidelines*, Waterlines Report Series No. 82, National Water Commission, Canberra, 191 pp.

Additional model simulations and or scenarios may be needed to generate results to answer stakeholder questions or concerns arising following consultation of the EIS. However, at the time of writing this document the potential questions or concerns that may arise are not known. Therefore, the predictive error/uncertainty and data worth assessment presented here are focused on the model parameters as a whole without regard to any specific area.

1.2 PEST Introduction

PEST is a software package for parameter estimation and error/uncertainty analysis of computer models[3]. It is widely used in the groundwater modelling community and understood by regulatory agencies.

PEST is model independent and makes use of any model that reads its parameter input files and writes its model outcome output files in ASCII format. PEST adjusts model parameters to achieve a minimum difference between actual measurements and model generated output. This is done using the Gauss-Marquardt-Levenberg method to make its estimations and for nonlinear models, such as the BGP model, it is an iterative process requiring multiple model runs. A single PEST simulation may be as few runs as one run for each parameter being estimated to several thousand runs to reduce an objective function to a user specified value. As described in the user manual, PEST can be subdivided into three functionally separate components:

- Parameters/excitations
- Observations
- Nonlinear estimation and predictive analysis algorithm

Real world observations being matched by the model are weighted. PEST minimises the weighted sum of squared residuals, also known as the objective function or phi. The weightings are assigned to observations by the user and can be used to make some observations more important than others in meeting a specified objective function. Weightings can also be applied to different types of observations if the different types of observations also have different orders of magnitude in value, such as the two different types used in the BG model: head observations and river flux observations. The weights in this case can be assigned to these observations to reduce the potential for one type of observation with larger values to dominate the parameter estimation process just because the numbers are large.

[3] Dougherty, J. 2002. PEST Model-Independent Parameter Estimation User Manual: 5th Edition. Queensland Australia: Watermark Numerical Computing.

1.2.1 PEST Modes

PEST is parameter estimation software with a focus on data interpretation, model calibration and predictive analysis. PEST can be run in different modes depending on the model anticipated outcome and focus. The modes include:

- Parameter Estimation (calibration)
- Regularization
- Predictive Analysis
- Pareto

PEST adjusts model parameters to achieve a minimum difference between actual measurements and model generated output. The traditional use of PEST is to calibrate a model in "parameter estimation mode" where-by an objective function comprised of the sum of weighted squared deviations or residuals are minimized, known as phi.

PEST can also be run in "regularization mode" which is a variation of the traditional parameter estimation or calibration mode, but uses a more complex set of algorithms to address complex models with many different parameters that may lead to non-unique solutions when used with the traditional analysis. There are different types of regularization including SVD and SVD-Assist which are mentioned here, but a detailed review is beyond the scope of this document.

While the goal of the parameter estimation process of PEST is to lower the objective function (phi), the goal in "predictive analysis mode" in PEST aims to maximise or minimise a specified prediction while maintaining the model in a calibrated state with exceeding a specified objective function level. The role of model calibration is achieved using parameter estimation and or regularization modes the predictive analysis mode is used in data interpretation.

The "Pareto" mode in PEST is used to explore a model's predictive uncertainty. The Pareto mode analysis makes use of a "tradeoff curve", also known as a "Pareto front", between two objective functions by varying parameters. This mode is used when an objective function possess two components that cannot be simultaneously minimised. The Pareto front results provide quantitative bounding probabilities through multiple simulations, and allow the calculation of predictive confidence intervals.

The mode chosen in PEST is implemented by setting the PESTMODE variable in the PEST control file to "estimation", "regularization", "prediction" or "Pareto".

For the work described in this document, PEST was run in regularization mode and subsequently in estimation mode. The regularization simulations used a subset of the model parameter values for hydraulic conductivity, ET, ET extinction depth, and recharge zones.

This subset was chosen to primarily include the conductivity and recharge zones with sparse calibration data which were expected to have lower impact on the model calibration. This was done as a screening step. The parameters values estimated from this were accepted and the model was updated. This work is described in Section 2.2.

1.2.2 PEST Output

PEST provides different results depending on which simulation mode is chosen. However, as discussed in section 1.2.1, PEST is primarily used to estimate parameter values by matching observations with a resulting minimum objective function and thus outputs an optimized set of model parameters.

At the end of a PEST simulation, being comprised of potentially hundreds of individual runs, parameter and observation sensitivities are written to output files. PEST observation sensitivities are not typically as useful as parameter sensitivities. Parameter sensitivities reported by PEST are specifically parameter composite sensitivities. Parameter composite sensitivities are the calculated for each model parameter by PEST obtained from the Jacobian matrix modulated by the weight attached to each observation divided by the number of observations. The parameter composite sensitivities are the sensitivity of each individual parameter with respect to all observations. PEST also provides parameter composite scaled sensitivities, also known as relative composite sensitivities, or these can be calculated outside of PEST from composite sensitivities. The composite scaled sensitivities are the product of a parameter's composite sensitivity multiplied by its value or the absolute log of the parameter value if the parameter is log transformed. The composite scaled sensitivity provides a measure of composite model outcomes with respect to a fractional change in the value of the parameter.

PEST also outputs parameter correlation coefficients (PCC) and parameter 95% confidence intervals (PCI) when run in estimation (calibration) mode. When run in regularization mode the PCC and PCI statistics cannot be calculated. The PCC values indicate which parameters might be correlated to one another such that a unique value cannot be estimated because the changes in one parameter can be offset the changes in another parameter and the ratio of the two can be varied such that no effect on model outcome is observed. The PCI values indicate the uncertainty associated with a parameter assuming linearity exists and do not take into account the user assigned upper and lower bounds. The PCI values may be extremely large if the parameters are correlated and not uniquely estimated based on the existing observation dataset.

The sensitivity of the full BGP EIS parameter set was evaluated for 1) only the head observations, 2) the combined head and river reach flux observations. Highly correlated parameter pairs were identified and 95% confidence intervals were calculated for each parameter. This work is described in Section 2.3.

1.2.3 GENLINPRED Using PEST Results

The GENLINPRED utility uses PEST output was used to generate parameter identifiabilites (define) based on the previous PEST runs. GENLINPRED uses the PEST control file, and the PEST generated Jacobian matrix and sensitivities to calculate parameter identifiability and predictive uncertainty achieved through calibration.

Parameter identifiabilty is defined by Doherty and Hunt[4] as "the capability of model calibration to constrain parameters used by the model.", and quantitatively defined as "the direction of cosine between a parameter and its projection onto the calibration solution space." The relative uncertainty reduction provided by GENLINPRED indicates the extent to which the calibration process reduces parameter uncertainty during estimation relative to pre-calibration level. Together these statistics provide insight into the ability to uniquely estimate parameters of interest through calibration. Parameter sensitivities provide insight into identifiable parameters but do not take into account parameter correlations. Parameter correlations can make a parameter unidentifiable because as one parameter is changed to match observations another can be changed offsetting the results of the changes related to the first, and the correlated parameters can be varied in ratios without any effect on model outcomes. Parameter identifiability and relative parameter reduction error allow for parameter correlation. These statistics are qualitative and are reported as a value between zero, completely non-identifiable and no reduction in calibration error, and one, being completely identifiable and providing error reduction through calibration. Thus, identifiability values close to 1 show that a parameter can be estimated accurately with the observation data provided. However, a value of 1 for identifiability only indicates that the null space contribution to the parameter estimation error is zero, while measurement noise still contributes to the parameter estimation error.

The results of the GENLINPRED analysis indicate which parameters can be accurately predicted with the observation data provided. This work is described in Section 2.4.

1.2.4 PEST Inputs

The two key inputs to PEST are observation data and parameters. For this interim report the focus of the assessment was on the steady-state model and included two types of model observations and parameters.

<u>Observation Data (487 total)</u>

- Bore head observations (482 values grouped by layer)
  - Layer 1 – 269 Alluvial Targets (Groups Head 1 and 19)
  - Layer 2 – 160 Tertiary Targets (Group Head 2)
  - Layer 4 – 3 Rewan Formation Targets (Group Head 4)
  - Layer 5 – 3 RCM Targets (Group Head 5)

[4] Doherty, J. And Hunt, R. 2009. Two statistics for evaluating parameter identifiability and error reduction. Journal of Hydrology 366, 119-127.

- Layer 9 – 19 FCCM Targets (Listed only as Permian) (Group Head 9)
- Layer 18 – 28 Back Creek Group Targets (Group Head 18)

- River cumulative reach flux values (5 values/reaches - Figure 1-1, Group Flux)
    - Bowen River (single reach)
    - Isaac-Connors River System (4 reaches)

Parameters (Up to 113 used in PEST)

- Horizontal conductivity (kx - 40 zones)
- Vertical conductivity (kz - 40 zones)
- Recharge rates (r - 17 zones)
- Evapotranspiration rates (ET rate or et - 4 zones - Figure 1-1)
- Evapotranspiration extinction depths (ET extinction depth or ed - 4 zones - Figure 1-1)
- General head boundary conductance (ghc - southern boundary 4 zones - Figure 1-1)
- General head boundary head (gh - southern boundary 4 zones - Figure 1-1)

The parameter zones for hydraulic conductivity and recharge are associated with specific geologic formations and occur in one or more model layers and are referred to throughout the report as related to PEST results (Table 1.1).

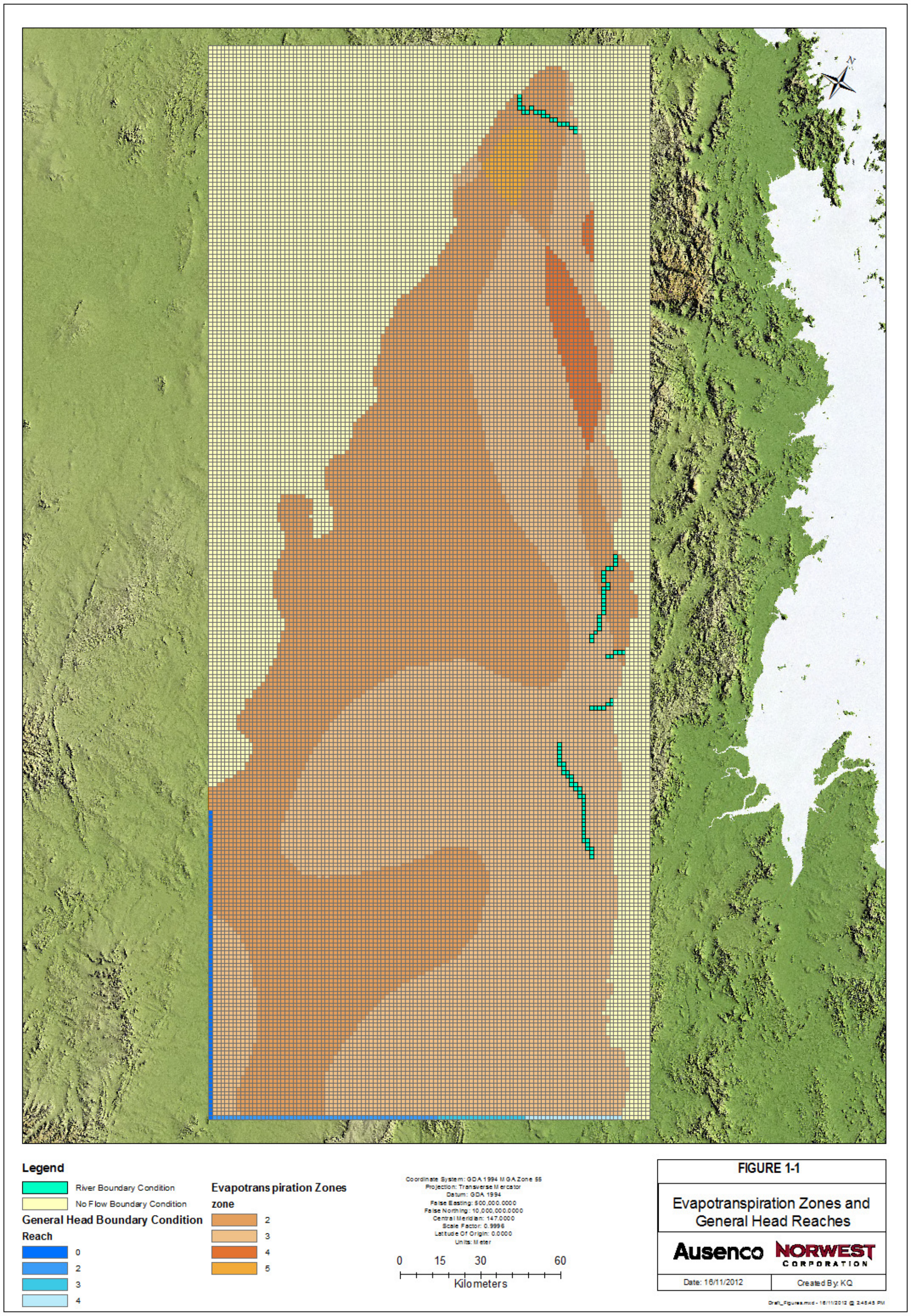
There are four general head boundary zones: gh0, gh2, gh3, and gh4, all of which are along the southern boundary of the basin (Figure 1-1), and there are four evapotranspiration zones defined in the model: et2, et3, et4, and et5 with zones et2 and et3 covering the majority of the basin (Figure 1-1).

All simulations were run using log-transformed parameter values, parameter upper and lower bounds were assigned based on values reported in the BGP EIS conceptual hydrogeologic model, and approximate standard deviations were assigned by taking the difference in the upper and lower bounds and dividing by four. Additionally, all models were run with a head close convergence criteria of 0.001 m.

TABLE 1.1
MODEL HYDRAULIC CONDUCTIVITY AND RECHARGE PARAMETER ZONES WITH ASSOCIATED GEOLOGIC FORMATIONS AND PRIMARY LAYERS

Primary Model Layer	Age	Formation	Model Zone	Notes
1	Quaternary	River Alluvium (Nebo Area)	1	
1	Quaternary	River Alluvium (Basin Wide)	2	
1	Quaternary	River Alluvium (SW area of model)	28	Zone 28 represents hydraulic conductivity only, while zones 1 and 2 are used to represent recharge in the same area.
1,2	Quaternary	Colluvium	3	
1,2	Tertiary	Basalt Flows	4	
1,2	Tertiary	Duaringa Fm	5	
1,2	Tertiary	Suttor Fm	6	
1,2	Tertiary	Emerald Fm	7	
1,2	Tertiary	Ferricrete	26	
1,2	Tertiary	Intrusives	27	
1,2	Tertiary/Triassic	Moolayember Fm	8	
1,2	Permian Outcrop	Blackwater Group	25	
3	Triassic	Clematis Group (Clematis Sandstone)	9	
4	Triassic	Rewan Fm	10	
5,6,7	Late Permian	Rangal Coal Measures (RCM)	11,12,13, 31-36	RCM recharge represented by zone 13 only in layer 1. For hydraulic conductivity zone 12 represents interburden, all others represent RCM coal.
8,9,10	Late Permian	Fort Cooper Coal Measures (FCCM)	14,15,16	FCCM recharge represented by zone 16 only in layer 1. For hydraulic conductivity zones 14 and 16 represent interburden, zone 15 represents lumped FCCM coal.
11,12,13,14,15,16,17	Late Permian	Moranbah Coal Measures (MCM)	17-23, 41-46	MCM recharge represented by zone 23 only in layer 1. For hydraulic conductivity zones 18, 20 and 22 represent interburden, all other represent MCM coal.
18	Middle Permian	Back Creek Group	24	

FIGURE 1-1
BOWEN GAS PROJECT STUDY AREA



2 PEST AND GENLINPRED RESULTS

The Parameter Estimation (PEST) software and associated data analysis utilities were used to assess steady-state calibration parameter sensitivities, errors, and uncertainties in the BGP EIS base case model.

2.1 PEST SIMULATIONS

In order to better understand the BGP EIS model behaviour, predictions, and data gaps, several PEST simulations were run using the current model in steady-state.

The PEST simulations included the following:

1) Parameter Estimation Regularization Mode
   a. Head targets
   b. Hydraulic horizontal and vertical conductivity zones
   c. ET rate zones and associated extinction depths
   d. Recharge zones
2) Parameter SVD-Assist Regularization
   a. Head targets
   b. Cumulative river flux targets
   c. Hydraulic horizontal and vertical conductivity zones
   d. ET rate zones and associated extinction depths
   e. Recharge zones
   f. General head boundary conductance
   g. General head boundary heads
3) Parameter Estimation Mode (Calibration) without Regularization
   a. Head targets
   b. Hydraulic horizontal and vertical conductivity zones
   c. ET rate zones and associated extinction depths
   d. Recharge zones
   e. General head boundary conductance
   f. General head boundary heads
4) Parameter Estimation Mode (Calibration) without Regularization
   a. Same as #3 plus Cumulative river flux targets

2.2 PEST REGULARIZATION SIMULATION

The parameters estimated from the first simulation incorporating regularization were accepted and the model was updated with the calibrated values. This was a first attempt at identifying automated calibration results using PEST with the BGP ESI model. The observations were all provided an initial weight of 1 and setup only in a single lumped observation group.

This first simulation was set up to primarily include those conductivity zones that are not associated with the large number of head calibration points in layer 1 (including alluvium, colluvium, basalt and Tertiary sediments) to calculate the sensitivity of the other formation-assigned properties on the head calibration targets, under the assumption that the alluvium and basalt layers would dominate the sensitivity analysis because the majority of head targets are in these model formations. Similarly recharge zones 1 and 2, which are associated with the alluvial aquifer system recharge, were not included in the first PEST simulation because they were expected to dominate the sensitivity analysis.

Overall, the PEST simulation was successfully implemented and converged. However, the resulting final objective function was very high with a phi of 4.4E4.

2.2.1 PEST Regularization Parameter Sensitivities

The results of this simulation indicated numerous insensitive parameters relative to the highest sensitivities associated with ET extinction depth parameter zones ed2 and ed3 (Figure2-1). The large number of insensitive parameters is due to the majority of calibration targets being in the upper layers 1 and 2, i.e. within the alluvium, colluvium and basalt. The changes to hydraulic conductivity values in zones within the deeper layers have less of an impact on matching head observations and thus are less sensitive relative to parameters ed2 and ed3. However, it is clear from this simulation, the ET extinction depths, specifically in zones 2 and 3, have the greatest sensitivity to model predictions with composite sensitivity values of 0.87 and 0.62 and composite scaled sensitivity values of 1.02 and 0.71 respectively. ET zones 2 and 3 are the largest zones covering the majority of the model domain. The remaining parameters have relatively lower sensitivity values approaching zero indicating potential problematic parameters in PEST estimations.

The composite sensitivity values are significantly lower for the majority of parameters compared to the composite scaled sensitivity values. This shows the relative individual parameter sensitivities based on their estimated value given the range of values vary for the different types of parameters. This shows that while some parameters are insensitive relative to the entire parameter set that their relative individual sensitivity to the available observations is higher and are more likely to be estimated by the observation data set.

2.2.2 PEST Regularization Parameter Value Changes

The PEST results were allowed to change the selected parameters to fit the lowest objective function. This resulted in the adjustment of each parameter included in the PEST simulation

(Figures 2-2 to 2-8). The majority of parameters were only slightly adjusted. However, while the vertical hydraulic conductivity for zone 16 (kz16) had a low sensitivity of 0.047, the value associated with kz16 was associated with the greatest change, by a factor change of 798, from the initially assigned value of 1.0E-8 to 7.9E-6.

Several parameters were only increased by a factor of less than 2 or decreased by a factor of 0.5 or lower.

Several other parameters were increased by a factor of greater than 2:

- MCM interburden (kz18)
- Back Creek Group (kz24)
- Basalt (r4)
- Duaringa Fm (r5)
- Rewan Fm (r10)
- MCM coal seam outcrop/subcrop (r13)

and others decreased by a factor of 0.5 or less:

- Back Creek Group (kx24)
- Colluvium (r3)
- Permian Black Water Group (r25)
- RCM coal seams (kx33)
- RCM coal seams (kx34)
- et2
- et3

FIGURE 2-1
PEST COMPOSITE AND COMPOSITE SCALED SENSITIVITIES AFTER FIRST PEST RUN

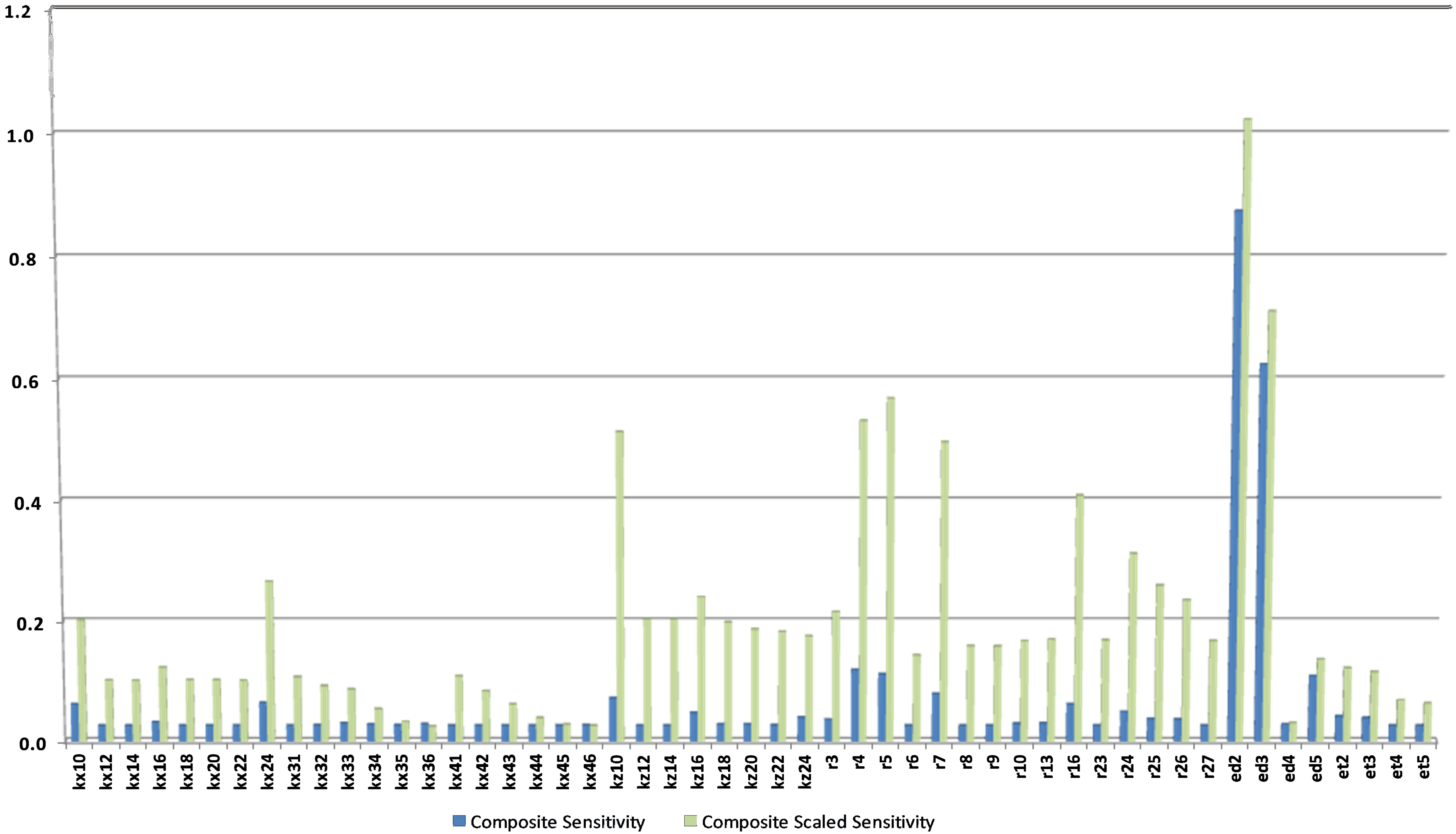


FIGURE 2-2
INTERBURDEN HORIZONTAL HYDRAULIC CONDUCTIVITY CHANGES RELATIVE TO FIRST PEST RUN

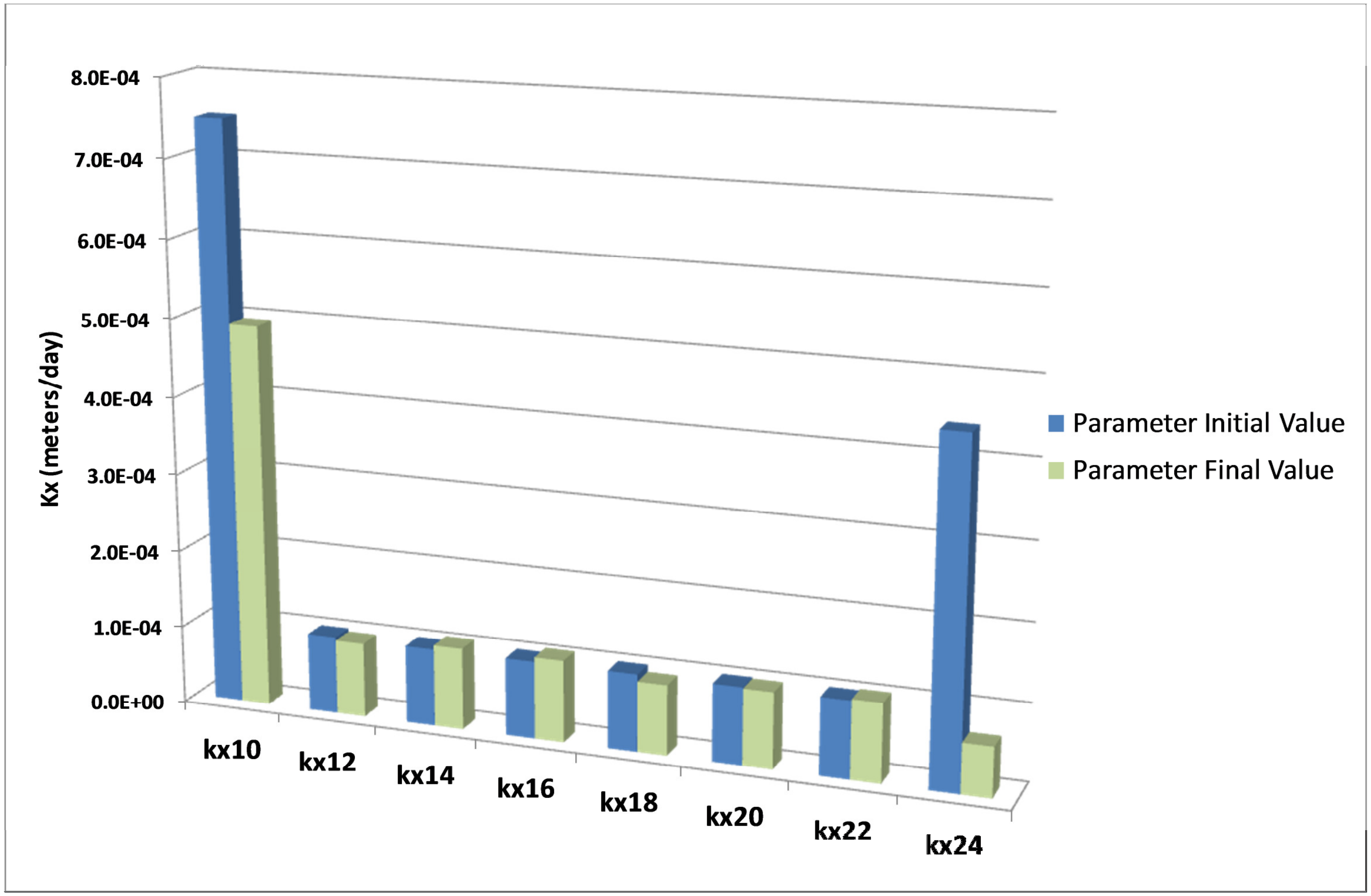


FIGURE 2-3
INTERBURDEN VERTICAL HYDRAULIC CONDUCTIVITY CHANGES RELATIVE TO FIRST PEST RUN

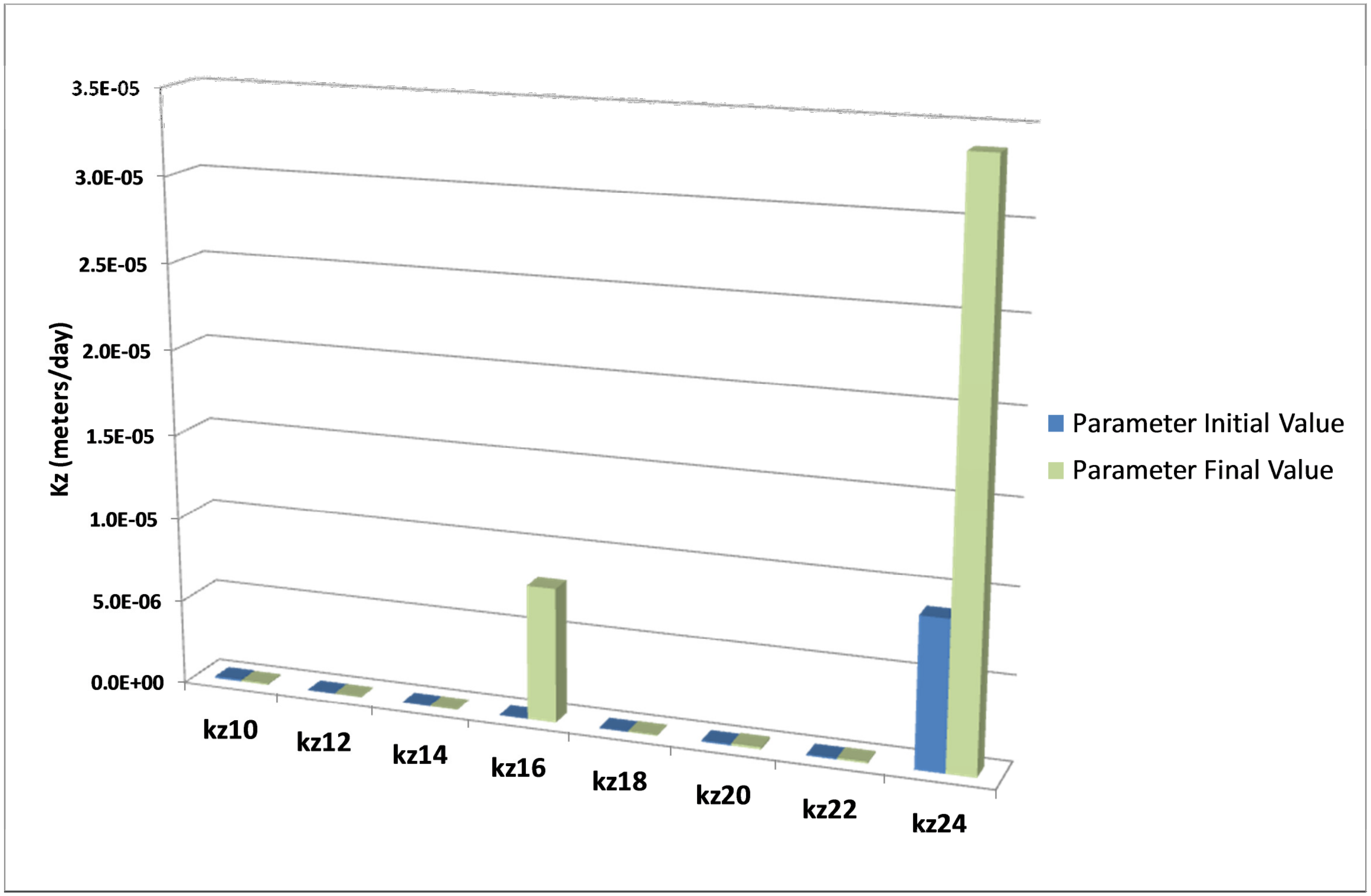


FIGURE 2-4
SELECTED INTERBURDEN VERTICAL HYDRAULIC CONDUCTIVITY CHANGES RELATIVE TO FIRST PEST RUN

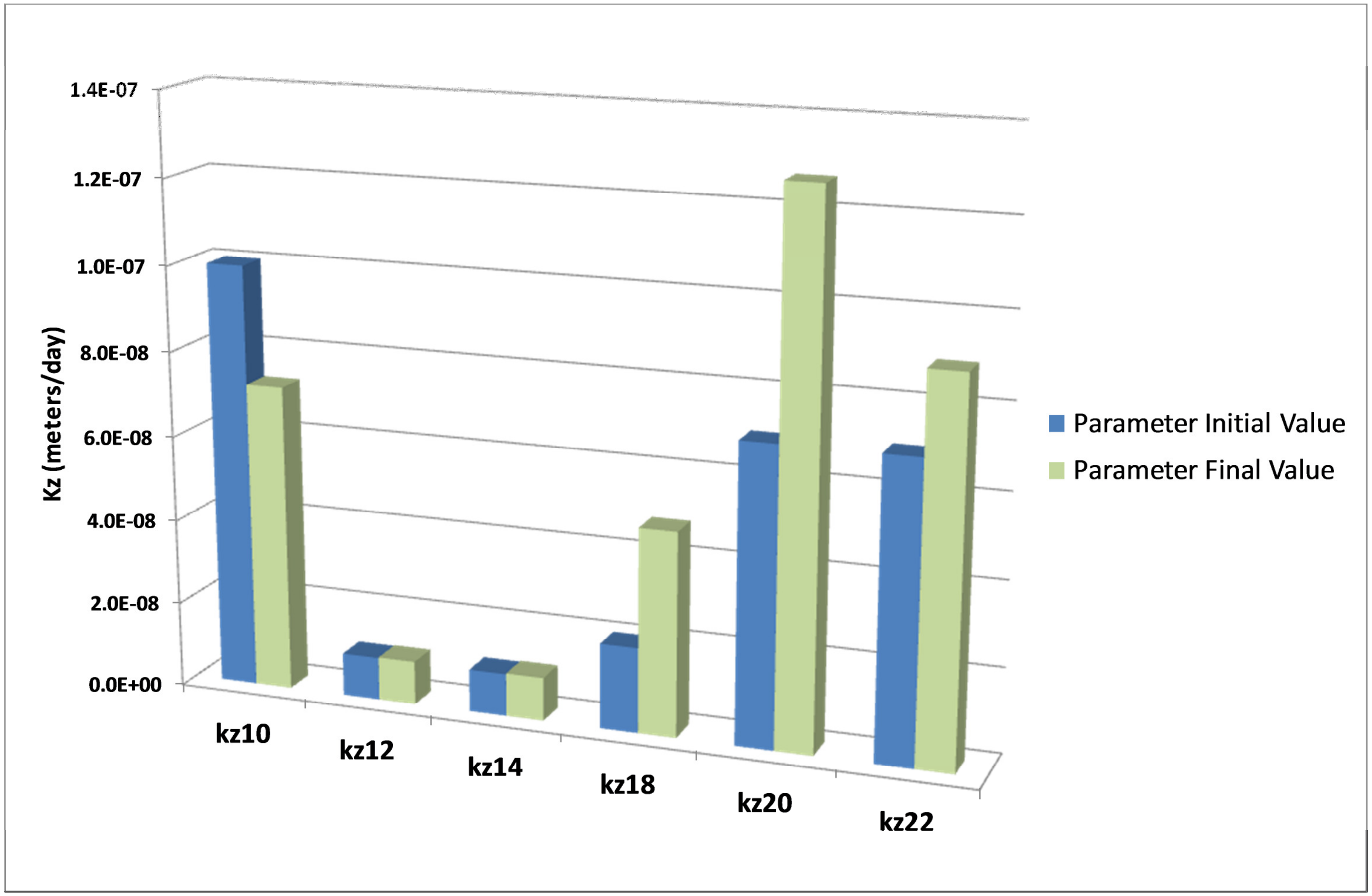


FIGURE 2-5
RECHARGE RATE CHANGES RELATIVE TO FIRST PEST RUN

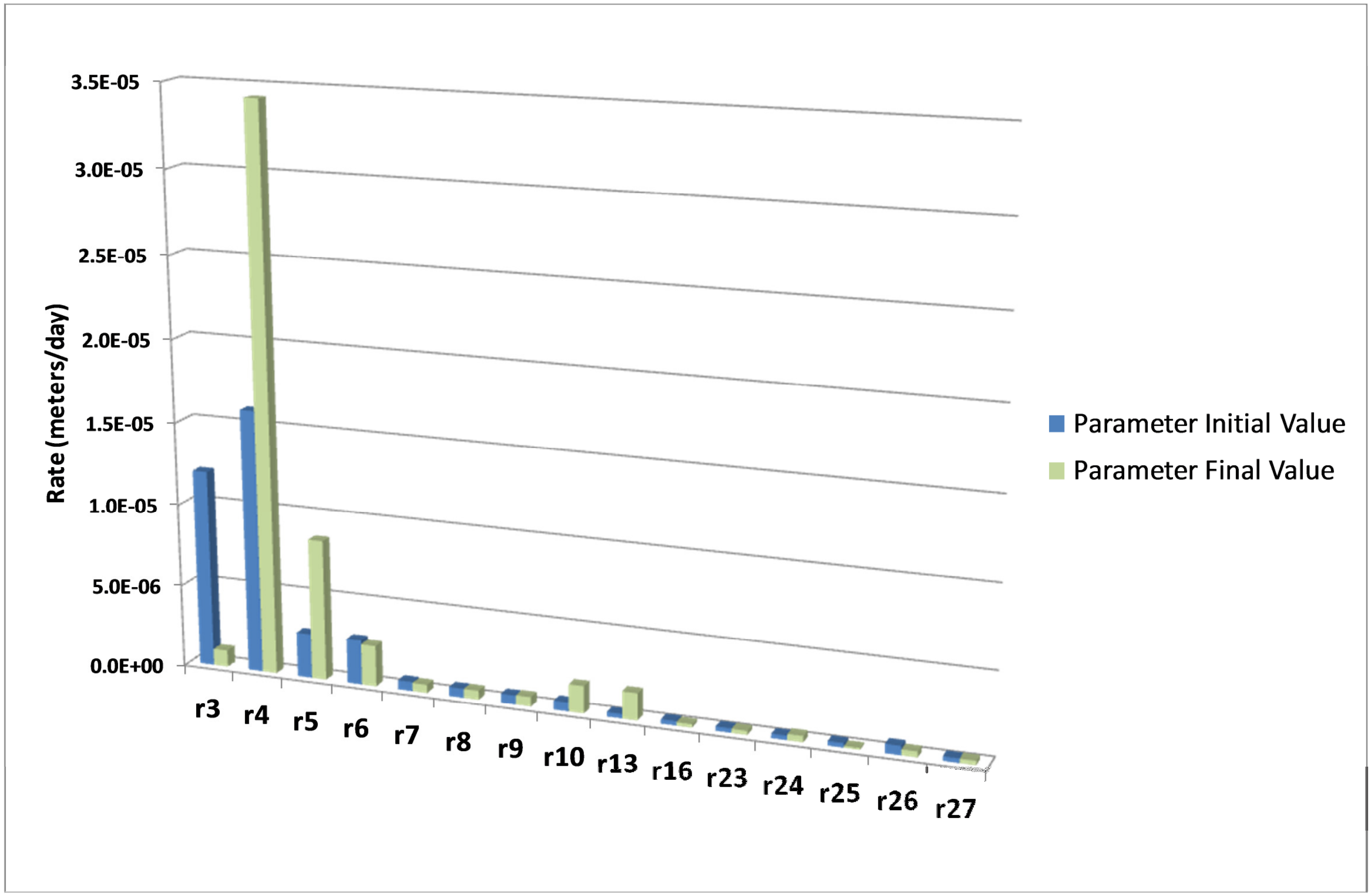


FIGURE 2-6
SELECTED RECHARGE RATE CHANGES RELATIVE TO FIRST PEST RUN

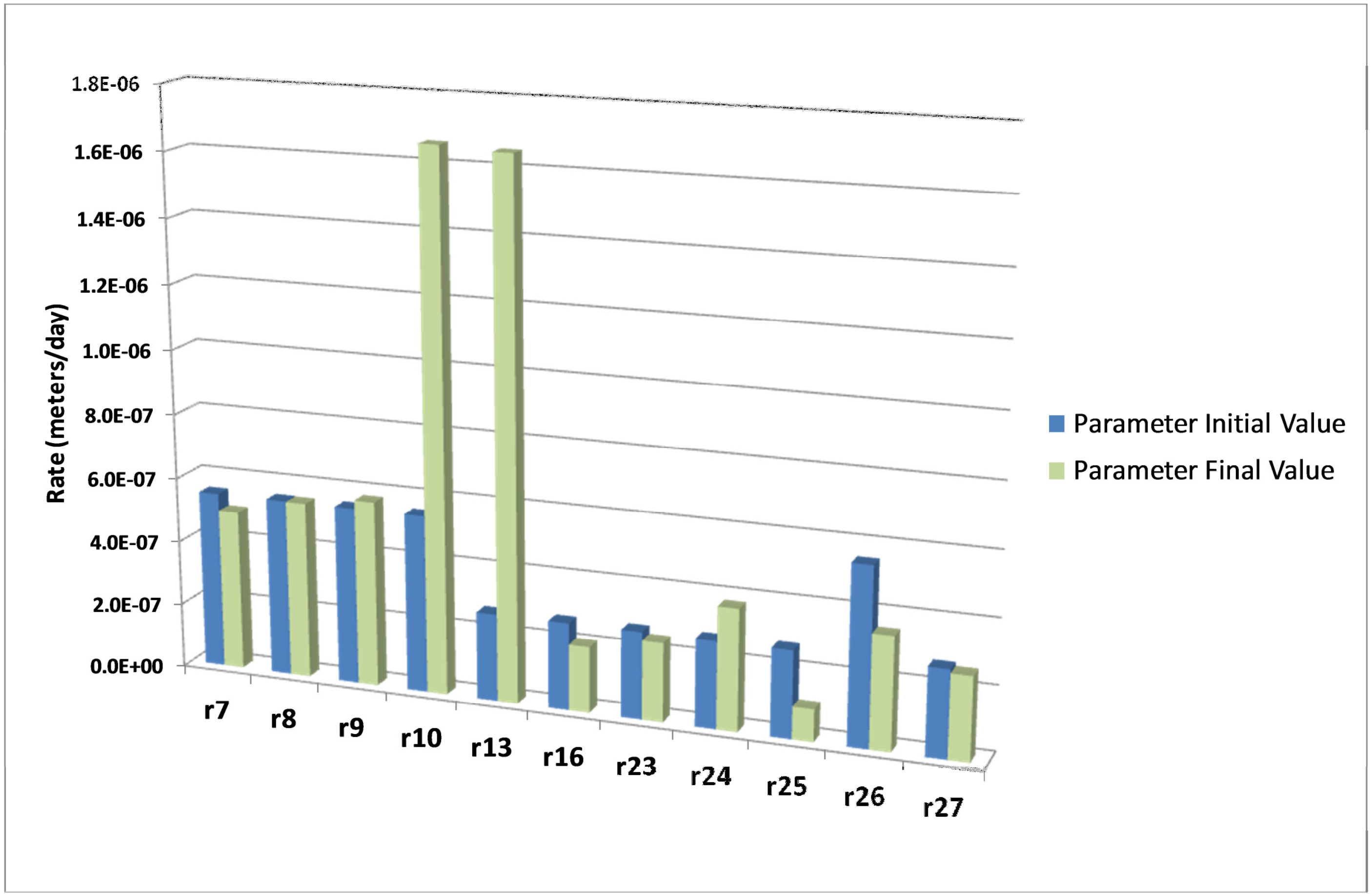


FIGURE 2-7
EVAPOTRANSPIRATION RATE CHANGES RELATIVE TO FIRST PEST RUN

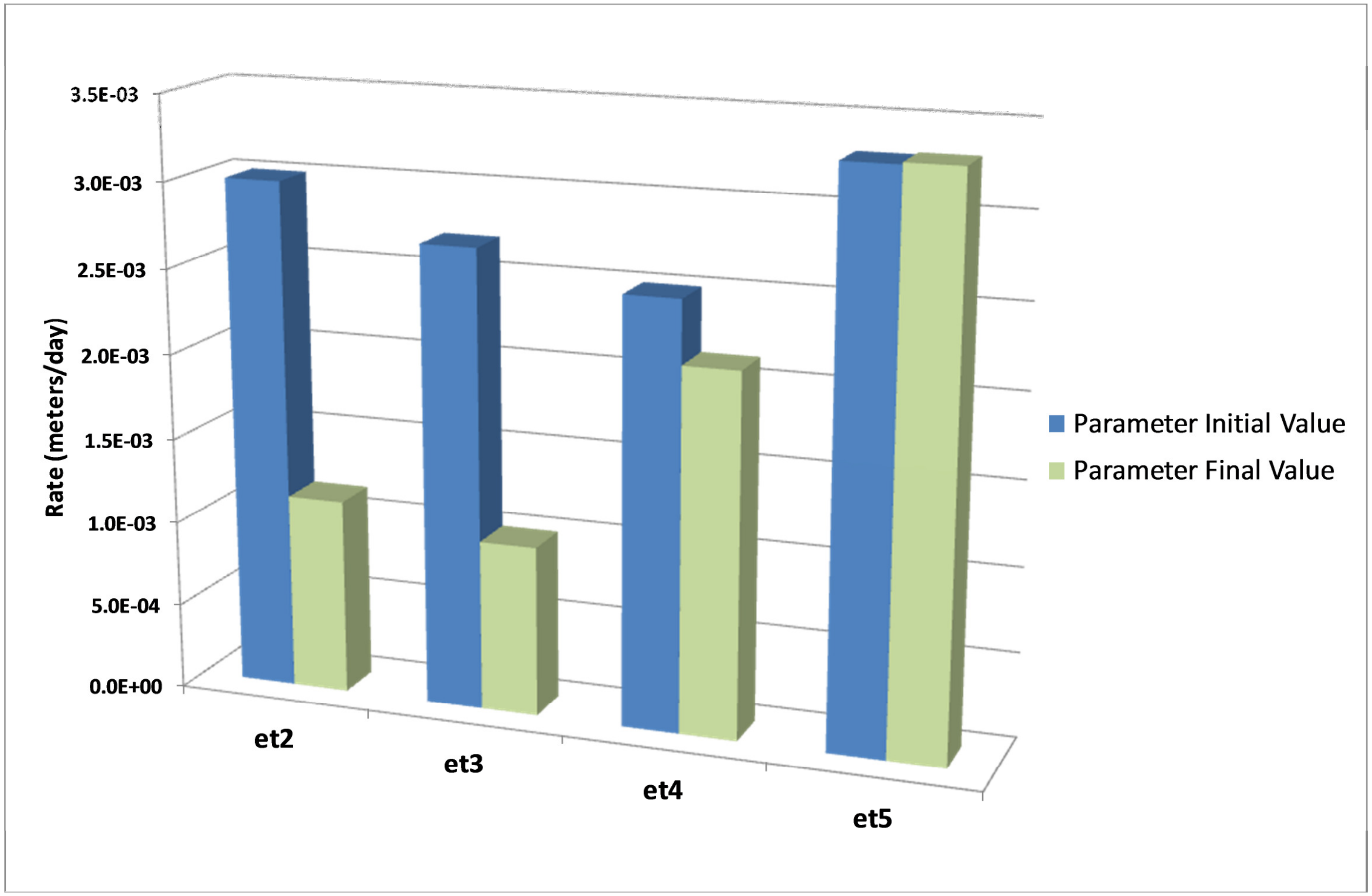
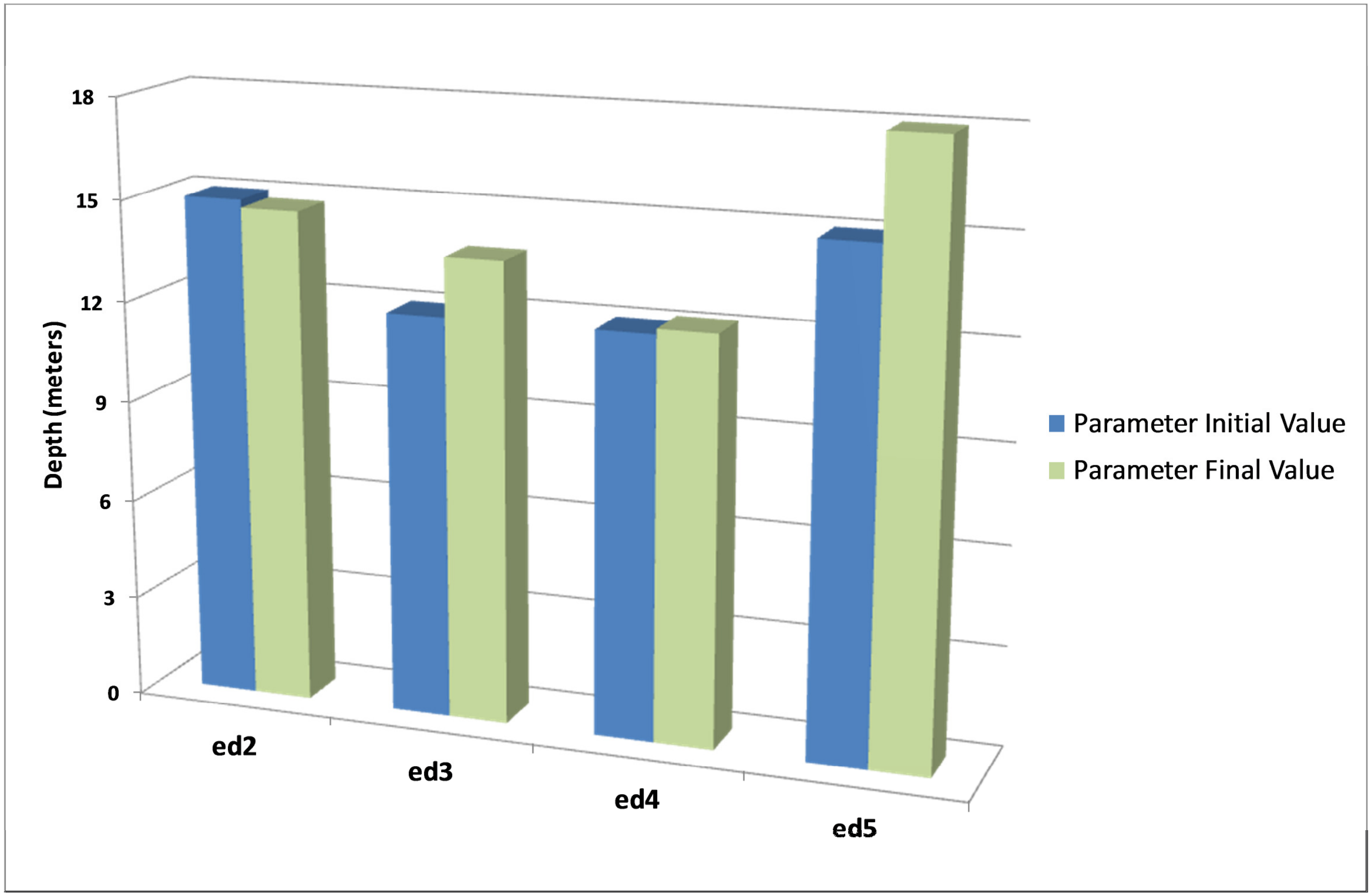


FIGURE 2-8
EVAPOTRANSPIRATION EXTINCTION DEPTH CHANGES RELATIVE TO FIRST PEST RUN



2.3 PEST ESTIMATION SIMULATIONS

Two additional PEST simulations were carried out in parameter estimation (i.e., calibration) mode. The estimated parameters from the previous PEST simulation were adopted as an updated parameter set for these simulations. The first simulation used only head observations and the second incorporated river reach flux observations in addition to head observations.

The observation heads in both models were assigned as groups for each layer using the layer number as the group number, and with the layer 1 alluvium head observations split between the Nebo area alluvium in the east (Head 1 group) and the other layer 1 head observations (Head 19 group). The "Head 9" group is associated with model layer 9, the Fort Cooper Coal Measures, but were labelled as Permian bores in the government database and due to a lack of more detail assigned to layer 9.

The cumulative flux from the model river reaches 0 through 4 (Figure 1-1) were assigned in the model using the lowest factor, 0.25, of estimated groundwater gains assumed applicable for this study.

Weightings assumed to be proportional to the inverse of measurement uncertainty were used. A weight of 0.02 was used for the river reach flux observations to produce a phi contribution similar to that of the head observations and to represent greater measurement error, while the head observations were assigned a weight of 0.5. The weightings are based on the order of magnitude for the observations. Head observation values are on the order of 100 to 500 meters. A weighting of 0.5 is used to represent the inverse of measurement uncertainty which would be plus or minus 2 meters which is reasonable for head measurement uncertainty. River reach flux values range between 3,000 and 16,000 m^3/day. Thus, a river reach flux weight of 0.02 would indicate 50 m^3/day measurement uncertainties. The resulting total phi for the PEST simulation with both observation types is 17,183. The weights result in contributions of similar magnitude to phi for the head and river flux observations (Table 2.1).

All other model and PEST settings remained the same between simulations. The results were used to determine the importance of including the river reach flux observations in the calibration of the model. Comparison of the composite sensitivities provides insight into the additional support in reducing predictive error provided by using the flux observations.

Although observation heads were grouped, additional analysis is required on the relevant outcomes of each grouping. All results beyond the contributions to phi are reported relative to two groupings: all head observations as one group, and the five river reach flux observations as another.

TABLE 2.1
MODEL OBSERVATION GROUP INDIVIDUAL CONTRIBUTIONS TO PHI

Observation group	Contribution to phi
HEAD 1 - EAST ALLUVIUM	2,237
HEAD 2 - TERTIARY	5,990
HEAD 4 - REWAN FM	489.8
HEAD 5 - RCM	82.53
HEAD 9 - PERMIAN	4,123
HEAD 18 - BACK CREEK GROUP	3,232
HEAD 19 - WEST ALLUVIUM	105.5
RIVER FLUX - ALL 5 REACHES	924.1

2.3.1 PEST Estimation Parameter Sensitivities

The PEST estimation sensitivities show similar results to the initial PEST regularization simulation where ET extinction depths in zones 2 and 3 (ed2 and ed3) show the greatest composite and composite scaled sensitivity values (Figures 2-9 to 2-11). The largest composite and composite scaled sensitivities are 5.4 and 6.4, respectively, for ed2 and all other sensitivity values are compared relative to these values. The sensitivity values are approximately an order of magnitude higher for the ET extinction depth zones compared to the sensitivity values from the PEST regularization simulation, and are related to the addition of the river flux observations.

The results also show a relatively higher composite sensitivity and even higher composite scaled sensitivity for recharge zone 2 (r2) compared to other parameters besides ed2 and ed3. Recharge zone 2 is one of the additional parameters incorporated for these PEST simulations compared to the initial PEST regularization simulation.

Both the horizontal and vertical conductivity parameter zones are relatively insensitive compared to the ET extinction depths and recharge zone 2. However, while the conductivity parameter zones are less sensitive compared to ET and recharge, review of the horizontal conductivity parameter group independently shows relatively higher sensitivity values for several parameter zones when compared to the other horizontal conductivity zones and includes:

- Alluvium (kx1and kx2)
- Duaringa Formation (kx5)
- Rewan Formation (kx10)
- Back Creek Group (kx24)

The higher relative sensitivities are related to the larger set of observation groups being located within these zones.

Similarly, when the vertical conductivity parameter zones are reviewed independent of the other types of parameters, a few parameter zones are relatively more sensitive:

- Duaringa Formation (kz5)
- Rewan Formation (kz10)
- FCCM Interburden (kz16)
- Back Creek Group (kz24)

The Quaternary alluvium vertical hydraulic conductivity parameter zones are not associated with high sensitivity values while the horizontal hydraulic conductivity values are. The horizontal conductivity controls lateral movement of groundwater with greater spatial interconnectivity while the vertical movement of groundwater is controlled by two layers with different vertical hydraulic conductivity values. The vertical hydraulic conductivity values and bounding ranges for alluvium (kz1 and kz2) are relatively much larger compared to the underlying layer vertical hydraulic conductivity parameter values (e.g. Back Creek Group) making them insensitive to the matching of heads and river flux values, because the matching is controlled by the much lower vertical hydraulic conductivity of the underlying layer conductivity parameter zones, such as the Back Creek Group (kz24).

Comparison of the duplicate PEST model simulations only with different observation groups, head and river reach flux observations for one simulation and head observations only for the other simulation, shows the beneficial contribution to model calibration and sensitivity from including river reach flux observations (Figures 2-12 to 2-14). The river flux observations adds significant sensitivity and parameter estimation error reduction for ET extinction depth and ET rate zones 2, 3 and 4 (ed2, ed3, ed4, et2, et3 and et4), and recharge zone 2 (r2). Additionally, while the horizontal and vertical conductivity zones have relatively lower sensitivity values overall, the inclusion of river reach flux observations also notably increased the horizontal conductivity zone sensitivities for alluvium (kx1 and kx2) and the Duaringa Formation (kx5), and for vertical conductivity sensitivity associated with the Duaringa Formation (kz5).

FIGURE 2-9
EVAPOTRANSPIRATION, GENERAL HEAD, AND RECHARGE COMPOSITE AND COMPOSITE SCALED SENSITIVITIES

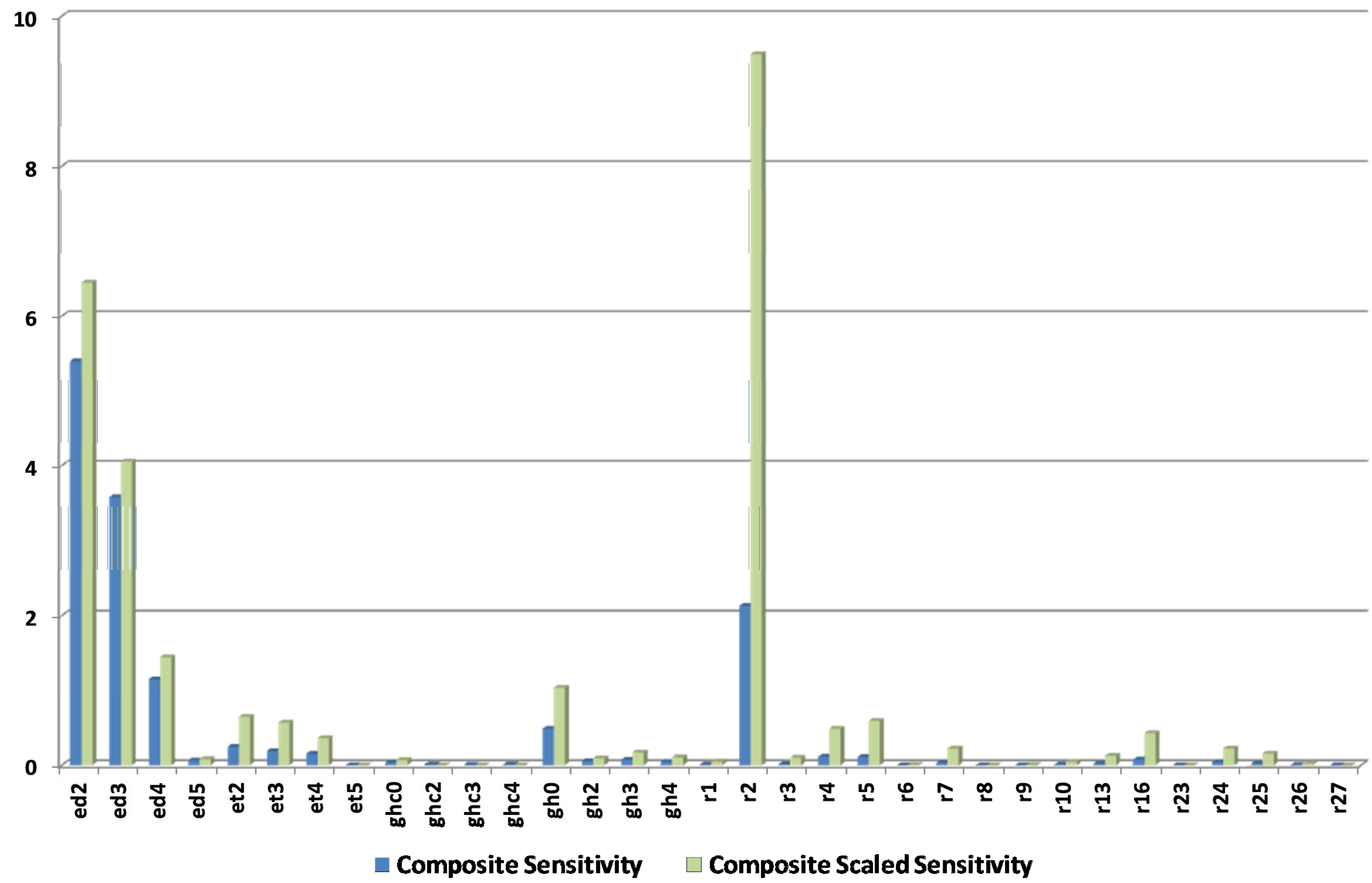


FIGURE 2-10
HORIZONTAL HYDRAULIC CONDUCTIVITY COMPOSITE AND COMPOSITE SCALED SENSITIVITIES

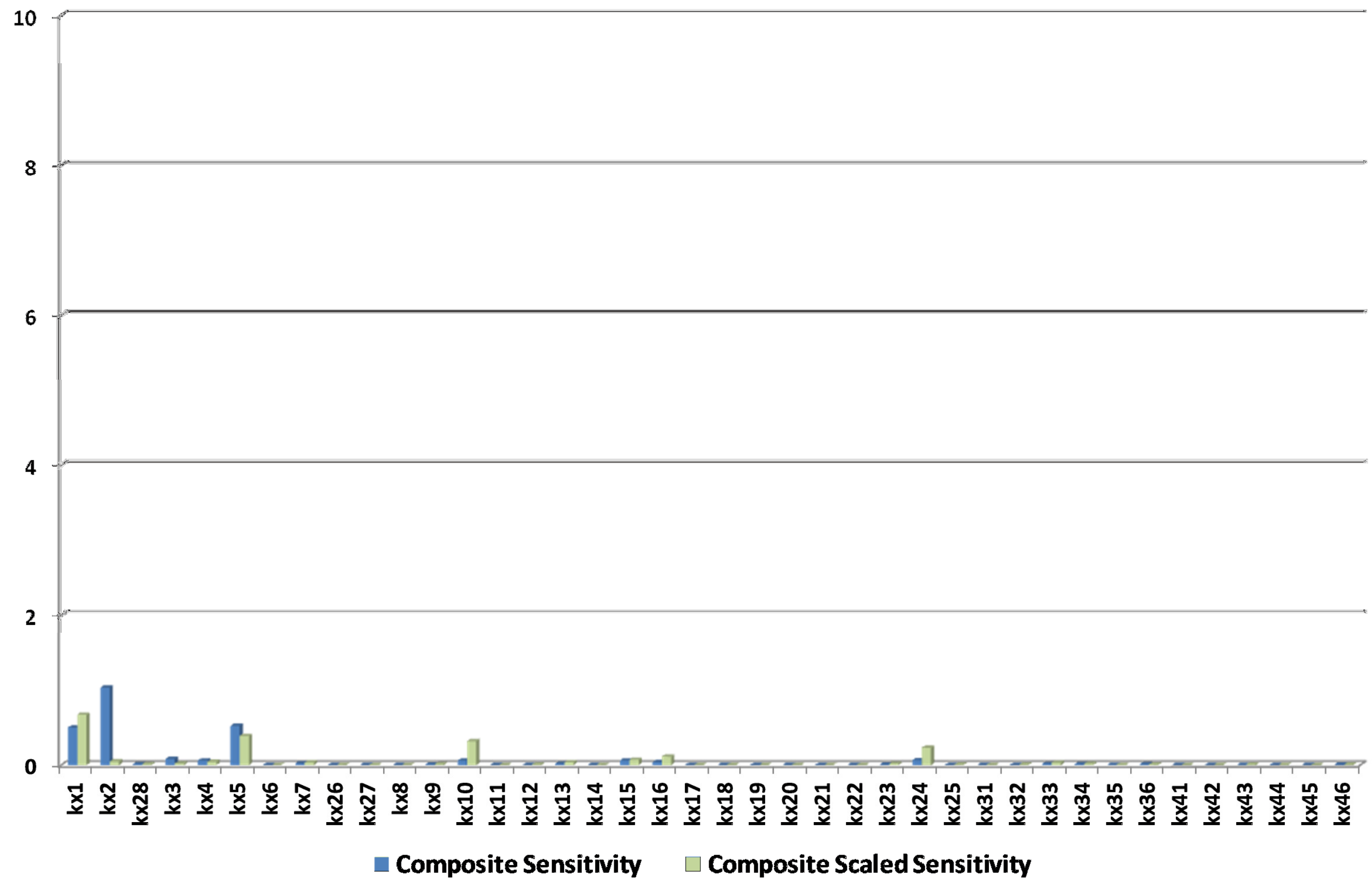


FIGURE 2-11
VERTICAL HYDRAULIC CONDUCTIVITY COMPOSITE AND COMPOSITE SCALED SENSITIVITIES

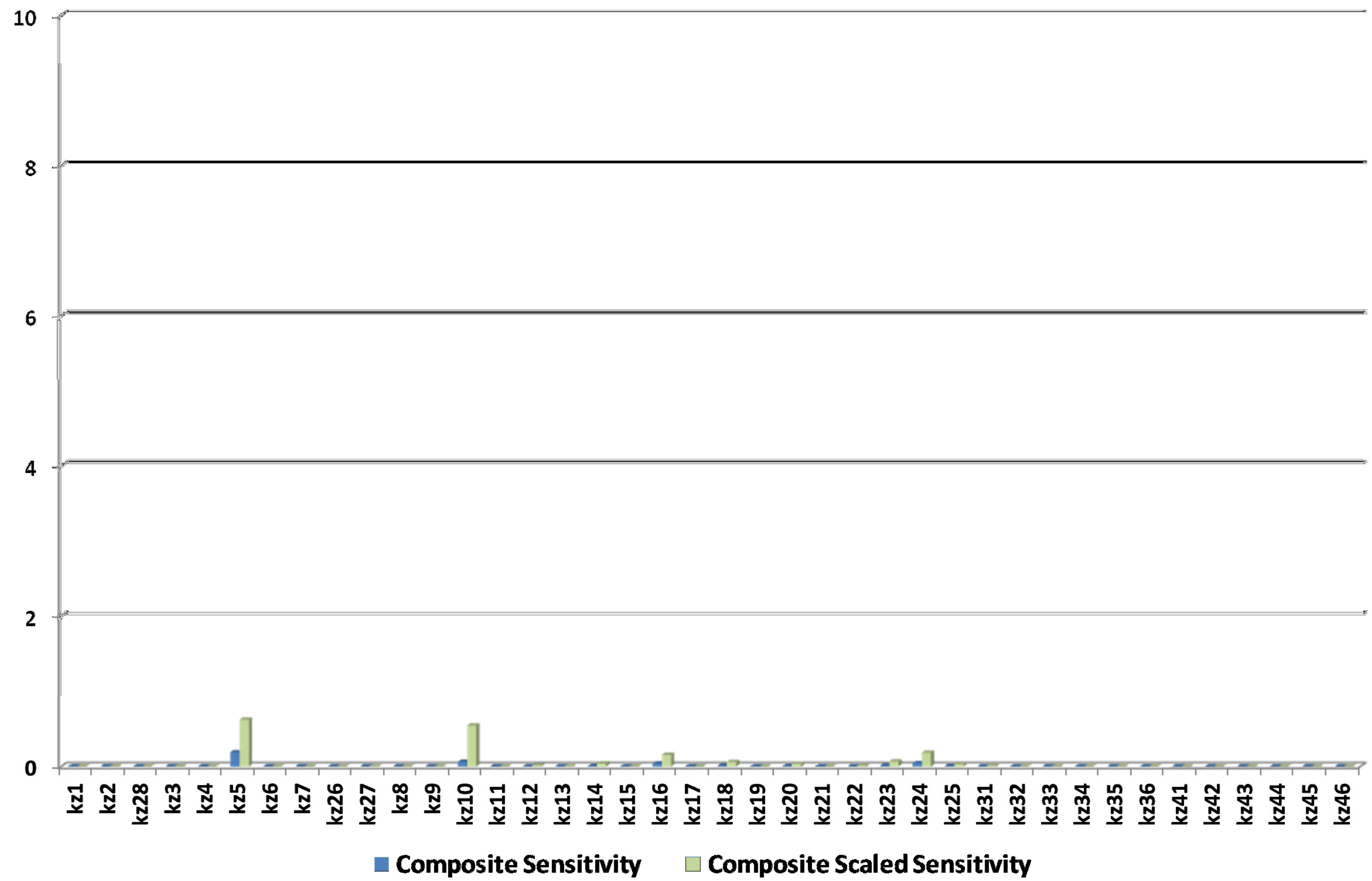


FIGURE 2-12

EVAPOTRANSPIRATION, GENERAL HEAD, AND RECHARGE COMPOSITE SCALED SENSITIVITIES FOR HEAD AND RIVER FLUX, AND HEAD ONLY OBSERVATIONS

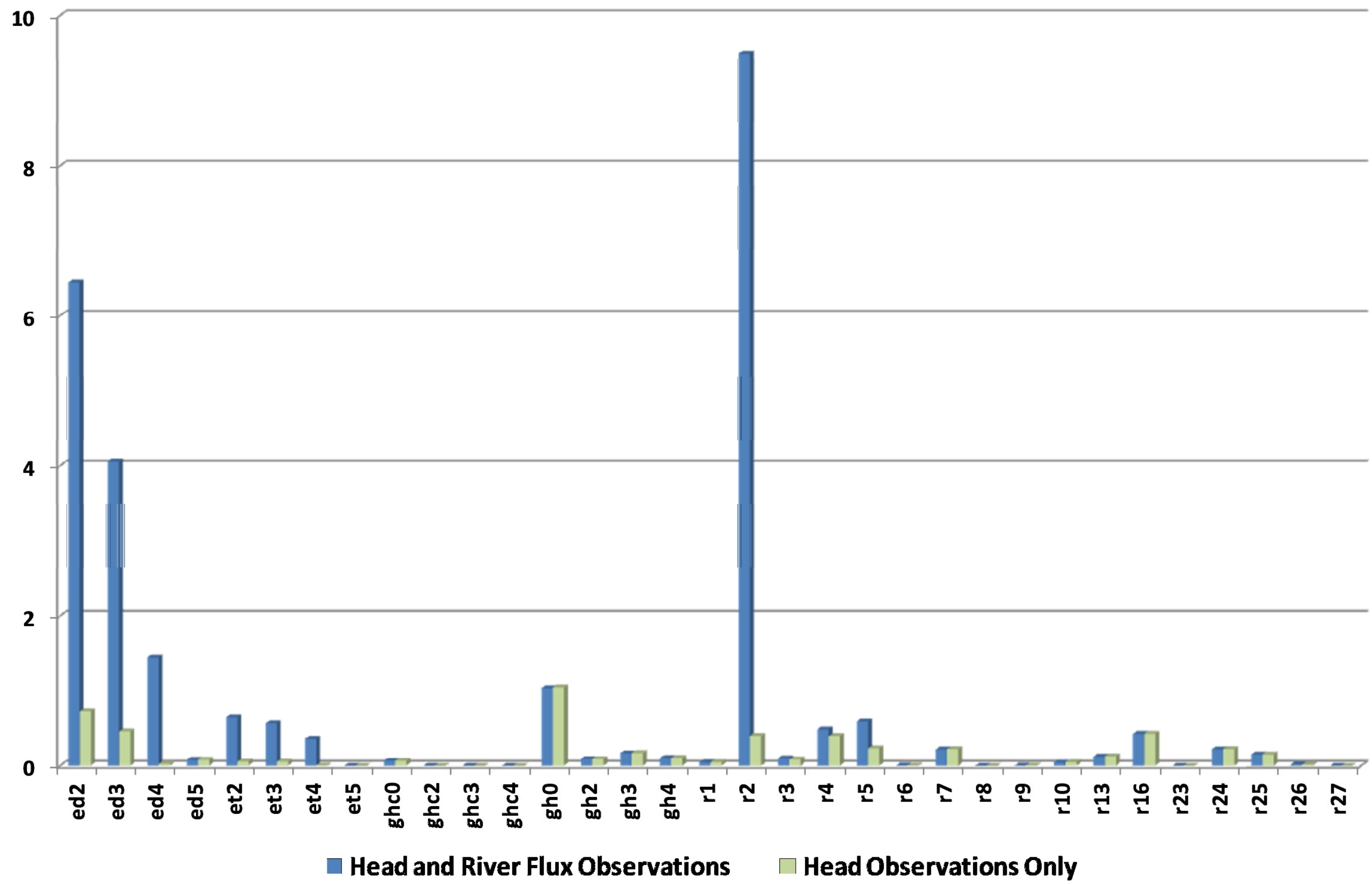


FIGURE 2-13
HORIZONTAL HYDRAULIC CONDUCTIVITY COMPOSITE SCALED SENSITIVITIES FOR HEAD AND RIVER FLUX, AND HEAD ONLY OBSERVATIONS

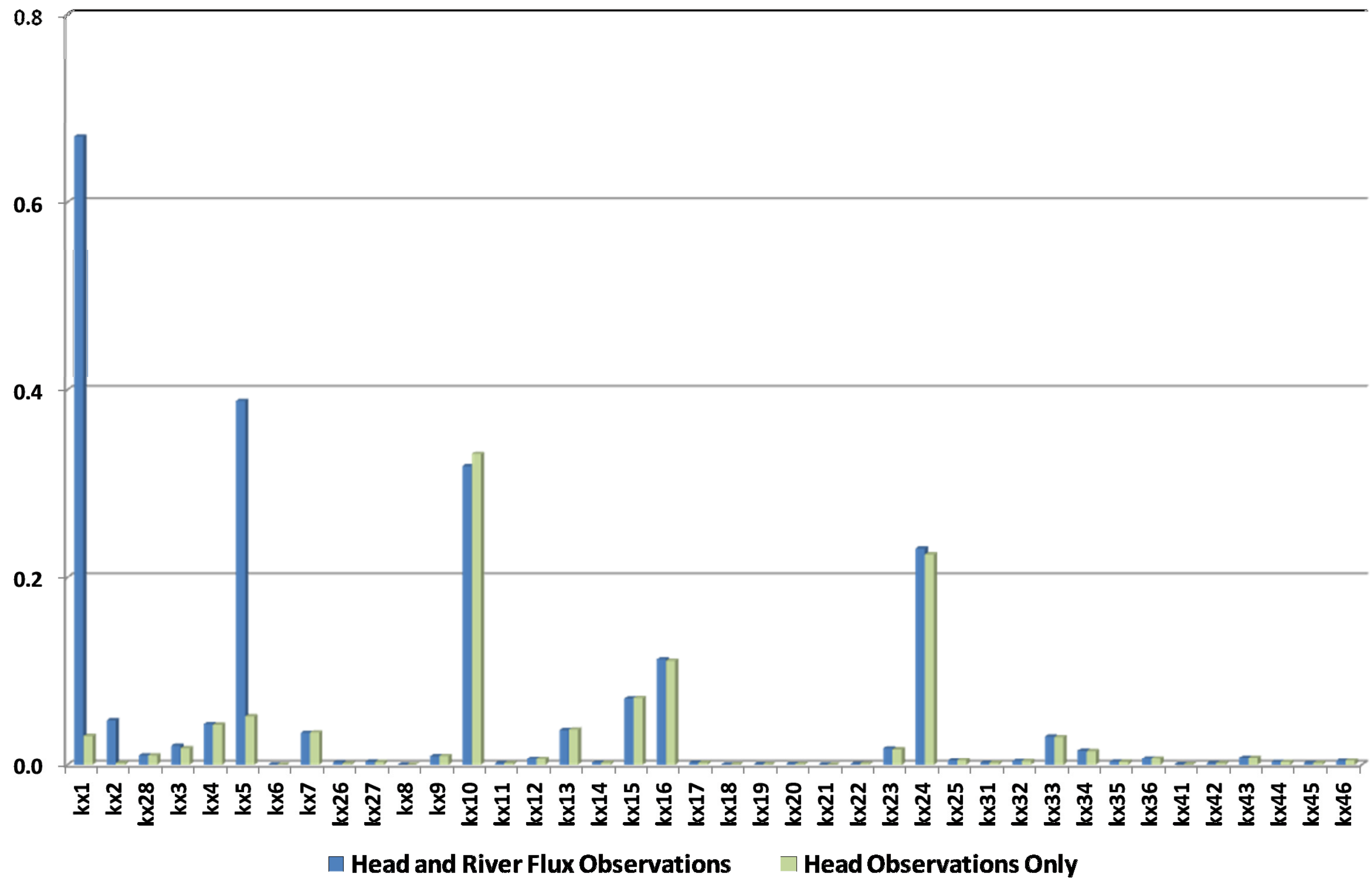
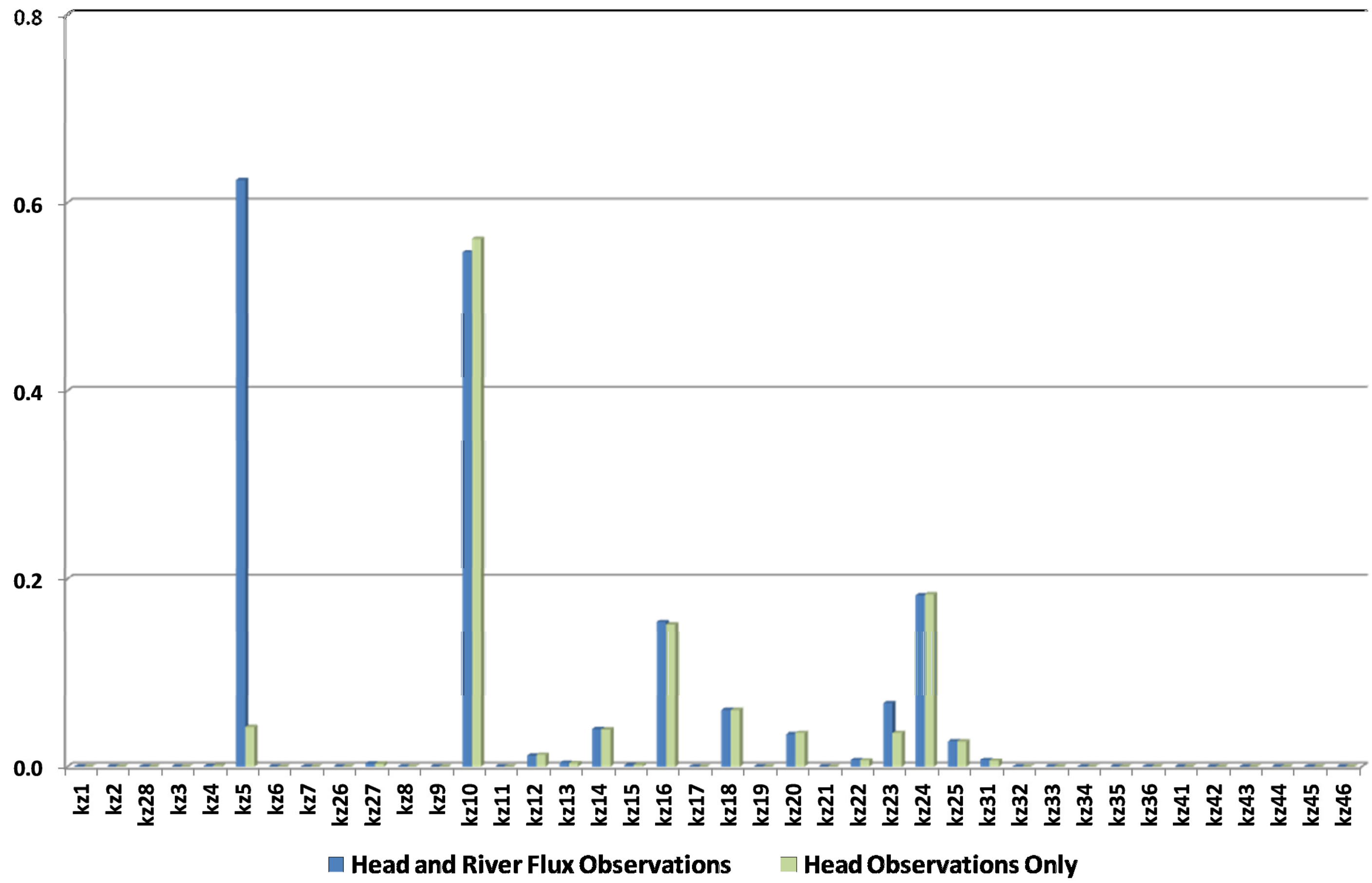


FIGURE 2-14
VERTICAL HYDRAULIC CONDUCTIVITY COMPOSITE SCALED SENSITIVITIES FOR HEAD AND RIVER FLUX, AND HEAD ONLY OBSERVATIONS



2.3.2 PEST Estimation Parameter Correlation Coefficients

PEST estimation (calibration) mode provides a parameter correlation coefficient (PCC) matrix. This matrix indicates the potential for parameters to be related to one another such that they cannot be independently estimated and results in parameter insensitivity for the correlated pairs. The parameter correlation coefficients indicate 11 pairs from the available 113 parameters have high (>0.95) correlation coefficients (Table 2.2). These same parameters with high correlation coefficients are also primarily associated with relatively lower parameter sensitivities. Some of the correlations are intuitive in that the physical properties within a zone are related and could be tied to one another such as the horizontal-vertical conductivity values of zones 24 and 10, and the inverse relationship between ET extinction depth and ET rate observed for zones ed4-et4 and ed5-et5. While some parameters may be highly correlated based on the correlation coefficients it is still possible for these parameters to be accurately estimated. However, the correlations point out potentially problematic parameters and when insensitive parameters are identified the PCC support a possible reason for insensitivity and how the parameters can be handled in the model such as tying the horizontal and vertical conductivity values for a specific zone.

TABLE 2.2
MODEL PARAMETER PAIRS ASSOCIATED WITH HIGH CORRELATIONS COEFFICIENTS

Correlated Parameters	Parameter Correlation Coefficients (PCC)	
	Head & River Flux Obs.	Head Obs. Only
ed4-et4	-1.000	-1.000
ed5-et5	-0.999	-0.999
kx24-r24	0.998	0.999
kx24-kz24	0.997	0.998
ghc4-gh4	-0.997	-0.998
kx7-r7	0.994	0.994
ghc2-gh2	0.962	0.982
kx45-kx46	-0.962	-0.958
kx4-r4	0.960	0.971
kx10-kz10	0.955	0.964
gh0-kz10	-0.918	-0.954

2.3.3 PEST Estimation 95% Confidence Intervals

The majority of parameters 95% confidence intervals (PCI) are extremely large, orders of magnitude beyond specified bounds as reported in the BGP EIS conceptual model, as a result of parameter insensitivity and cannot be accurately predicted based on the currently available observations (Tables 2.3 to 2.6).

The PCI for thirteen parameters are estimated with reasonable upper and lower limits compared to BGP EIS conceptual model upper and lower bounds (Tables 2.3 to 2.5 - highlighted in blue). The parameters with accurately calculated PCI values are also those parameters identified with relatively higher composite and scaled composite sensitivities, but also includes parameters with relatively lower parameter sensitivities including: recharge parameter zones r1 (alluvium), r4 (basalt) and r5 (Duaringa Fm); ET rate parameter zones et2 and et3; and horizontal hydraulic conductivity zones kx3 and kx4. However, the relative composite scaled sensitivities of r4, r5, et2, et3 are higher when compared to the horizontal hydraulic conductivities indicating potentially significant sensitivities then when compared to r2, ed2 and ed3.

The parameter correlation coefficient matrix shows high PCC values (> 0.95) for three of the parameters for which reasonable PCI are calculated: kx4 (layer 1 basalt), r4 (basalt) and gh0. Thus, while these three parameters are highly correlated they can still be predicted with accuracy.

TABLE 2.3
ET EXTINCTION DEPTH AND RATE ZONES, AND GENERAL HEAD BOUNDARY CONDUCTANCE AND HEAD REACHES 95% CONFIDENCE INTERVALS AND UPPER AND LOWER BOUNDS

		95% percent confidence limits		Specified Bounds	
Parameter (zone)	Estimated Value*	Lower Limit*	Upper Limit*	Lower Bound*	Upper Bound*
ed2	15.6	10.5	23.3	10	18
ed3	13.5	8.9	20.6	10	18
ed4	18.0	2.9E-178	1.1E+180	10	18
ed5	18.0	1.4E-80	2.3E+82	10	18
et2	0.0023	8.1E-08	63.7	1.0E-03	5.0E-03
et3	0.0010	6.9E-07	1.5	1.0E-03	5.0E-03
et4	0.0042	4.2E-303	4.2E+297	1.0E-03	5.0E-03
et5	0.0043	4.3E-303	4.3E+297	1.0E-03	5.0E-03
ghc0	0.011	1.9E-27	6.7E+22	1.0E-04	1
ghc2	1.0	1.0E-300	1.0E+300	1.0E-04	1
ghc3	1.0	1.0E-300	1.0E+300	1.0E-04	1
ghc4	1.0	1.0E-300	1.0E+300	1.0E-04	1
gh0	137.2	48.2	390.6	50	200
gh2	50.0	1.4E-262	1.8E+265	50	200
gh3	200.0	9.7E-96	4.1E+99	50	200
gh4	200.0	2.0E-298	1.0E+300	50	200

*All values in meters per day except ed and gh values are reported in meters

TABLE 2.4
RECHARGE RATE ZONES 95% CONFIDENCE INTERVALS AND UPPER AND LOWER BOUNDS

Parameter (zone)	Estimated Value*	95% percent confidence limits		Specified Bounds	
		Lower Limit*	Upper Limit*	Lower Bound*	Upper Bound*
r1	8.0E-05	7.9E-09	8.1E-01	5.0E-06	8.0E-05
r2	3.5E-05	8.1E-06	1.5E-04	5.0E-06	8.0E-05
r3	1.0E-06	1.7E-15	579.7	1.0E-06	5.0E-05
r4	5.0E-05	5.7E-07	4.4E-03	1.0E-06	5.0E-05
r5	3.4E-06	1.7E-08	6.8E-04	5.0E-07	1.0E-05
r6	1.1E-06	7.8E-97	1.7E+84	5.0E-07	1.0E-05
r7	1.2E-07	1.1E-34	1.2E+20	1.0E-07	1.0E-05
r8	4.2E-07	4.2E-307	4.2E+293	1.0E-07	1.0E-05
r9	8.2E-06	8.2E-306	8.2E+294	1.0E-07	5.0E-05
r10	1.0E-05	7.1E-130	1.4E+119	1.0E-07	1.0E-05
r13	1.0E-05	5.0E-205	2.0E+194	1.0E-07	1.0E-05
r16	2.4E-06	6.4E-55	9.4E+42	1.0E-07	1.0E-05
r23	1.0E-05	1.0E-305	1.0E+295	1.0E-07	1.0E-05
r24	2.6E-06	5.8E-19	1.1E+07	1.0E-07	1.0E-05
r25	1.1E-07	2.5E-127	4.7E+112	1.0E-07	1.0E-05
r26	1.0E-07	1.0E-307	1.0E+293	1.0E-07	1.0E-05
r27	1.2E-07	1.2E-307	1.2E+293	1.0E-07	1.0E-05

*All values in meters per day

TABLE 2.5
HORIZONTAL HYDRAULIC CONDUCTIVITY PARAMETER ZONES 95% CONFIDENCE INTERVALS AND UPPER AND LOWER BOUNDS

		95% percent confidence limits		Specified Bounds	
Parameter (zone)	Estimated Value*	Lower Limit*	Upper Limit*	Lower Bound*	Upper Bound*
kx1	21.7	1.2	401	2.5	250
kx2	0.9	0.1	10.1	0.2	20
kx3	1.8	0.1	42.5	0.1	10
kx4	0.2	0.0012	30.5	1.0E-02	10
kx5	0.2	0.0073	4.5	5.0E-03	0.5
kx6	2.7	1.7E-66	4.1E+66	0.1	10
kx7	2.1E-02	1.6E-29	2.7E+25	5.0E-03	0.5
kx8	9.1E-04	9.1E-304	9.1E+296	5.0E-04	5.0E-02
kx9	5.0E-02	5.0E-302	5.0E+298	5.0E-02	5
kx10	6.1E-06	3.7E-289	1.0E+278	1.0E-06	1.0E-02
kx11	6.9E-04	6.9E-304	6.9E+296	1.0E-04	0.2
kx12	1.4E-05	1.4E-305	1.4E+295	1.0E-06	1.0E-02
kx13	4.5E-03	2.6E-282	7.9E+276	1.0E-04	0.2
kx14	2.2E-04	2.2E-304	2.2E+296	1.0E-06	1.0E-02
kx15	6.8E-02	9.6E-28	4.8E+24	1.0E-04	0.2
kx16	1.4E-03	2.0E-29	1.0E+23	1.0E-06	1.0E-02
kx17	6.1E-03	6.1E-303	6.1E+297	1.0E-04	0.2
kx18	1.1E-05	1.1E-305	1.1E+295	1.0E-06	1.0E-02
kx19	1.1E-03	1.1E-303	1.1E+297	1.0E-04	0.2
kx20	3.4E-05	3.4E-305	3.4E+295	1.0E-06	1.0E-02
kx21	5.2E-04	5.2E-304	5.2E+296	1.0E-04	0.2
kx22	4.7E-04	4.7E-304	4.7E+296	1.0E-06	1.0E-02
kx23	1.0E-04	1.0E-304	1.0E+296	1.0E-04	0.2
kx24	3.1E-04	6.8E-17	1.4E+09	1.0E-06	1.0E-02
kx25	7.2E-04	7.2E-304	7.2E+296	1.0E-05	1.0E-02
kx26	5.2E-03	5.2E-303	5.2E+297	1.0E-05	5.0E-02
kx27	1.5E-04	1.6E-118	1.5E+110	1.0E-05	5.0E-04
kx28	6.6E+00	5.3E-06	8.2E+06	0.2	20
kx31	9.5E-05	9.5E-305	9.5E+295	5.3E-06	9.5E-05
kx32	1.3E-04	1.3E-304	1.3E+296	1.1E-04	1.0E-03
kx33	5.0E-03	4.4E-66	5.6E+60	1.1E-03	1.1E-02
kx34	5.0E-02	9.4E-37	2.7E+33	1.1E-02	5.3E-02
kx35	9.1E-02	1.5E-217	5.6E+214	5.3E-02	0.106
kx36	2.1E-01	9.3E-96	4.8E+93	0.106	0.211
kx41	6.9E-05	6.9E-305	6.9E+295	5.3E-06	9.5E-05
kx42	1.9E-04	1.9E-304	1.9E+296	1.1E-04	1.0E-03
kx43	1.1E-02	1.1E-302	1.1E+298	1.1E-03	1.1E-02
kx44	5.3E-02	5.3E-302	5.3E+298	1.1E-02	5.3E-02
kx45	1.1E-01	1.1E-301	1.1E+299	5.3E-02	0.11
kx46	2.1E-01	2.1E-301	2.1E+299	0.106	0.21

*All values in meters per day

TABLE 2.6
VERTICAL HYDRAULIC CONDUCTIVITY PARAMETER ZONES 95% CONFIDENCE INTERVALS AND UPPER AND LOWER BOUNDS

		95% percent confidence limits		Specified Bounds	
Parameter (zone)	Estimated Value*	Lower Limit*	Upper Limit*	Lower Bound*	Upper Bound*
kz1	2.5E-01	2.5E-301	2.5E+299	2.5E-01	7.5
kz2	2.0E+00	2.0E-300	1.0E+300	2.0E-02	2
kz3	1.9E-01	1.9E-301	1.9E+299	1.0E-02	2
kz4	1.5E-02	5.0E-83	4.8E+78	1.0E-03	2
kz5	5.0E-04	2.3E-09	108.8	5.0E-04	5.0E-02
kz6	1.1E-02	1.1E-302	1.1E+298	1.0E-02	2
kz7	4.7E-03	4.7E-303	4.7E+297	5.0E-04	5.0E-02
kz8	1.4E-05	1.4E-305	1.4E+295	1.0E-05	1.0E-03
kz9	5.0E-03	5.0E-303	5.0E+297	5.0E-03	0.5
kz10	1.6E-09	3.4E-264	7.6E+245	1.0E-09	1.0E-04
kz11	6.6E-04	6.6E-304	6.6E+296	1.0E-05	1.0E-02
kz12	4.3E-07	4.3E-307	4.3E+293	1.0E-09	1.0E-04
kz13	8.5E-05	8.5E-305	8.5E+295	1.0E-05	1.0E-02
kz14	1.2E-08	1.2E-308	1.2E+292	1.0E-09	1.0E-04
kz15	2.1E-03	2.1E-303	2.1E+297	1.0E-05	1.0E-02
kz16	1.0E-04	1.1E-34	9.0E+25	1.0E-09	1.0E-04
kz17	3.6E-04	3.6E-304	3.6E+296	1.0E-05	1.0E-02
kz18	8.3E-07	4.7E-100	1.4E+87	1.0E-09	1.0E-04
kz19	1.9E-03	1.9E-303	1.9E+297	1.0E-05	1.0E-02
kz20	2.7E-06	1.9E-186	3.9E+174	1.0E-09	1.0E-04
kz21	6.8E-05	6.8E-305	6.8E+295	1.0E-05	1.0E-02
kz22	1.5E-06	1.5E-306	1.5E+294	1.0E-09	1.0E-04
kz23	7.0E-08	2.0E-57	2.4E+42	1.0E-09	1.0E-03
kz24	1.0E-04	2.1E-17	4.9E+08	1.0E-09	1.0E-04
kz25	3.7E-06	6.8E-242	2.0E+230	1.0E-06	1.0E-03
kz26	4.8E-03	4.8E-303	4.8E+297	1.0E-05	5.0E-03
kz27	1.9E-06	4.9E-133	7.2E+120	1.0E-06	1.0E-04
kz28	2.2E-02	2.2E-302	2.2E+298	2.0E-02	2
kz31	4.1E-06	4.1E-306	4.1E+294	1.3E-06	4.8E-05
kz32	1.2E-04	1.2E-304	1.2E+296	2.8E-05	5.0E-04
kz33	1.5E-03	1.5E-303	1.5E+297	2.8E-04	5.5E-03
kz34	8.5E-03	8.5E-303	8.5E+297	2.8E-03	2.7E-02
kz35	1.7E-02	1.7E-302	1.7E+298	1.3E-02	5.3E-02
kz36	3.3E-02	3.3E-302	3.3E+298	2.7E-02	0.106
kz41	1.1E-05	1.1E-305	1.1E+295	1.3E-06	4.8E-05
kz42	1.1E-04	1.1E-304	1.1E+296	2.8E-05	5.0E-04
kz43	1.1E-03	1.1E-303	1.1E+297	2.8E-04	5.5E-03
kz44	6.3E-03	6.3E-303	6.3E+297	2.8E-03	2.7E-02
kz45	1.7E-02	1.7E-302	1.7E+298	1.3E-02	5.3E-02
kz46	3.2E-02	3.2E-302	3.2E+298	2.7E-02	0.106

*All values in meters per day

2.4 GENLINPRED Identifiability and Error/Uncertainty Variance Reduction

The sensitivities and Jacobian matrix along with the PEST control file from the PEST estimation simulations were used with the GENLINPRED utility to generate parameter identifiabilities (Figures 2-15 to 2-17) and estimates of calibration error/uncertainty variance reduction (Figures 2-18 to 2-20). Results of the error and uncertainty variance reduction are similar and only the uncertainty variance reduction is presented for simplicity.

The identifiability values indicate that 23 of the 113 parameters are identifiable assuming a cut-off of 0.95 (Figures 2-15 to 2-17). This indicates that the 23 parameters with identifiability values close to 1 can be estimated accurately with the observation data provided. However, a value of 1 only indicates that the null space contribution to the parameter estimation error is zero, while measurement noise still contributes to the parameter estimation error.

The 23 identifiable parameters include horizontal hydraulic conductivity parameter zones primarily in model layers 1 and 2 associated with:

- Alluvium (kx1, kx2 and kx28)
- Colluvium (kx3)
- Tertiary basalt (kx4)
- Duaringa Formation (kx5),

And, in the Permian model formations:

- FCCM in layer 9 (kx15)
- MCM uppermost interburden in layer 10 (kx16)
- Back Creek Group in layer 18 forming the model base (kx24)

Also included in the 23 identifiable parameters are vertical hydraulic conductivity parameter zones:

- Duaringa Formation (kz5)
- MCM uppermost interburden in layer 10 (kz16)
- MCM interburden in layer 12 (kz18)
- MCM GML coal seam in layer 17 (kz23)
- Back Creek Group in layer 18 forming the model base (kz24)

The Quaternary alluvium/colluviums (kz1, kz2 and kz3) and Tertiary basalt (kz4) vertical hydraulic conductivity parameter zones are not identifiable, while the horizontal hydraulic conductivity values are. This supports the sensitivity results in section 2.3.1 and PCI calculations in section 2.3.3.

As previously described, the horizontal conductivity controls lateral movement of groundwater with greater spatial similarity, while the vertical movement of groundwater is controlled by two layers with different vertical hydraulic conductivity values. The vertical hydraulic conductivity values and bounding ranges for kz1, kz2, kz3 and kz4 are relatively much larger compared to the underlying layer vertical hydraulic conductivity values (e.g. Back Creek Group), making them insensitive to the matching of heads and river flux, values because the matching is primarily controlled by the much lower vertical hydraulic conductivity of the underlying layer conductivity parameter zones, such as the Back Creek Group (kz24).

The other identifiable parameters and parameter types include:

- Evapotranspiration extinction depth zone 2 (ed2)
- Evapotranspiration extinction depth zone 3 (ed3)
- Evapotranspiration extinction depth zone 5 (ed5)
- General head boundary conductance zone 0 (ghc0)
- General head boundary head zone 0 (gh0)
- Recharge zone 2 (r2 - alluvium)
- Recharge zone 4 (r4 - basalt)
- Recharge zone 5 (r5 - Duaringa Fm)
- Recharge zone 16 (r16 - FCCM Interburden)

The other 93 parameters are considered non-identifiable (Figures 2-15 to 2-17). The non-identifiable parameters, noted with identifiabilities less than 0.95, are those which affect the value of the data output but which cannot be estimated accurately. Identification of these parameters assists in determining areas where additional data collection could be directed in conjunction with parameter sensitivities, PCC and PCI values. However, some of these parameters may also be non-observable parameters, such that they do not have an effect on the data predictions.

Supporting evidence is also presented in the calculated relative uncertainty variance reduction through calibration (Figures 2-18 to 2-20). The results indicate that overall the same parameters that are identifiable are those associated with significant reductions in their uncertainty variance through calibration. However, there are some parameters that have lower relative uncertainty variance reduction compared to identifiability, including:

- Alluvium (kx28)
- Duaringa Formation (kz5)
- MCM interburden in layer 12 (kz18)
- MCM GML coal seam in layer 17 (kz23)
- Evapotranspiration extinction depth zone 5 (ed5)

- Recharge zone 5 (r5)
- Recharge zone 16 (r16)

Both the identifiability of parameters and relative uncertainty variance reduction show the contribution of river flux observations to reducing prediction uncertainty compared to only using head observations. For most parameters, including those that are identifiable and have larger relative uncertainty variance reduction values, the inclusion of river flux observations are observable and contribute to lowering predictive error in most cases.

FIGURE 2-15
IDENTIFIABILITY OF HORIZONTAL CONDUCTIVITY PARAMETERS WITH HEAD AND RIVER FLUX, AND HEAD ONLY OBSERVATIONS

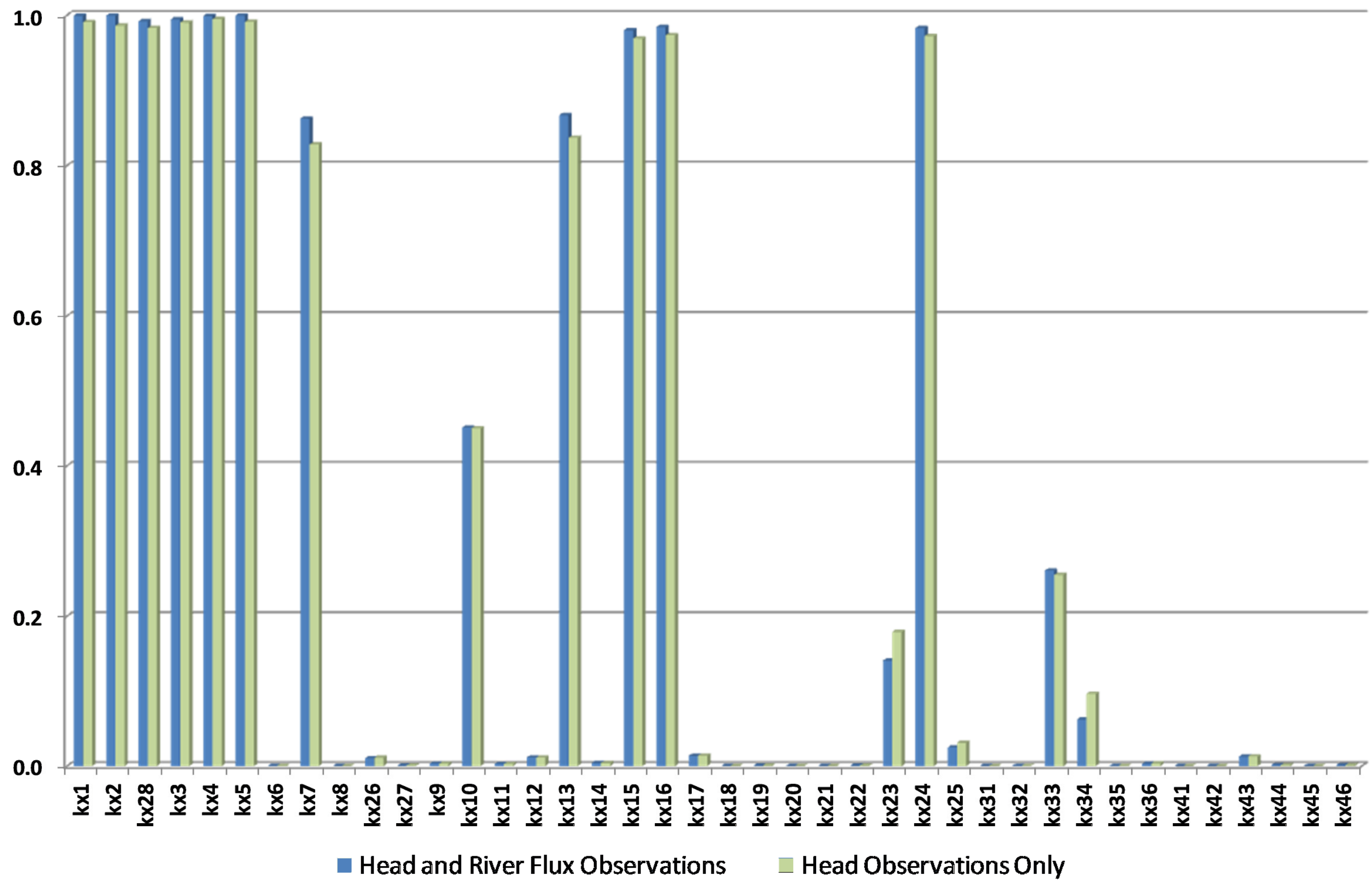


FIGURE 2-16
IDENTIFIABILITY OF VERTICAL CONDUCTIVITY PARAMETERS WITH HEAD AND RIVER FLUX, AND HEAD ONLY OBSERVATIONS

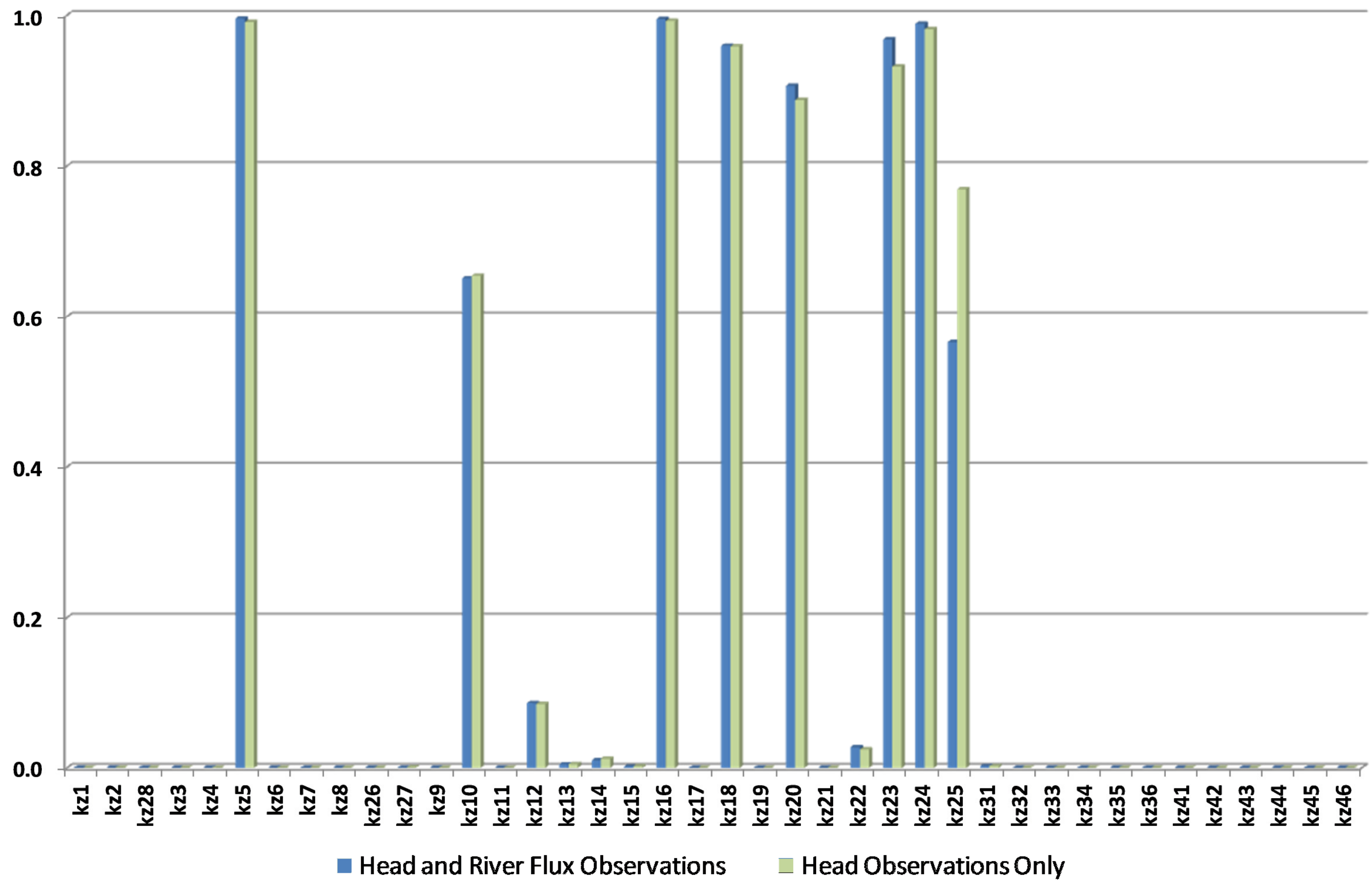


FIGURE 2-17
IDENTIFIABILITY OF ET, GH AND RECHARGE PARAMETERS WITH HEAD AND RIVER FLUX, AND HEAD ONLY OBSERVATIONS

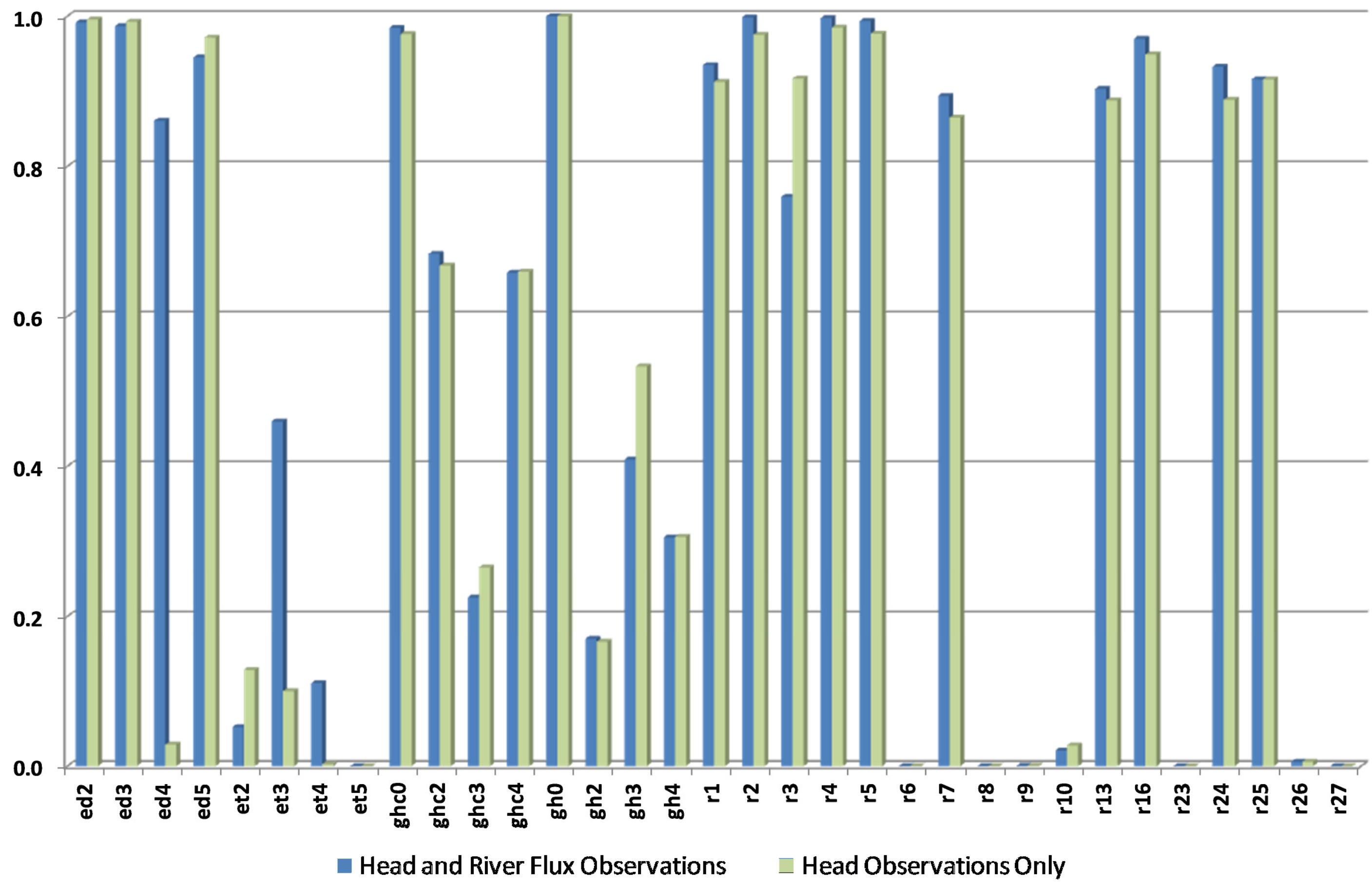


FIGURE 2-18

RELATIVE UNCERTAINTY VARIANCE REDUCTION - HORIZONTAL HYDRAULIC CONDUCTIVITY PARAMETERS WITH HEAD AND RIVER FLUX, AND HEAD ONLY OBSERVATIONS

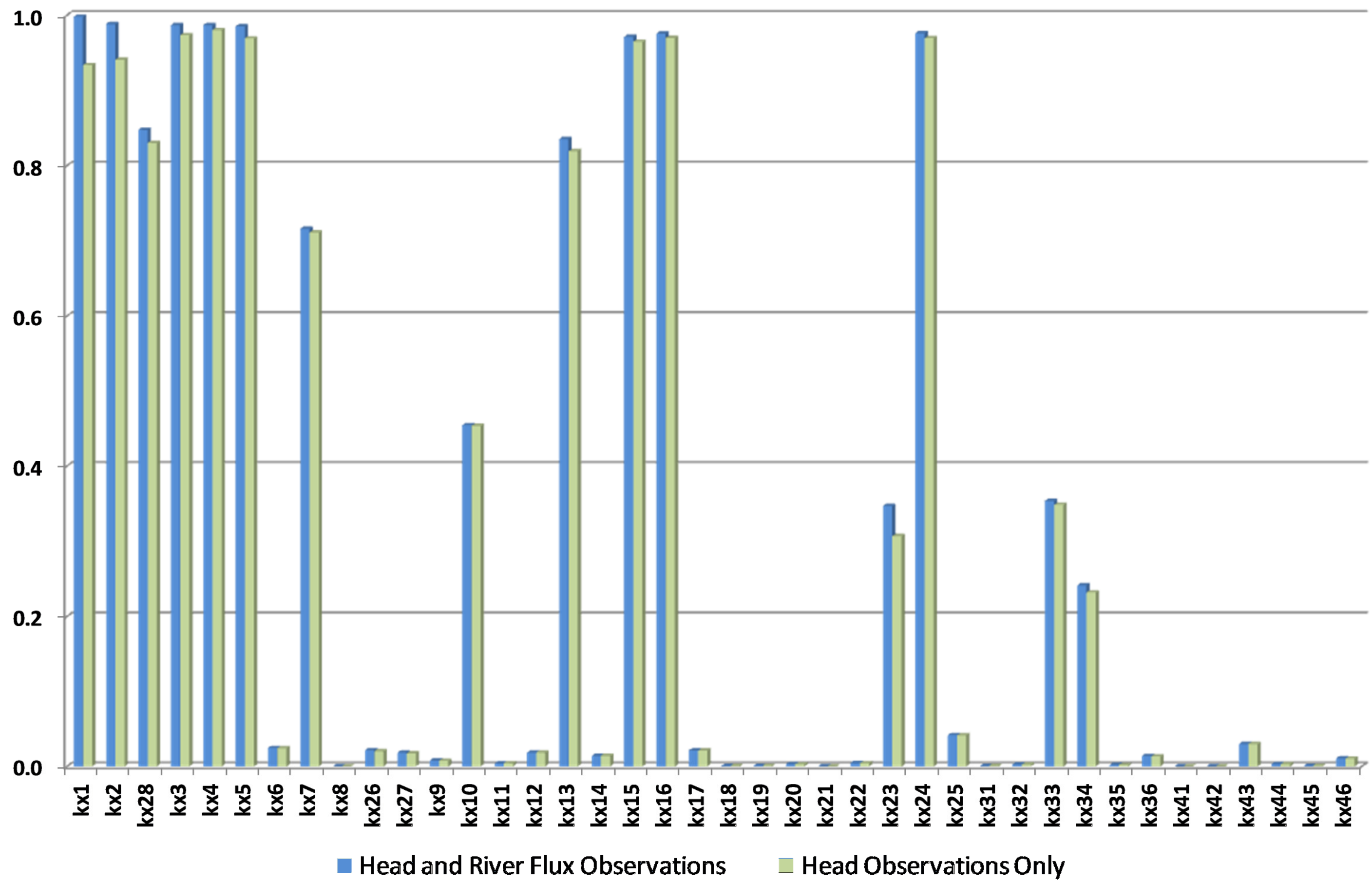


FIGURE 2-19
RELATIVE UNCERTAINTY VARIANCE REDUCTION - VERTICAL HYDRAULIC CONDUCTIVITY PARAMETERS WITH HEAD AND RIVER FLUX, AND HEAD ONLY OBSERVATIONS

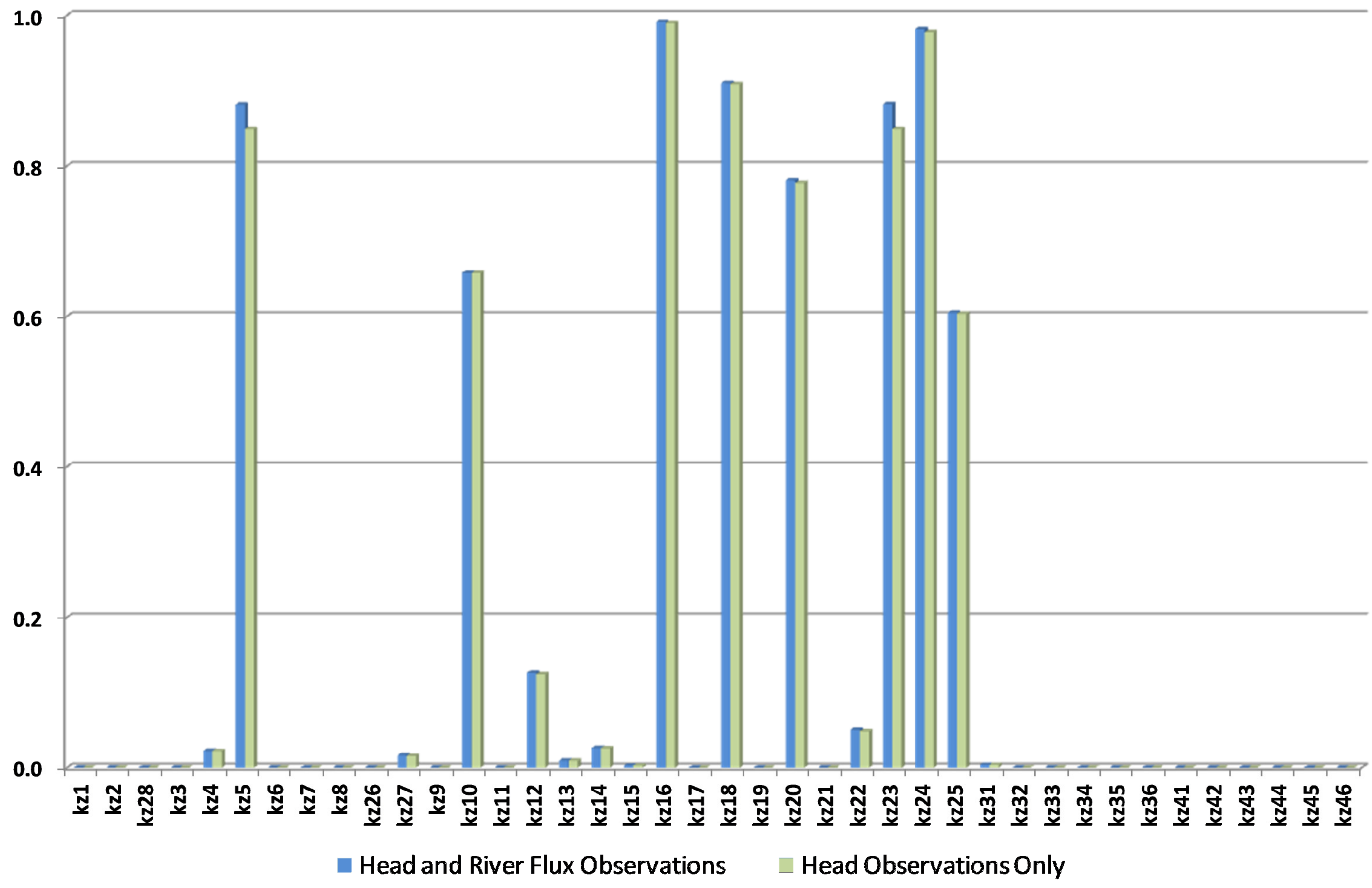
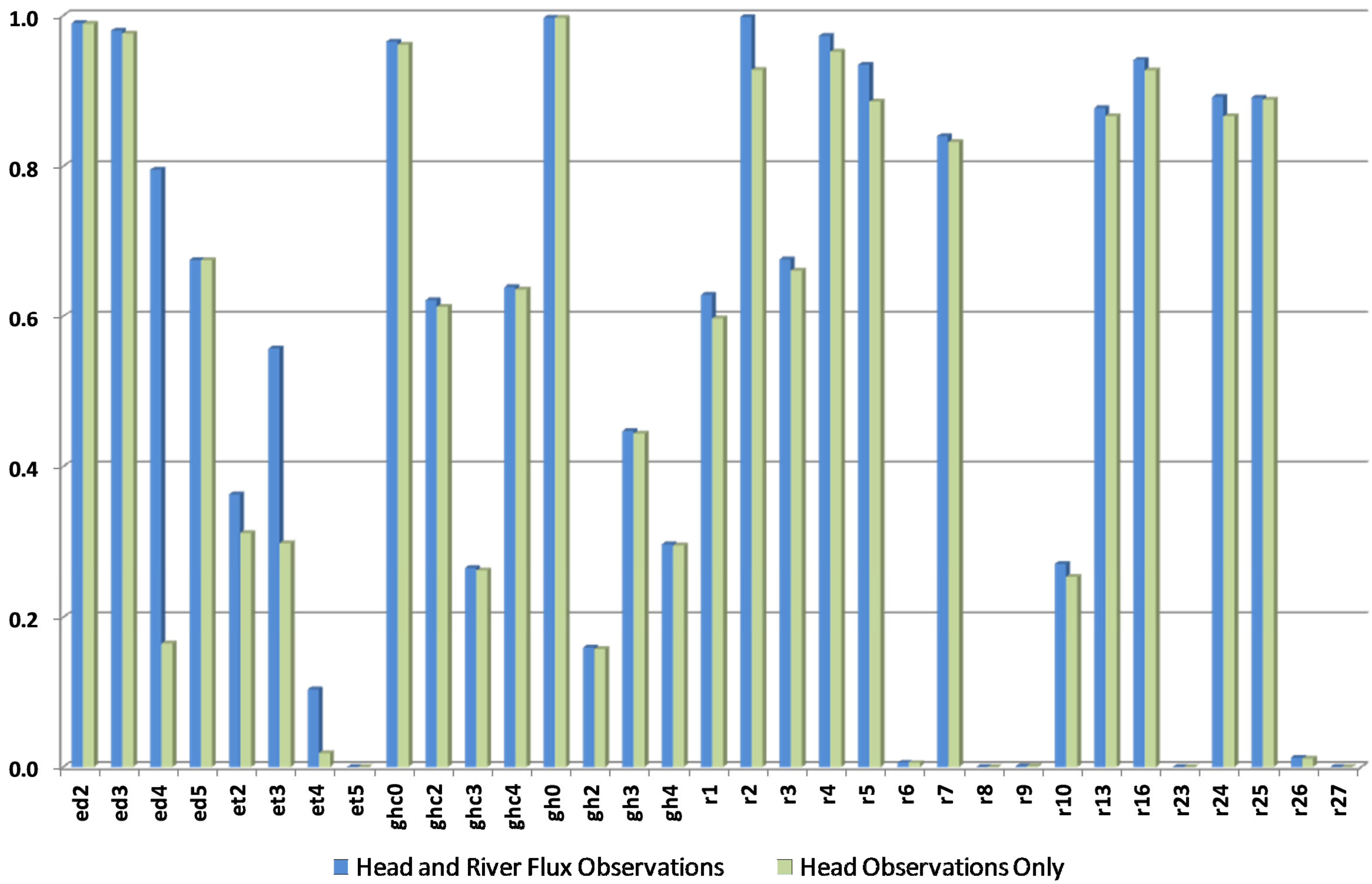


FIGURE 2-20
RELATIVE UNCERTAINTY VARIANCE REDUCTION – ET, GH AND RECHARGE PARAMETERS WITH HEAD AND RIVER FLUX, AND HEAD ONLY OBSERVATIONS



2.5 SVD-ASSIST PEST SIMULATION

Horizontal and vertical hydraulic conductivity, recharge rate, and ET rate and extinction depth zones along with GHB head and conductance, and river conductance reaches were used in the creation of PEST SVD-Assist files for parameter estimation. The results of the SVD-Assist can be used in PEST Null Space Monte Carlo simulations. Pilot points were not implemented for this set of simulations. Observations of both head and river reach flux were used as observations.

PEST was first run using NOPTMAX set to 1 such that only derivatives with respect to all parameters are calculated. A total of 118 model runs, one for each parameter, were first implemented to calculate parameter sensitivities and the Jacobian matrix.

Next, the PEST utility SUPCALC was used to evaluate the results of the sensitivity run resulting in a minimum and maximum number of super parameters to use in the SVD-Assist analysis.

Using 45 super parameters chosen based on SUPCALC results, the SVDAPREP PEST utility was used to create a SVD-Assist PEST control file. PEST was then run using the SVD PEST control file 45 times per optimisation iteration determined by the number of super parameters selected (45).

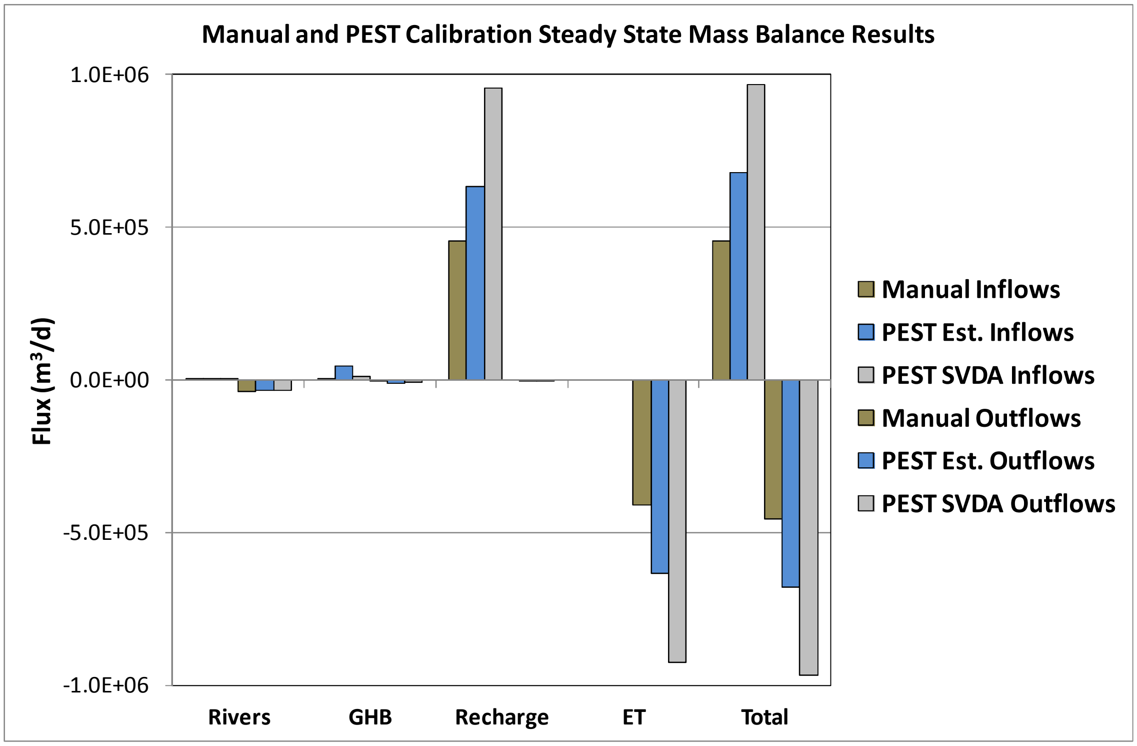
Prior to performing Null Space Monte Carlo simulations a final PEST simulation was taken to update the Jacobian matrix with the final SVD-Assist values. This was done using the PARREP utility to build an updated PEST control file using the base PEST control file and the optimised base parameter values and running PEST using NOPTMAX set to zero, making PEST run only once with the optimised parameter values.

The BGP EIS model PEST files are prepared for a Null Space Monte Carlo simulation.

2.6 PEST REALIZATIONS MASS BALANCES

PEST iteratively decreased the model error in matching heads and river flux observations. However, each decrease in error resulted in an increase in the total water budget, the significance of which is not readily recognized (Figure 2-21). It also resulted in increased groundwater inflow, now greater than outflow, primarily along the south eastern most general head boundary reach 4. The hydrogeologic conceptual model postulates that groundwater movement is predominantly south out of the model southern domain, which was also the case for the manual calibration, but deviates to a greater inflow with the PEST estimation results. Additional review and analysis of the general head boundary conditions and supporting information is warranted.

FIGURE 2-21
COMPARISON OF MANUAL AND PEST CALIBRATED MASS BALANCES



3 BGP MODEL NULL SPACE MONTE CARLO ANALYSIS

3.1 BGP MODEL NULL SPACE MONTE CARLO PROCESS

Null Space Monte Carlo (NSMC) analysis was undertaken for assessment of predictive uncertainty related to predictions made by the BGP model of the northern Bowen Basin, Queensland, Australia developed in support of the EIS. NSMC is often used to examine uncertainty in model predictions. NSMC was implemented in this case using PEST. PEST NSMC methodology is based on the generation of many different parameter sets, all of which are conceptually reasonable, and calibrate the model with a specified level of objective function acceptance. Each of these generated parameter fields constitute a realization that may include any level of detail - well beyond that which can be represented uniquely in a calibrated model. The uncertainty of a prediction can be analysed through simulations carried out using the calibration-constrained realizations.

NSMC simulations were used to develop a set of quantitative bounding statistics on the EIS BGP numerical model drawdown results. NSMC effectively takes a calibrated set of model parameters found through the use of PEST and SVD-Assist, and creates realizations by “tweaking” parameter values out of calibration based on a random number generator or through a random field generator based on a variogram(s), and tries to re-calibrate. NSMC defines stochastic parameter sets projected onto null space while maintaining calibration.

The steady state BGP model was first calibrated against 487 observations including 482 head values from domestic water bores and five river flux reach values using PEST SVD-Assist as described in section 2.5. The final set of 128 parameter zones used in the SVD-Assist calibration included horizontal and vertical hydraulic conductivities, three recharge rate zones, two evapotranspiration rate zones, and two evapotranspiration extinction depth zones selected based on sensitivities generated by prior PEST analyses described in sections 1 and 2. However, the horizontal and vertical hydraulic conductivity zones for each production coal seam were initially set as two main zones, one for each of the two RCM coal seam targets the Leichhardt and the Vermont, and one for the four MCM coal seam targets the Q, P, GM and GML seams, and for the NSMC simulations each individual target coal seam is represented by its own zone number but with similar values. The initial values and ranges for input did not change just the zone numbers which allows PEST to modify the conductivity values in each target coal seam in the BGP model independently. The final steady state calibrated parameter set was then updated in the BGP model and used to generate new PEST control files for SVD-Assisted NSMC analysis. Transient calibration was not performed due to a lack of transient targets which also resulted in the inability to analyse predictive uncertainty around the storage values used in transient model predictions of drawdown. Thus, the evaluation of prediction uncertainty is predicated on the steady state calibration and does not include uncertainty associated with the selected storage values.

The PEST utility RANDPAR was used to generate 100 random new parameter sets based on the SVD-Assist calibrated parameter values. The resulting 100 random parameter sets generated using RANDPAR were then projected onto null space using the PEST utility PNULPAR resulting in a final 100 sets of model parameters for NSMC. The final 100 generated parameter sets were then used to perform 100 PEST estimation simulations using the PARREP utility to place the parameters into the PEST control file after the completion of a previous run. Because the random parameter sets were generated from a calibrated parameter set, the simulation results for each set are not far from the acceptable objective function and only a single optimisation run is performed providing a set of final parameters that will be used in the prediction model simulations. The final set of parameters were then used to assess prediction uncertainty by simulating the transient Bowen Basin model using each of the 100 parameter sets that calibrate the steady state model and comparing the drawdown output at the end of CSG production. The uncertainty analysis focused on the transient model base case scenario with production simulated only for the BGP.

3.2 BGP Model Null Space Monte Carlo Results

The NSMC analysis indicates that the original EIS base case scenario results were conservative in that the maximum predicted drawdown and areal extent of 5 meter drawdown in the CSG target coal seams and the overlying formations were greater than the upper 95% confidence intervals determined from the PEST calibrated model and NSMC analysis and in no NSMC case was a 2 meter draw down created by CSG production in the shallow unconfined alluvial and tertiary basalt aquifers represented in Layer 1 of the BGP model. In most cases the maximum drawdown and 5 meter drawdown areal extents, while greater than the upper 95% confidence intervals, were close to the results from the upper 95% confidence intervals and often matched maximums indicating conservative predictions, or predictions of greater areal impact extent and maximum drawdown, compared to the estimates of potential impacts predicted by the EIS base case model parameter set.

Not all of the 100 parameter sets produced results. Convergence issues were observed in several parameter sets and those simulations were aborted prior to predicting drawdown at the anticipated stress period related to the end of CSG production. This resulted in a subset of 66 of the 100 parameter sets used in the final statistical NSMC analysis. Summary statistics were calculated for the 135 parameters assessed in the analysis and are compared to the EIS base case model (Appendix A).

The 5 meter draw down contours were exported from the NSMC model parameter set results related to the 5 meter draw down areas calculated from the statistical minimum, maximum, lower 95% confidence interval, and upper 95% confidence interval areas for visual comparison to the EIS base case results for each of the primary CSG production seams represented in the model (Appendix B). If the calculated statistical 5 meter drawdown area was not an exact match to a parameter set result area from the 66 model results, the parameter set most closely representing that area was selected. Visual comparison shows that the 5 meter draw down areas for the EIS base case closely match those for the maximums produced from the NSMC simulations indicating that the extent of impact described by the EIS base case is closer to a worst case scenario. Only for the MCM GML target seam, as represented in layer 17 of the BGP model, was the areal 5 meter drawdown extent greater in the EIS base case compared to the maximum generated by the NSMC results (Table 3.1).

Maximum drawdown values at the end of CSG production were obtained from each production seam represented in the BGP model for all 66 NSMC simulations and compared to the EIS base case (Table 3.2). The EIS base case predicted greater maximum drawdown values for the RCM Leichhardt and MCM GML coal seam targets compared to the 66 NSMC simulations supporting conservative predictions reported for the EIS base case. The overlying Rewan Formation /aquitard vertically separating the Tertiary and Quaternary aquifers from the RCM showed a higher maximum drawdown in the NSMC simulations compared to the EIS base case, and for those same simulations producing greater drawdown in the Rewan Formation the overlying aquifers did not show a drawdown of 2 meters or higher indicating that the potential for impact to shallow unconfined aquifers is low.

TABLE 3.1
5 METER DRAWDOWN AREAL EXTENT SUMMARY STATISTICS FOR CSG PRODUCTION LAYERS AT THE END OF CSG PRODUCTION

Parameter Case	L5 (RCM - Leichhardt)	L7 (RCM - Vermont)	L11 (MCM - Q-GMU)	L15 (MCM - GM)	L17 (MCM - GML)
EIS Base Case	3242	1447	551	2158	1825
Minimum	1312	423	131	916	284
Maximum	3398	2059	574	2183	1343
Average	2441	1292	468	1812	669
Standard Deviation	618	445	117	277	337
Median	2252	1188	515	1873	567
Lower 95% CI	2292	1184	440	1745	588
Upper 95% CI	2590	1399	496	1879	750
5th Percentile	1711	667	145	1263	303
95th Percentile	3292	1895	538	2135	1253

TABLE 3.2
MAXIMUM DRAWDOWN (METERS) SUMMARY STATISTICS FOR CSG PRODUCTION LAYERS AND OVERLYING REWAN AQUITARD AT THE END OF CSG PRODUCTION

Parameter Case	L4 (Rewan/Permian)	L5 (RCM - Leichhardt)	L7 (RCM - Vermont)	L11 (MCM - Q-GMU)	L15 (MCM - GM)	L17 (MCM - GML)
EIS Base Case	22.6	403	485	26.0	283	191
Minimum	6.9	363	41.6	16.8	17.9	11.8
Maximum	46.4	404	291	34.1	483	38.0
Average	20.1	391	97.4	25.0	189	20.3
Standard Deviation	9.1	17.6	61.0	2.47	158	6.83
Median	20.3	402	77.9	25.9	129	18.3
Lower 95% CI	17.9	387	83	24.4	151	18.7
Upper 95% CI	22.3	396	112	25.6	228	22.0
5th Percentile	9.4	363	46	19.2	28	12.8
95th Percentile	38.4	404	201	26.2	466	30.9

4 BGP MODEL PARETO FRONT ANALYSIS

4.1 BGP MODEL PARETO FRONT PROCESS

PEST software was also used to assess BGP model predictive uncertainty by implementing a Pareto front analysis using the transient base case BGP only production transient model. Because there are no available transient targets the steady state targets were placed into the transient model in the stress period just prior to the onset of pumping thus simulating steady state conditions up to that point. The 128 calibrated parameters were used in the Pareto front PEST control file along with the modelled observation heads instead of actual target heads. This results in the initial Pareto front objective function values being close to zero and deviations away from this are relative to the change in parameters. The Pareto front analysis is predicated on the ability of the model to make a hypothesised prediction by changing parameters based on incremental changes in the weight applied to the prediction observation. The objective function of the predicted observation can be plotted against the objective function of all other observations to produce the Pareto front. The Pareto front represents the trade-off between the matching of two objective functions where neither can be simultaneously satisfied. The two objective functions are the calibration and prediction objective functions. The calibration objective function is the starting point for the analysis and comprises the calibration dataset with the prediction observation having zero weight. The weight of the prediction observation is incrementally increased and the parameters adjusted to match the prediction and minimize the total objective function.

Pareto mode in PEST provides quantitative bounding probabilities through multiple simulations, and allows the calculation of predictive confidence intervals. The predictive confidence intervals are identified in Pareto Front analysis differently than in NSMC. Instead of warping parameter values and trying to re-calibrate as is done in NSMC, Pareto mode causes the PEST simulations to traverse the Pareto front by assigning ever-increasing weights to selected observations or observation groups specified by the user. The different assigned observation weights results in PEST writing a Pareto objective function file that can be plotted and mapped to observe the trade-off in model calibration for fit to the predicted observation.

The prediction observation chosen for this analysis is a drawdown of 2 meters at a hypothetical well placed in the alluvium near the Braeside borefield in the Isaac Connors alluvium near the eastern model boundary. While the prediction could be any such hypothetical prediction, the chosen prediction was selected as drawdown at a well in an area with higher usage indicating a potentially more sensitive area. The drawdown of 2 meters was selected based on the DNRM trigger threshold of 2 meter water level declines in shallow unconfined aquifers associated with CSG operations.

The 128 parameters were selected for the Pareto front analysis. The selected parameters are the same parameters selected for the NSMC analysis and are primarily comprised of horizontal and vertical hydraulic conductivity. Similar to the NSMC parameters the parameters selected for Pareto front analysis did not include storage because transient targets were not available and thus the impacts of storage on predictions could not be assessed.

4.2 BGP MODEL PARETO FRONT RESULTS

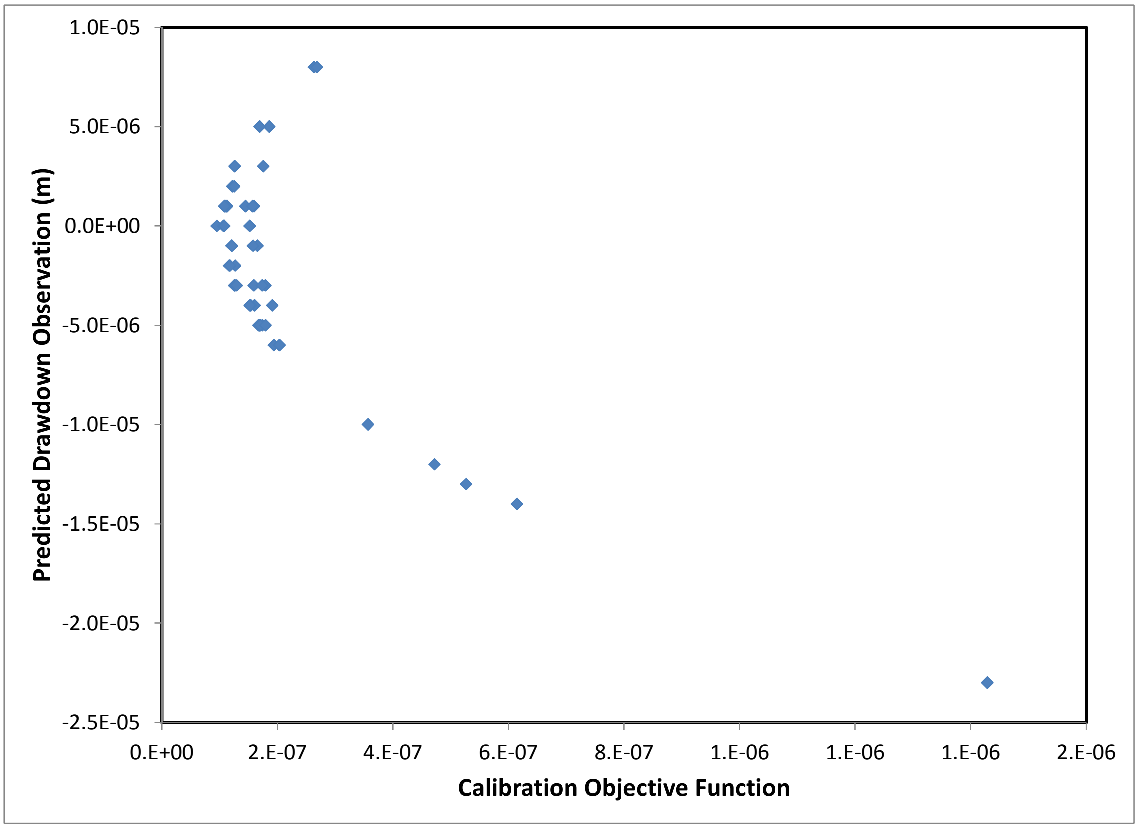
The Pareto front results were reviewed after 53 optimization iterations and 13,629 model calls. The 53 optimization iterations provide the contribution to the objective function, phi, for each observation group which in this case is all the calibration observation heads as one group, the regularization group as another, and the single prediction observation associated with the hypothetical well and drawdown at the end of CSG production.

None of the 53 optimization iterations produced a 2 meter or greater drawdown at the selected location in the Braeside borefield alluvium although the simulations were terminated before the largest weighting factor of 1 was applied. However, the 53rd optimization iteration was associated with a weighting factor of 0.866 and close to the final value of 1 indicating that the Pareto front analysis as defined was near completion.

The trade-off between the prediction of drawdown at the hypothetical well and the sum of the contributions from each calibration observation group, heads and regularization in this case, to the calibration objective function indicates that the 2 meter drawdown prediction cannot be achieved without significant degradation of the model calibration to the observed heads (Figure 4-1).

The drawdown predictions are very small (-2.3E-5 to 8E-6 meters), much less than reasonably quantifiable (Figure 4-1). Additionally, many of the model predictions of drawdown are negative values indicating that the water level at the well has increased and not decreased. These very small numbers are more likely due to noise and the model cannot predict such small changes with any certainty. However, even with the prediction of small drawdown values the calibration objective function shows two orders of magnitude degradation. The degradation in model calibration in trying to reach greater values of drawdown indicates that the predicted drawdown of 2 meters or more in the Braeside borefield alluvium at the end of CSG production is highly unlikely.

FIGURE 4-1
PEST PARETO FRONT PREDICTED DRAWDOWN OBSERVATION VERSUS CALIBRATION OBJECTIVE FUNCTION



5 RECOMMENDATIONS

This report describes the BGP model parameter and predictive uncertainty analyses using PEST. Priority areas in general for new monitoring locations can be evaluated using the current results. The existing results can also be built upon to add further value using additional PEST analyses with hypothetical observation placement and testing data to identify optimum observation locations and types, and additional NSMC and Pareto front analyses incorporating storage for calibration and as an adjustable parameter.

New monitoring/testing wells should include quantification of horizontal and vertical hydraulic conductivity and static head values for coal measure interburden and Permian formations at depth close to that of the coal measures or deeper such as the Back Creek Group. Optimal locations for such wells can be tested through additional model PEST simulations.

5.1 PEST AND GENLINPRED ANALYSIS OF THEORETICAL NEW MONITORING LOCATIONS

GENLINPRED can be used to provide insight into the gathering of new data from different theoretical monitoring locations and data types. New monitoring well locations can be assessed in their ability to reduce parameter estimation and model calibration error by placing theoretical monitor wells in the model, either on a grid basis or through other prior information. Then, running PEST to calculate parameter sensitivities to the new theoretical observations and create a Jacobian matrix which can then be used with GENLINPRED to provide a qualitative assessment as to which locations provide the most reduction in error. Similarly, the incorporation of other observation types may be tested, including surface water monitoring locations, ET monitoring locations, or recharge testing areas.

5.2 PREDICTIVE UNCERTAINTY AND DATA WORTH USING TRANSIENT MODEL

The focus to date has been on the predictive error/uncertainty and data worth around the steady-state model. The hydraulic conductivities, vertical and horizontal, are key primary parameters controlling steady-state groundwater flow model results, however in predictive transient simulations the Permian specific storage parameters are just as important in predictions as hydraulic conductivities and should be assessed and used in model calibration.

Similar statistical analyses can be employed for the transient BGP EIS model including storage as an adjustable parameter, providing further confidence in model predictions. However, in order to provide a transient predictive error and data worth analysis observation data is required. As noted in the BGP EIS groundwater model report the only transient data available is CSG well data that is associated with two phase flow and requires additional work or corrections to be properly represented in a single phase model. There may also be the potential to incorporate newly acquired monitor well data that is not associated with two phase flow as Arrow continues with its environmental data gathering.

6 SUMMARY OF ASSESSMENT

PEST in regularization and estimation (calibration) modes and the associated GENLINPRED utility were used for the initial assessment of parameter predictive error/uncertainty and data worth of the BGP EIS base case steady-state model as presented. The initial PEST parameter estimation results and sensitivities, and analysis of identifiabilities and predictive error reduction using the GENLINPRED utility, provide insight into parameter predictive uncertainty and data worth for the parameters in the existing EIS base case BGP model in steady-state. The parameter identifiabilties and sensitivities were used to select 128 parameters for NSMC and Pareto front analysis of BGP model prediction uncertainty. A summary of the predictive uncertainty and data worth analysis is provided:

GENLINPRED Results

- A set of 23 out of 113 parameters are identifiable
- Calibration resulted in relative error/uncertainty variance reduction the 23 parameters
- Supports determining areas of data acquisition

PEST Parameter Estimation Mode Results

- Parameters sensitive to model calibration identified
- Parameters insensitive to model calibration identified
- 95% confidence intervals on parameter values identified
- Supports determining areas of data acquisition

PEST SVD-Assist Mode Results

- Additional reduction in parameter error estimation
- New set of parameters resulting in lower calibration and mass balance error
- Incorporated new conductivity zone numbers for coal measures
- Prepped for NSMC and Pareto simulations removing the least identifiable parameters

PEST BGP Model Prediction Uncertainty Results (NSMC and Pareto)

- Generated model parameter summary statistics
- Generated 5 meter drawdown areal extent summary statistics
- Generated maximum drawdown summary statistics
- Low probability of 2 meters or more drawdown within unconfined shallow aquifers
- BGP EIS base case model is conservative predicting drawdown on the higher end within the CSG production layers for both spatial extent and maximums.

The majority of observations used in calibration are head observations found within layers 1 and 2 representing alluvium and Tertiary basin infill resulting in the lowest relative parameter error/uncertainty for those parameter zones. The relatively few head observations available in the Permian formations provide some control in reducing the parameters associated with the Permian zones in the BGP EIS model. However, the error/uncertainty for the hydraulic conductivity zones of the Permian formations is still relatively high and the model would benefit from additional monitoring wells and testing in those zones. Specifically testing the interburden for horizontal and vertical conductivities separating the coal measures would greatly increase the confidence in model predictions.

While, the drawdown predictions are focused on impacts to the shallower aquifers, as these are the most important receptors that could be impacted by CSG operations, the model should also be calibrated with respect to values in the deeper formations targeted by CSG operations, because these are the formations that will have large quantities of groundwater extracted from them, and attention to parameter sensitivities in the deeper layers including interburden should also be considered for analysis.

APPENDIX A

BGP MODEL NSMC PARAMETER SUMMARY STATISTICS

TABLE A.1

NSMC BGP MODEL ALLUVIUM, BASALT, UNDIFFERENTIATED BLACKWATER GROUP PERMIAN SUBCROP/OUTCROP, AND TERTIARY AND TRIASSIC SEDIMENTS HORIZONTAL AND VERTICAL CONDUCTIVITY PARAMETER ZONES SUMMARY STATISTICS

	Horizontal Conductivity Parameters														
	Alluvium			Colluvium	Basalt	Tertiary Sediments			Triassic Sediments			Ferricrete	Intrusives	BWG	BCG
Parameter Statistic	**kx1**	**kx2**	**kx28**	**kx3**	**kx4**	**kx5**	**kx6**	**kx7**	**kx8**	**kx9**	**kx10**	**kx26**	**kx27**	**kx25**	**kx24**
EIS Base Case	40	1.0	1.00	1.0	5.00E-02	5.00E-02	1.0	5.00E-02	7.50E-04	0.050	7.50E-04	5.00E-02	5.00E-04	5.00E-04	4.40E-04
Minimum	2.50	0.53	0.55	4.52	6.74E-02	6.88E-02	0.10	4.87E-02	5.00E-04	0.050	8.42E-05	1.00E-05	1.00E-05	1.00E-02	1.23E-05
Maximum	3.39	0.58	1.72	4.98	7.14E-02	7.43E-02	10.0	6.18E-02	5.00E-02	5.000	1.00E-02	5.00E-02	5.00E-04	1.00E-02	3.33E-05
Mean	2.94	0.57	1.09	4.68	6.95E-02	7.23E-02	0.55	5.45E-02	7.93E-03	1.460	1.28E-03	4.66E-03	2.30E-04	1.00E-02	1.70E-05
Standard Deviation	0.27	0.01	0.20	0.10	9.07E-04	1.04E-03	2.08	2.23E-03	1.03E-02	1.891	1.32E-03	8.12E-03	2.00E-04	5.24E-18	3.24E-06
Median	2.87	0.57	1.10	4.65	6.95E-02	7.25E-02	0.10	5.41E-02	4.42E-03	0.594	1.27E-03	1.78E-03	1.78E-04	1.00E-02	1.70E-05
95% Upper CI	3.00	0.57	1.14	4.70	6.97E-02	7.25E-02	1.05	5.51E-02	1.04E-02	1.916	1.60E-03	6.62E-03	2.78E-04	1.00E-02	1.78E-05
95% Lower CI	2.87	0.56	1.04	4.66	6.93E-02	7.20E-02	0.05	5.40E-02	5.45E-03	1.004	9.65E-04	2.70E-03	1.82E-04	1.00E-02	1.63E-05
95th Percentile	3.25	0.58	1.38	4.89	7.10E-02	7.38E-02	0.12	5.84E-02	2.30E-02	5.000	2.65E-03	1.89E-02	5.00E-04	1.00E-02	2.16E-05
5th Percentile	2.54	0.54	0.70	4.56	6.80E-02	7.06E-02	0.10	5.25E-02	7.07E-04	0.050	1.90E-04	2.72E-05	1.00E-05	1.00E-02	1.38E-05

	Vertical Conductivity Parameters														
	Alluvium			Colluvium	Basalt	Tertiary Sediments			Triassic Sediments			Ferricrete	Intrusives	BWG	BCG
Parameter Statistic	**kz1**	**kz2**	**kz28**	**kz3**	**kz4**	**kz5**	**kz6**	**kz7**	**kz8**	**kz9**	**kz10**	**kz26**	**kz27**	**kz25**	**kz24**
EIS Base Case	2.00	0.100	1.00E-01	0.100	5.00E-03	5.00E-03	1.00E-01	5.00E-03	1.00E-05	5.00E-03	1.00E-07	5.00E-03	5.00E-06	5.00E-06	8.80E-06
Minimum	0.25	0.010	1.27E-02	0.010	5.00E-03	2.38E-03	1.00E-02	5.00E-04	1.00E-05	5.00E-03	4.62E-08	1.00E-05	1.00E-06	1.09E-06	7.59E-05
Maximum	24.2	2.000	2.00E+00	1.975	7.97E-01	4.21E-03	1.00E+00	5.00E-02	8.07E-04	5.00E-01	1.01E-06	5.00E-03	1.00E-04	1.00E-03	1.00E-04
Mean	3.73	0.319	3.79E-01	0.221	1.55E-01	3.24E-03	2.05E-01	8.30E-03	1.38E-04	1.13E-01	2.06E-07	6.56E-04	3.80E-05	2.29E-04	9.96E-05
Standard Deviation	4.38	0.445	4.48E-01	0.352	1.96E-01	3.17E-04	2.44E-01	9.54E-03	1.57E-04	1.32E-01	1.57E-07	1.06E-03	3.66E-05	3.16E-04	2.96E-06
Median	2.10	0.124	1.84E-01	0.109	8.28E-02	3.18E-03	1.11E-01	5.21E-03	9.16E-05	5.47E-02	1.93E-07	1.85E-04	2.80E-05	5.53E-05	1.00E-04
95% Upper CI	4.79	0.426	4.87E-01	0.306	2.02E-01	3.31E-03	2.64E-01	1.06E-02	1.76E-04	1.45E-01	2.44E-07	9.13E-04	4.68E-05	3.05E-04	1.00E-04
95% Lower CI	2.67	0.211	2.71E-01	0.136	1.07E-01	3.16E-03	1.46E-01	5.99E-03	1.00E-04	8.11E-02	1.68E-07	4.00E-04	2.92E-05	1.53E-04	9.89E-05
95th Percentile	12.51	1.253	1.39E+00	0.951	6.92E-01	3.85E-03	8.63E-01	2.25E-02	3.48E-04	4.31E-01	4.75E-07	2.74E-03	1.00E-04	1.00E-03	1.00E-04
5th Percentile	0.51	0.011	3.03E-02	0.012	6.07E-03	2.75E-03	1.70E-02	9.19E-04	1.77E-05	9.55E-03	6.92E-08	1.85E-05	1.00E-06	4.29E-06	1.00E-04

BWG = Blackwater Group, BCG = Back Creek Group

TABLE A.2
NSMC BGP MODEL RANGAL COAL MEASURES HORIZONTAL AND VERTICAL CONDUCTIVITY PARAMETER ZONES SUMMARY STATISTICS

	Horizontal Conductivity Parameters													
	Coal Seam													Interburden
Parameter Statistic	kx11	kx13	kx41	kx42	kx43	kx44	kx45	kx46	kx51	kx52	kx53	kx54	kx55	kx56	kx12
EIS Base Case	8.20E-04	8.20E-04	5.30E-05	5.30E-04	5.30E-03	0.0320	0.0790	0.159	5.30E-05	5.30E-04	5.30E-03	3.20E-02	0.079	0.159	1.00E-04
Minimum	1.00E-04	1.00E-04	5.33E-06	1.10E-04	1.10E-03	0.0530	0.0530	0.211	5.30E-06	1.35E-04	1.10E-03	1.10E-02	0.053	0.106	1.00E-06
Maximum	2.00E-01	1.91E-01	7.55E-05	1.00E-03	1.10E-02	0.0530	0.1060	0.211	7.77E-05	1.00E-03	1.10E-02	5.30E-02	0.106	0.211	1.00E-02
Mean	2.01E-02	1.39E-02	2.58E-05	4.21E-04	5.52E-03	0.0530	0.0758	0.211	2.40E-05	3.82E-04	3.84E-03	3.61E-02	0.101	0.187	7.35E-04
Standard Deviation	4.22E-02	2.94E-02	1.61E-05	2.59E-04	3.58E-03	0.0000	0.0249	0.000	1.53E-05	2.07E-04	2.26E-03	1.79E-02	0.014	0.042	1.68E-03
Median	4.06E-03	4.49E-03	2.11E-05	3.43E-04	5.20E-03	0.0530	0.0589	0.211	1.93E-05	3.37E-04	3.11E-03	4.22E-02	0.106	0.211	7.48E-05
95% Upper CI	3.03E-02	2.10E-02	2.97E-05	4.83E-04	6.38E-03	0.0530	0.0818	0.211	2.77E-05	4.32E-04	4.38E-03	4.05E-02	0.105	0.197	1.14E-03
95% Lower CI	9.93E-03	6.86E-03	2.19E-05	3.58E-04	4.65E-03	0.0530	0.0698	0.211	2.03E-05	3.32E-04	3.29E-03	3.18E-02	0.098	0.176	3.31E-04
95th Percentile	1.07E-01	7.50E-02	5.50E-05	1.00E-03	1.10E-02	0.0530	0.1060	0.211	5.10E-05	7.72E-04	8.45E-03	5.30E-02	0.106	0.211	3.49E-03
5th Percentile	2.41E-04	1.00E-04	7.62E-06	1.11E-04	1.10E-03	0.0530	0.0530	0.211	5.60E-06	1.56E-04	1.30E-03	1.10E-02	0.053	0.106	3.07E-06

	Vertical Conductivity Parameters													
	Coal Seam													Interburden
Parameter Statistic	kz11	kz13	kz41	kz42	kz43	kz44	kz45	kz46	kz51	kz52	kz53	kz54	kz55	kz56	kz12
EIS Base Case	1.64E-04	1.64E-04	1.06E-05	1.06E-04	1.06E-03	6.40E-03	1.58E-02	3.18E-02	1.06E-05	1.06E-04	1.06E-03	6.40E-03	0.0158	0.0318	1.00E-08
Minimum	1.04E-05	1.00E-05	1.34E-06	3.72E-05	2.75E-04	2.75E-03	1.33E-02	2.65E-02	1.33E-06	2.75E-05	3.67E-04	2.75E-03	0.0133	0.0265	1.00E-09
Maximum	1.00E-03	1.00E-03	4.75E-05	4.98E-04	5.50E-03	2.65E-02	5.30E-02	1.06E-01	4.75E-05	4.97E-04	5.50E-03	2.65E-02	0.0530	0.1059	1.00E-04
Mean	1.91E-04	4.23E-04	1.14E-05	1.69E-04	1.61E-03	1.00E-02	2.78E-02	5.70E-02	1.24E-05	1.41E-04	1.64E-03	1.03E-02	0.0277	0.0554	2.10E-05
Standard Deviation	2.38E-04	3.77E-04	1.12E-05	1.12E-04	1.30E-03	5.90E-03	9.72E-03	1.91E-02	1.08E-05	1.08E-04	1.16E-03	6.11E-03	0.0091	0.0189	3.64E-05
Median	1.13E-04	2.56E-04	6.91E-06	1.52E-04	1.23E-03	8.83E-03	2.71E-02	5.57E-02	9.60E-06	1.14E-04	1.35E-03	8.86E-03	0.0274	0.0499	1.90E-06
95% Upper CI	2.49E-04	5.14E-04	1.41E-05	1.96E-04	1.93E-03	1.14E-02	3.02E-02	6.16E-02	1.50E-05	1.67E-04	1.92E-03	1.18E-02	0.0299	0.0599	2.98E-05
95% Lower CI	1.34E-04	3.32E-04	8.72E-06	1.43E-04	1.30E-03	8.59E-03	2.55E-02	5.24E-02	9.82E-06	1.15E-04	1.36E-03	8.84E-03	0.0255	0.0508	1.22E-05
95th Percentile	7.92E-04	1.00E-03	3.43E-05	3.77E-04	4.58E-03	2.42E-02	4.47E-02	8.81E-02	3.54E-05	3.55E-04	4.16E-03	2.21E-02	0.0436	0.0936	1.00E-04
5th Percentile	1.24E-05	1.20E-05	1.68E-06	4.74E-05	3.41E-04	3.88E-03	1.53E-02	2.71E-02	1.54E-06	3.22E-05	4.82E-04	2.80E-03	0.0157	0.0315	4.89E-09

TABLE A.3
NSMC BGP MODEL MORANBAH COAL MEASURES HORIZONTAL CONDUCTIVITY PARAMETER ZONES SUMMARY STATISTICS

	Horizontal Conductivity Parameters														
	Interburden			Coal Seam											
Parameter Statistic	**kx18**	**kx20**	**kx22**	**kx17**	**kx19**	**kx21**	**kx23**	**kx31**	**kx32**	**kx33**	**kx34**	**kx35**	**kx36**	**kx61**	**kx62**
EIS Base Case	1.00E-04	1.00E-04	1.00E-04	8.20E-04	8.20E-04	8.20E-04	1.00E-04	5.30E-05	5.30E-04	5.30E-03	3.20E-02	0.079	0.159	5.30E-05	5.30E-04
Minimum	1.39E-06	1.00E-06	1.00E-06	1.00E-04	1.00E-04	1.00E-04	1.00E-04	5.30E-06	1.10E-04	1.10E-03	1.10E-02	0.053	0.106	5.30E-06	1.10E-04
Maximum	1.00E-02	5.46E-03	9.54E-03	2.00E-01	2.00E-01	2.00E-01	3.21E-03	9.50E-05	1.00E-03	1.10E-02	5.30E-02	0.106	0.109	9.50E-05	1.00E-03
Mean	7.71E-04	5.77E-04	1.17E-03	1.95E-02	3.51E-02	2.15E-02	2.64E-04	2.89E-05	5.44E-04	5.90E-03	4.86E-02	0.086	0.106	3.39E-05	3.11E-04
Standard Deviation	1.85E-03	8.95E-04	2.37E-03	4.16E-02	6.00E-02	3.97E-02	5.02E-04	2.45E-05	3.44E-04	4.09E-03	1.14E-02	0.024	0.0004	2.36E-05	2.87E-04
Median	9.50E-05	3.40E-04	1.31E-04	4.09E-03	4.96E-03	4.53E-03	1.53E-04	1.76E-05	4.56E-04	4.90E-03	5.30E-02	0.106	0.106	2.71E-05	1.59E-04
95% Upper CI	1.22E-03	7.93E-04	1.74E-03	2.95E-02	4.95E-02	3.11E-02	3.85E-04	3.48E-05	6.27E-04	6.89E-03	5.14E-02	0.092	0.106	3.96E-05	3.80E-04
95% Lower CI	3.24E-04	3.61E-04	6.03E-04	9.42E-03	2.06E-02	1.20E-02	1.43E-04	2.30E-05	4.61E-04	4.92E-03	4.58E-02	0.080	0.106	2.82E-05	2.42E-04
95th Percentile	4.32E-03	2.22E-03	8.01E-03	1.30E-01	2.00E-01	8.71E-02	4.87E-04	9.38E-05	1.00E-03	1.10E-02	5.30E-02	0.106	0.106	8.62E-05	1.00E-03
5th Percentile	2.83E-06	2.24E-05	1.28E-06	2.40E-04	1.24E-04	1.11E-04	1.00E-04	5.30E-06	1.10E-04	1.10E-03	1.46E-02	0.053	0.106	8.64E-06	1.10E-04

	Horizontal Conductivity Parameters - Continued															
	Coal Seam															
Parameter Statistic	**kx63**	**kx64**	**kx65**	**kx66**	**kx71**	**kx72**	**kx73**	**kx74**	**kx75**	**kx76**	**kx81**	**kx82**	**kx83**	**kx84**	**kx85**	**kx86**
EIS Base Case	5.30E-03	0.032	0.079	0.159	5.30E-05	5.30E-04	5.30E-03	0.0320	0.0790	0.159	5.30E-05	5.30E-04	5.30E-03	0.0320	0.079	0.159
Minimum	1.10E-03	0.011	0.053	0.106	5.30E-06	1.10E-04	1.10E-03	0.0110	0.0530	0.106	5.30E-06	1.10E-04	1.10E-03	0.0110	0.053	0.106
Maximum	1.10E-02	0.053	0.106	0.211	9.50E-05	1.00E-03	1.10E-02	0.0480	0.1060	0.211	9.50E-05	1.00E-03	1.10E-02	0.0530	0.106	0.211
Mean	1.01E-02	0.020	0.068	0.183	3.08E-05	3.70E-04	5.48E-03	0.0249	0.0674	0.125	4.41E-05	2.96E-04	3.23E-03	0.0252	0.062	0.149
Standard Deviation	2.42E-03	0.013	0.021	0.044	2.31E-05	2.86E-04	3.52E-03	0.0098	0.0180	0.035	3.28E-05	2.73E-04	3.11E-03	0.0160	0.017	0.044
Median	1.10E-02	0.011	0.054	0.211	2.33E-05	2.99E-04	4.30E-03	0.0238	0.0594	0.106	3.49E-05	1.78E-04	1.80E-03	0.0183	0.053	0.141
95% Upper CI	1.07E-02	0.023	0.073	0.193	3.64E-05	4.39E-04	6.33E-03	0.0273	0.0717	0.133	5.20E-05	3.61E-04	3.98E-03	0.0290	0.066	0.160
95% Lower CI	9.48E-03	0.017	0.063	0.172	2.52E-05	3.02E-04	4.63E-03	0.0225	0.0631	0.116	3.62E-05	2.30E-04	2.48E-03	0.0213	0.058	0.139
95th Percentile	1.10E-02	0.053	0.106	0.211	8.48E-05	1.00E-03	1.10E-02	0.0417	0.1060	0.211	9.50E-05	1.00E-03	1.10E-02	0.0530	0.106	0.211
5th Percentile	3.15E-03	0.011	0.053	0.106	8.58E-06	1.10E-04	1.10E-03	0.0110	0.0530	0.106	5.52E-06	1.10E-04	1.10E-03	0.0110	0.053	0.106

TABLE A.4
NSMC BGP MODEL MORANBAH COAL MEASURES VERTICAL CONDUCTIVITY PARAMETER ZONES SUMMARY STATISTICS

	Vertical Conductivity Parameters														
	Interburden			Coal Seam											
Parameter Statistic	kz18	kz20	kz22	kz17	kz19	kz21	kz23	kz31	kz32	kz33	kz34	kz35	kz36	kz61	kz62
EIS Base Case	2.00E-08	7.00E-08	7.00E-08	1.64E-04	1.64E-04	1.64E-04	7.00E-08	1.06E-05	1.06E-04	1.06E-03	6.40E-03	1.58E-02	3.18E-02	1.06E-05	1.06E-04
Minimum	1.00E-09	1.00E-09	1.00E-09	1.06E-05	1.00E-05	1.26E-05	2.20E-08	1.33E-06	2.75E-05	2.75E-04	2.90E-03	1.33E-02	2.65E-02	1.90E-06	2.75E-05
Maximum	1.00E-04	1.32E-05	1.00E-04	1.00E-03	1.00E-03	1.00E-03	1.00E-03	4.75E-05	5.00E-04	5.50E-03	2.65E-02	5.30E-02	1.06E-01	4.75E-05	5.00E-04
Mean	8.19E-06	8.65E-07	5.94E-06	1.70E-04	1.83E-04	1.95E-04	2.38E-04	4.32E-05	1.60E-04	1.63E-03	9.73E-03	3.16E-02	5.83E-02	2.61E-05	1.46E-04
Standard Deviation	2.09E-05	2.43E-06	1.65E-05	1.68E-04	2.26E-04	2.25E-04	3.75E-04	1.29E-05	1.24E-04	1.33E-03	5.44E-03	1.44E-02	2.10E-02	1.79E-05	1.17E-04
Median	2.63E-07	2.89E-08	3.23E-07	1.18E-04	1.14E-04	1.16E-04	1.75E-05	4.75E-05	1.25E-04	1.21E-03	7.73E-03	2.75E-02	5.25E-02	2.07E-05	1.14E-04
95% Upper CI	1.32E-05	1.45E-06	9.92E-06	2.10E-04	2.37E-04	2.49E-04	3.29E-04	4.64E-05	1.90E-04	1.95E-03	1.10E-02	3.51E-02	6.34E-02	3.04E-05	1.75E-04
95% Lower CI	3.16E-06	2.80E-07	1.95E-06	1.29E-04	1.28E-04	1.41E-04	1.48E-04	4.01E-05	1.30E-04	1.31E-03	8.41E-03	2.81E-02	5.33E-02	2.18E-05	1.18E-04
95th Percentile	6.14E-05	6.00E-06	4.19E-05	4.92E-04	7.82E-04	6.17E-04	1.00E-03	4.75E-05	4.49E-04	4.24E-03	2.04E-02	5.30E-02	9.76E-02	8.62E-05	1.00E-03
5th Percentile	1.23E-09	1.00E-09	2.48E-09	1.94E-05	1.76E-05	1.99E-05	8.20E-08	3.34E-06	3.85E-05	2.97E-04	3.69E-03	1.33E-02	3.07E-02	8.64E-06	1.10E-04

	Vertical Conductivity Parameters - Continued															
	Coal Seam															
Parameter Statistic	kz63	kz64	kz65	kz66	kz71	kz72	kz73	kz74	kz75	kz76	kz81	kz82	kz83	kz84	kz85	kz86
EIS Base Case	1.06E-03	6.40E-03	0.0158	0.0318	1.06E-05	1.06E-04	1.06E-03	6.40E-03	0.0158	0.0318	1.06E-05	1.06E-04	1.06E-03	6.40E-03	0.0158	0.0318
Minimum	2.84E-04	2.92E-03	0.0135	0.0265	1.60E-06	2.75E-05	2.75E-04	2.75E-03	0.0133	0.0265	1.33E-06	2.75E-05	2.75E-04	2.75E-03	0.0133	0.0265
Maximum	5.18E-03	2.65E-02	0.0530	0.1060	4.75E-05	4.20E-04	5.41E-03	2.64E-02	0.0530	0.1060	4.75E-05	4.99E-04	5.49E-03	2.65E-02	0.0530	0.1060
Mean	1.41E-03	1.04E-02	0.0280	0.0578	1.38E-05	1.54E-04	1.77E-03	9.47E-03	0.0306	0.0580	1.60E-05	1.53E-04	1.60E-03	1.11E-02	0.0318	0.0627
Standard Deviation	1.03E-03	6.00E-03	0.0092	0.0171	1.21E-05	9.76E-05	1.13E-03	5.25E-03	0.0135	0.0259	1.35E-05	1.12E-04	1.20E-03	6.42E-03	0.0127	0.0278
Median	1.07E-03	9.09E-03	0.0272	0.0562	8.52E-06	1.36E-04	1.63E-03	8.15E-03	0.0268	0.0547	1.26E-05	1.25E-04	1.32E-03	8.39E-03	0.0287	0.0587
95% Upper CI	1.66E-03	1.18E-02	0.0302	0.0619	1.67E-05	1.78E-04	2.04E-03	1.07E-02	0.0339	0.0642	1.93E-05	1.80E-04	1.89E-03	1.26E-02	0.0348	0.0694
95% Lower CI	1.16E-03	8.91E-03	0.0258	0.0537	1.09E-05	1.30E-04	1.50E-03	8.20E-03	0.0274	0.0518	1.28E-05	1.26E-04	1.32E-03	9.54E-03	0.0287	0.0560
95th Percentile	1.10E-02	5.30E-02	0.1060	0.2110	8.48E-05	1.00E-03	1.10E-02	4.17E-02	0.1060	0.2110	9.50E-05	1.00E-03	1.10E-02	5.30E-02	0.1060	0.2110
5th Percentile	3.15E-03	1.10E-02	0.0530	0.1060	8.58E-06	1.10E-04	1.10E-03	1.10E-02	0.0530	0.1060	5.52E-06	1.10E-04	1.10E-03	1.10E-02	0.0530	0.1060

TABLE A.5
NSMC BGP MODEL FORT COOPER COAL MEASURES HORIZONTAL AND VERTICAL CONDUCTIVITY PARAMETER ZONES SUMMARY STATISTICS

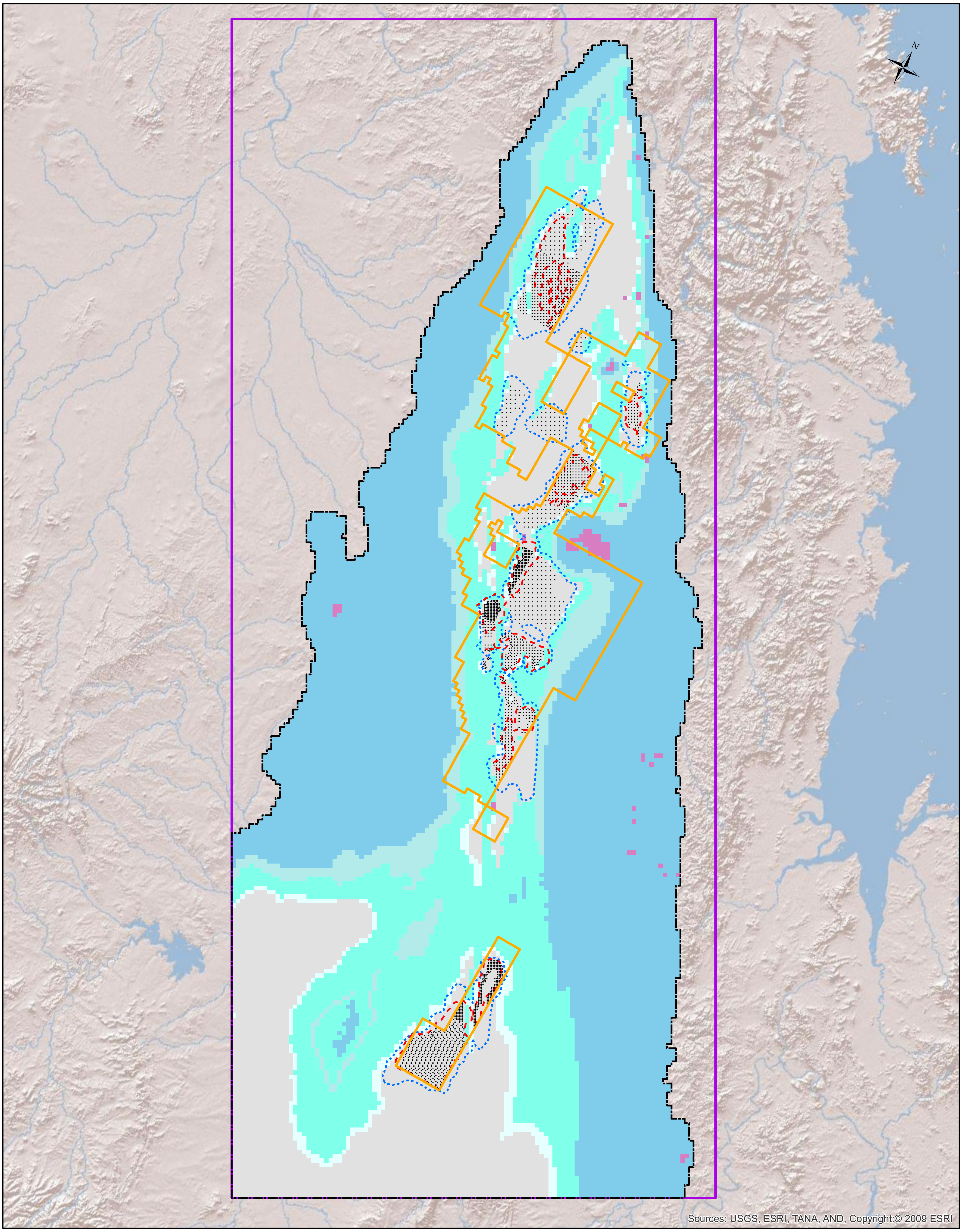
	Coal Measures		Interburden			
Parameter Statistic	**kx15**	**kz15**	**kx14**	**kx16**	**kz14**	**kz16**
EIS Base Case	4.40E-03	8.00E-05	1.00E-04	1.00E-04	1.00E-08	1.00E-08
Minimum	1.00E-04	1.00E-05	1.00E-06	7.55E-04	2.40E-06	2.21E-09
Maximum	1.47E-02	1.00E-03	1.00E-02	1.48E-03	1.00E-04	3.10E-08
Mean	2.76E-03	1.36E-04	2.28E-03	9.75E-04	1.20E-05	1.21E-08
Standard Deviation	3.31E-03	1.74E-04	3.27E-03	1.43E-04	1.31E-05	7.75E-09
Median	8.86E-04	8.06E-05	8.91E-04	9.11E-04	8.45E-06	1.08E-08
95% Upper CI	3.56E-03	1.78E-04	3.07E-03	1.01E-03	1.52E-05	1.40E-08
95% Lower CI	1.97E-03	9.39E-05	1.49E-03	9.40E-04	8.88E-06	1.03E-08
95th Percentile	9.22E-03	3.86E-04	1.00E-02	1.28E-03	2.78E-05	2.17E-08
5th Percentile	1.53E-04	1.06E-05	8.76E-06	8.50E-04	3.61E-06	2.72E-09

TABLE A.6
NSMC BGP MODEL EVAPOTRANSPIRATION RATE, EXTINCTION DEPTH AND RECHARGE PARAMETER ZONES SUMMARY STATISTICS

Parameter Statistic	**et2**	**et3**	**ed2**	**ed3**	**r2**	**r4**	**r5**
EIS Base Case	3.00E-03	2.70E-03	15.0	12.0	3.50E-05	1.60E-05	2.70E-06
Minimum	1.73E-03	1.00E-03	14.9	14.2	4.62E-05	5.00E-05	9.00E-06
Maximum	3.04E-03	1.00E-03	15.3	14.4	4.93E-05	5.00E-05	9.00E-06
Mean	2.55E-03	1.00E-03	15.1	14.3	4.91E-05	5.00E-05	9.00E-06
Standard Deviation	2.17E-04	6.56E-19	0.07	0.04	5.58E-07	3.41E-20	1.71E-21
Median	2.53E-03	1.00E-03	15.1	14.3	4.92E-05	5.00E-05	9.00E-06
95% Upper CI	2.60E-03	1.00E-03	15.1	14.3	4.92E-05	5.00E-05	9.00E-06
95% Lower CI	2.50E-03	1.00E-03	15.1	14.3	4.89E-05	5.00E-05	9.00E-06
95th Percentile	2.86E-03	1.00E-03	15.2	14.4	4.93E-05	5.00E-05	9.00E-06
5th Percentile	2.20E-03	1.00E-03	15.0	14.3	4.80E-05	5.00E-05	9.00E-06

APPENDIX B

BGP MODEL NSMC 5 METER DRAWDOWN STATISTICAL AREAL EXTENTS RELATIVE TO THE EIS BASE CASE PREDICTIONS



Legend

· Future BGP Production Wells

Minimum 5m Drawdown

5

Layer 5 Drawdown (m)

5

EIS Project Area

Active Model Extent

GW Model Domain

Layer 5 Formations

Leichhardt

RCM

FCM

MCM

Back Creek

Intrusives

Data Source

EIS Area, Production Facility Areas: Arrow, 2012

Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55

Projection: Transverse Mercator

Datum: GDA 1994

False Easting: 500,000

False Northing: 10,000,000

Central Meridian: 147

Scale Factor: 1

Latitude Of Origin: 0

Units: Meter

0 25 50 100

Kilometers

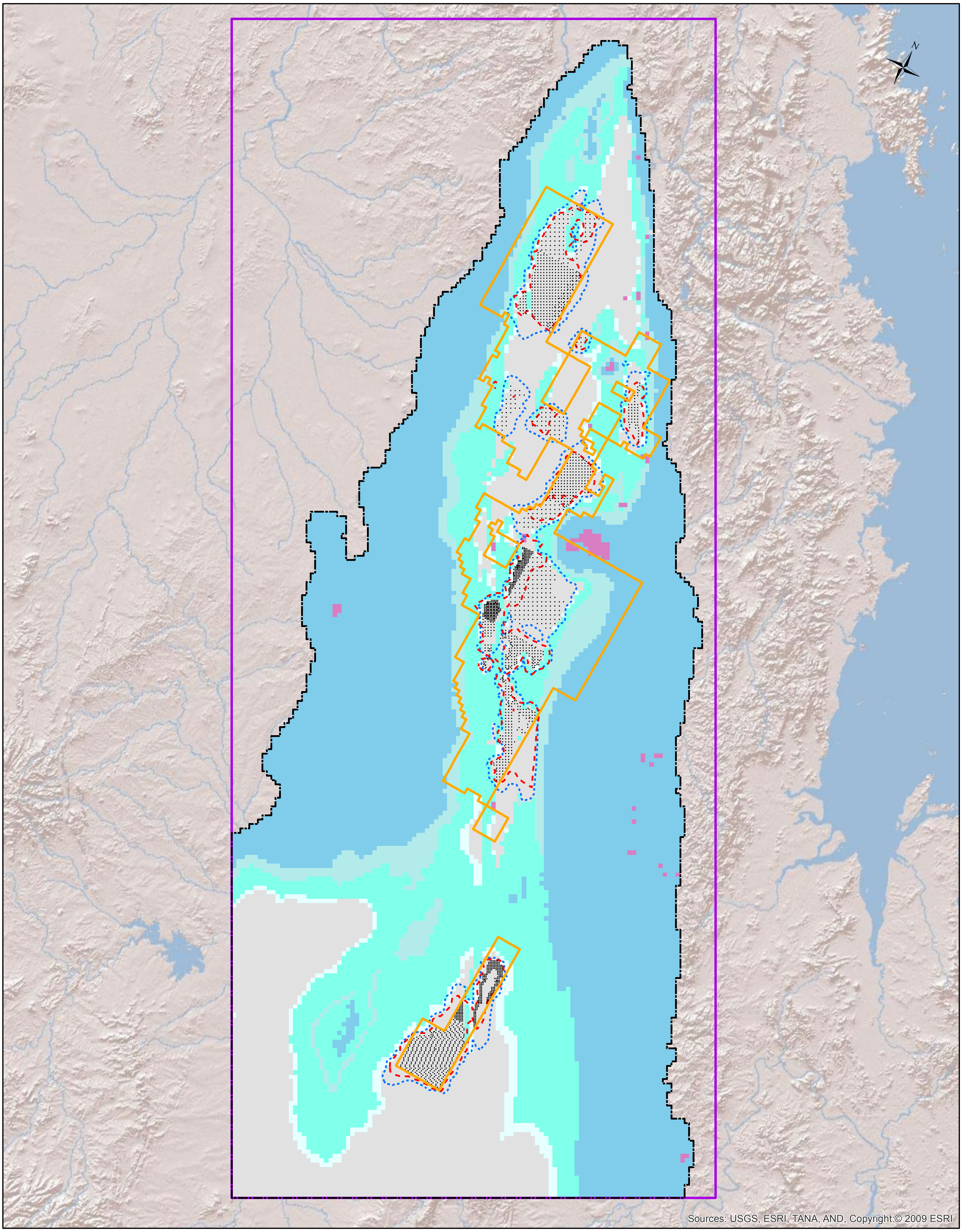
FIGURE B-1A

Modelled Drawdowns Layer 5 - BGP only Base Case at the end of CSG Production with Minimum 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:20:15 PM



Legend

· Future BGP Production Wells
Lower 95% confidence interval 5m drawdown
5
Layer 5 Drawdown (m)
5
EIS Project Area
Active Model Extent
GW Model Domain

Layer 5 Formations
Leichhardt
RCM
FCM
MCM
Back Creek
Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

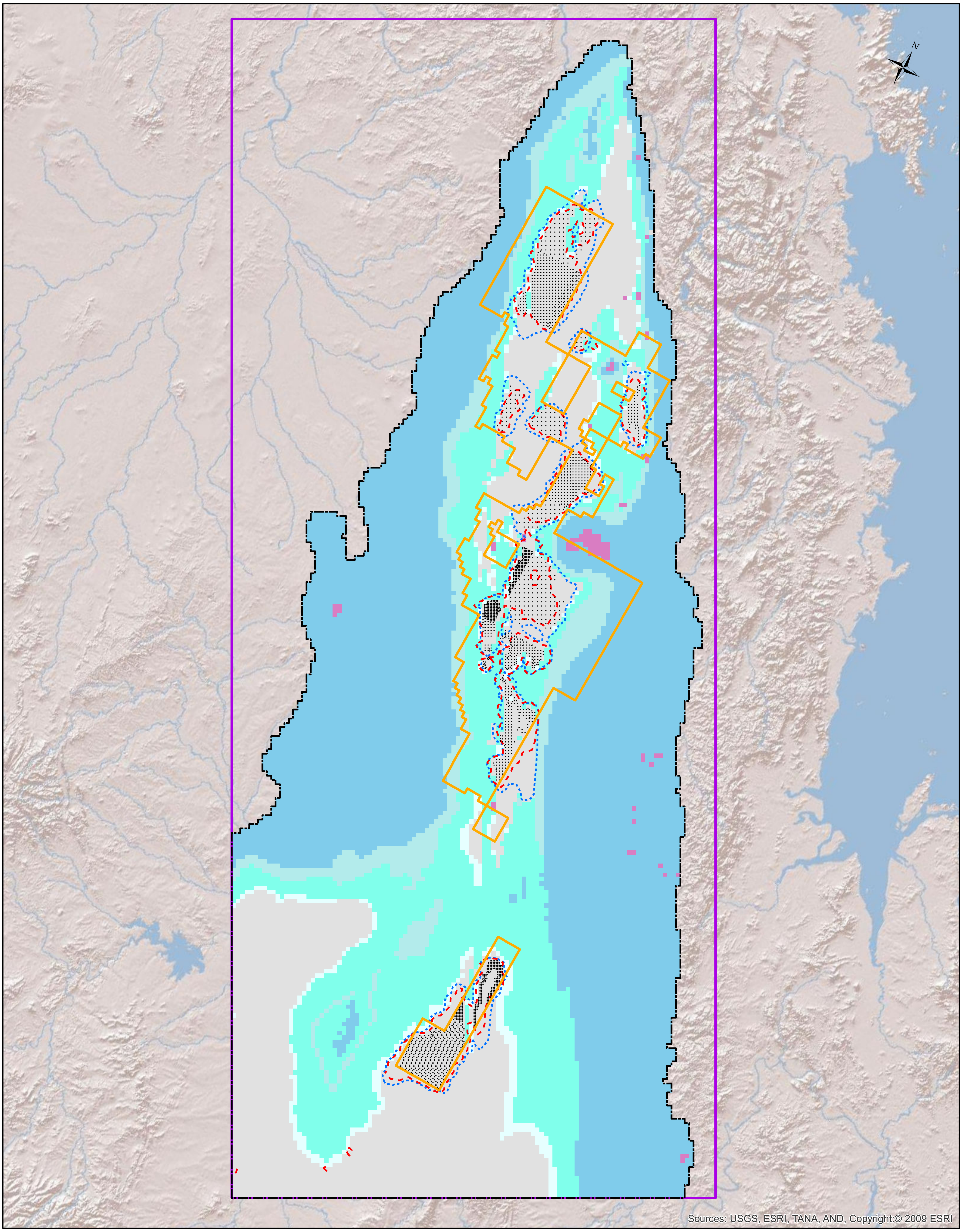
FIGURE B-1B

Modelled Drawdowns Layer 5 - BGP only Base Case at the end of CSG Production with Lower 95% Confidence Interval 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 | Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:36:40 PM



Legend

- Future BGP Production Wells

Upper 95% confidence interval 5m drawdown
- 5

Layer 5 Drawdown (m)
- 5
- EIS Project Area
- Active Model Extent
- GW Model Domain

Layer 5 Formations
- Leichhardt
- RCM
- FCM
- MCM
- Back Creek
- Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2013

0 25 50 100
Kilometers

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

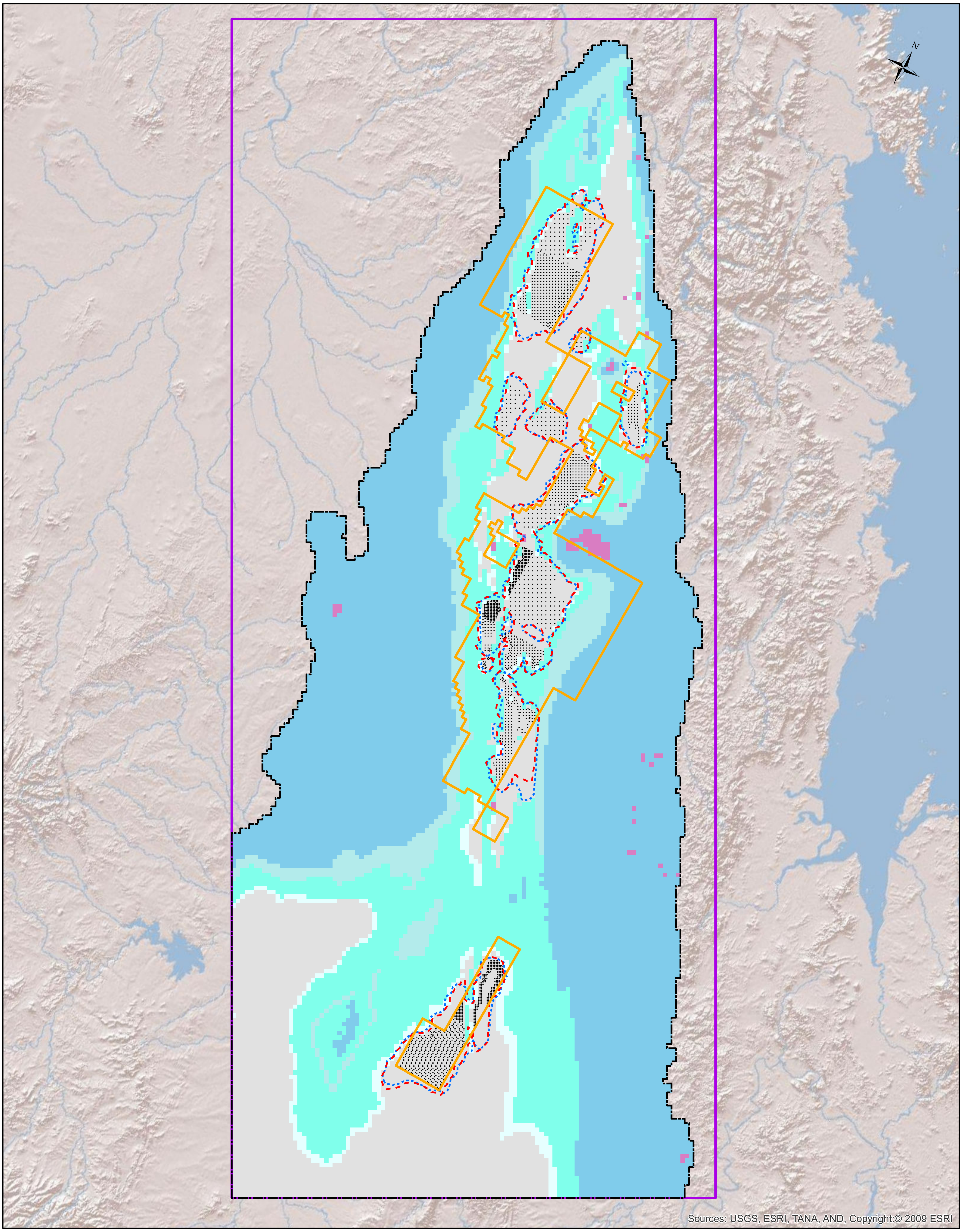
FIGURE B-1C

Modelled Drawdowns Layer 5 - BGP only Base Case at the end of CSG Production with Upper 95% Confidence Interval 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 | Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:42:52 PM



Legend

· Future BGP Production Wells

Maximum 5 m Drawdown

5

Layer 5 Drawdown (m)

5

EIS Project Area

Active Model Extent

GW Model Domain

Layer 5 Formations

Leichhardt

RCM

FCM

MCM

Back Creek

Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2013

0 25 50 100
Kilometers

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

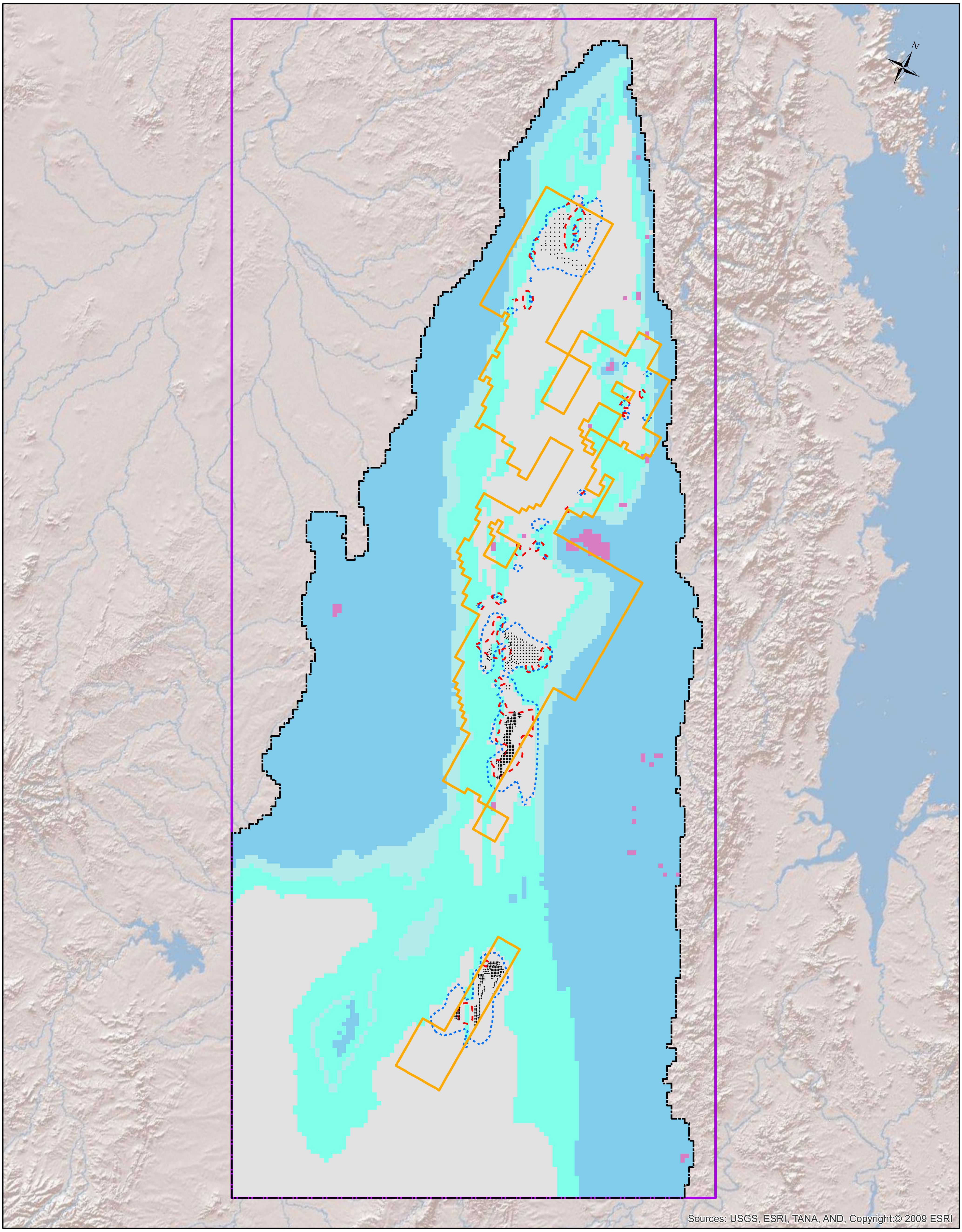
FIGURE B-1D

Modelled Drawdowns Layer 5 -
BGP only Base Case at the end of CSG
Production with Maximum 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013	Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:56:07 PM



Legend

· Future BGP Production Wells

Minimum 5m Drawdown

5

Layer 7 Drawdown (m)

5

EIS Project Area

Active Model Extent

GW Model Domain

Layer 7 Formations

Vermont (RCM)

FCM

MCM

Back Creek

Intrusives

Data Source

EIS Area, Production Facility Areas: Arrow, 2012

Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100

Kilometers

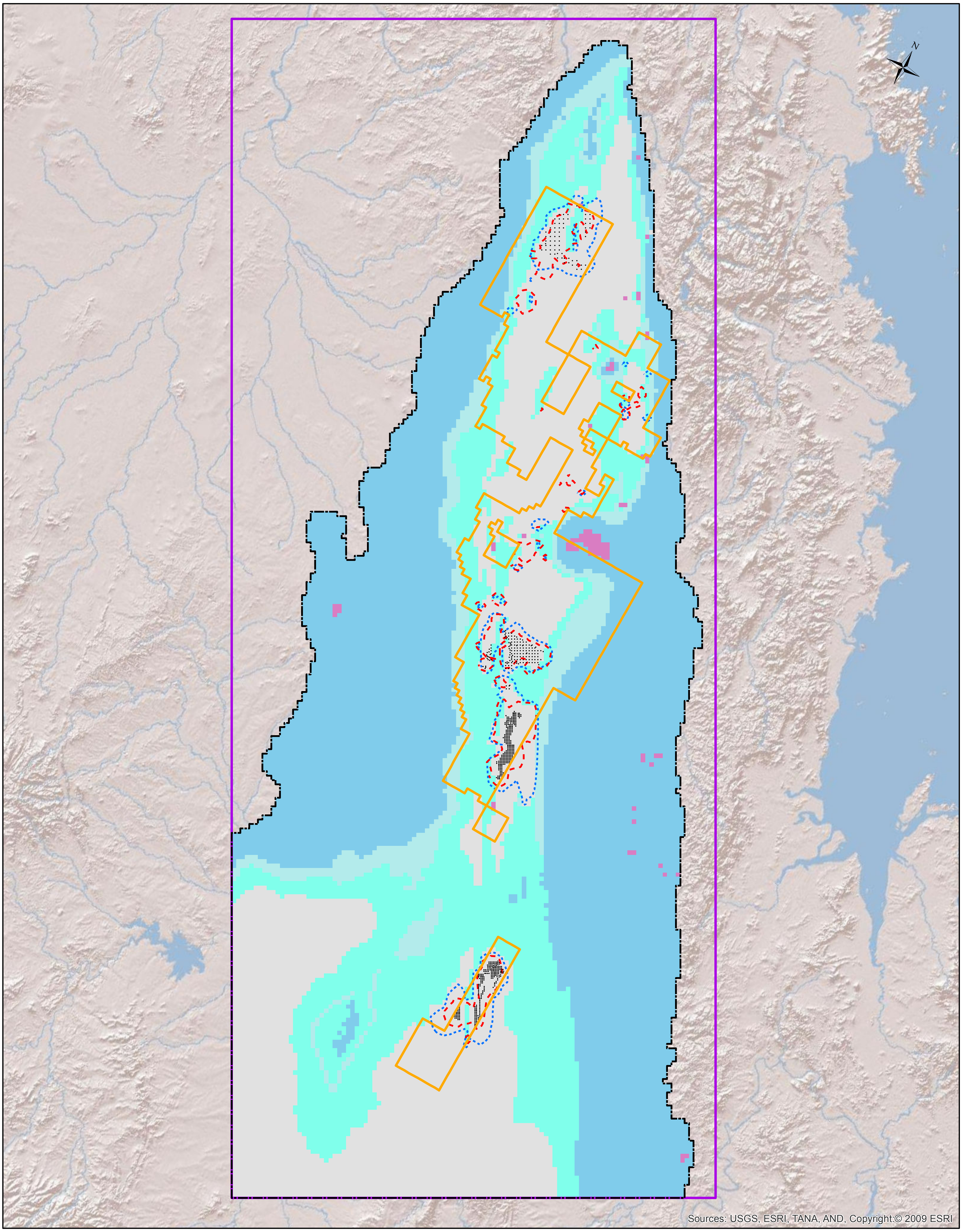
FIGURE B-2A

Modelled Drawdowns Layer 7 - BGP only Base Case at the end of CSG Production with Minimum 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 | Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:22:12 PM



Legend

- · Future BGP Production Wells
- Lower 95% confidence interval 5m drawdown
- 5
- Layer 7 Drawdown (m)
- 5
- EIS Project Area
- Active Model Extent
- GW Model Domain

Layer 7 Formations

- Vermont (RCM)
- FCM
- MCM
- Back Creek
- Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

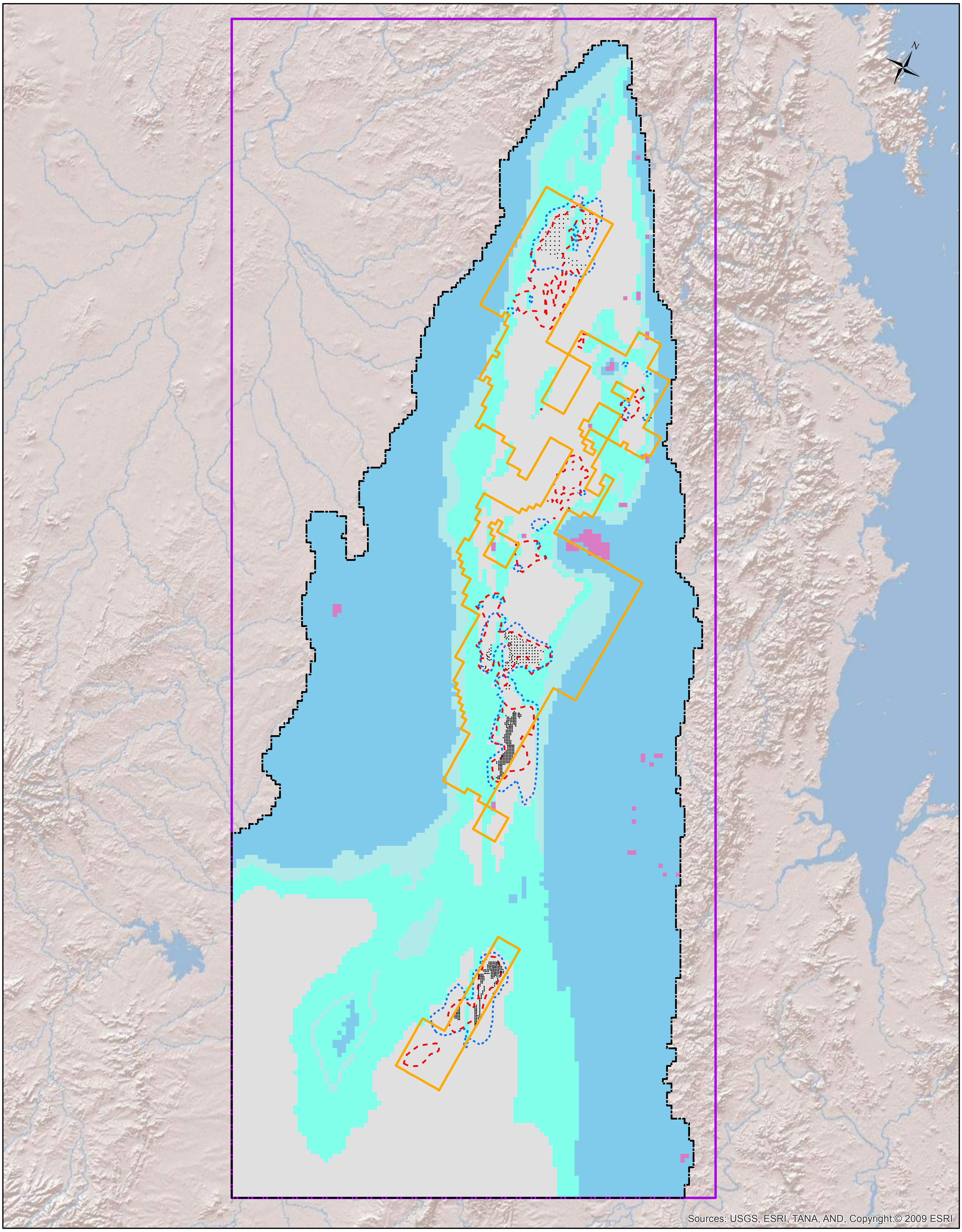
FIGURE B-2B

Modelled Drawdowns Layer 7 - BGP only Base Case at the end of CSG Production with Lower 95% Confidence Interval 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:37:57 PM



Legend

· Future BGP Production Wells

Upper 95% confidence interval 5m drawdown

5

Layer 7 Drawdown (m)

5

EIS Project Area

Active Model Extent

GW Model Domain

Layer 7 Formations

Vermont (RCM)

FCM

MCM

Back Creek

Intrusives

Data Source

EIS Area, Production Facility Areas: Arrow, 2012

Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100

Kilometers

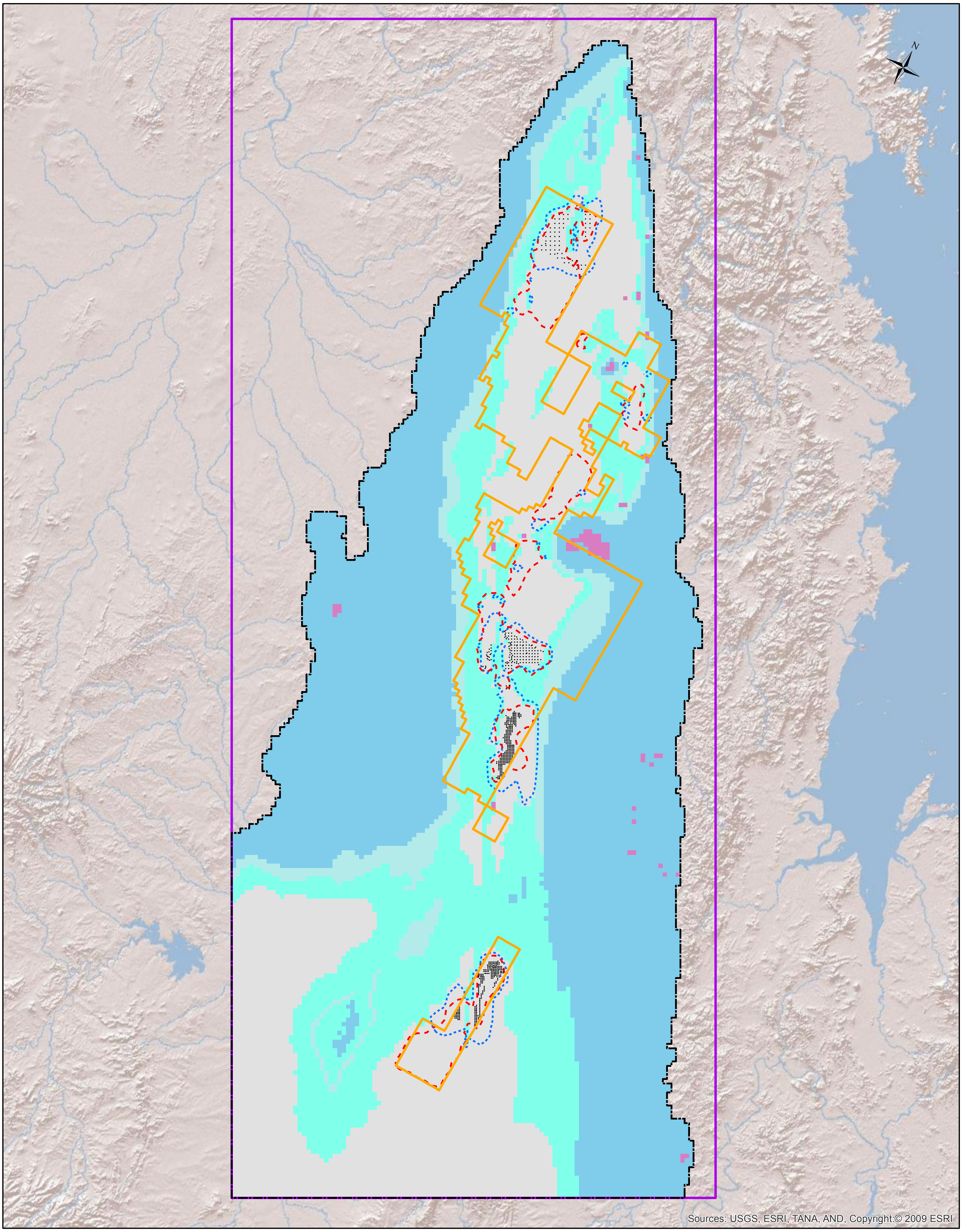
FIGURE B-2C

Modelled Drawdowns Layer 7 - BGP only Base Case at the end of CSG Production with Upper 95% Confidence Interval 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 | Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:43:58 PM



Legend

- Future BGP Production Wells
- Maximum 5 m Drawdown
  - 5
- Layer 7 Drawdown (m)
  - 5
- EIS Project Area
- Active Model Extent
- GW Model Domain

Layer 7 Formations

- Vermont (RCM)
- FCM
- MCM
- Back Creek
- Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

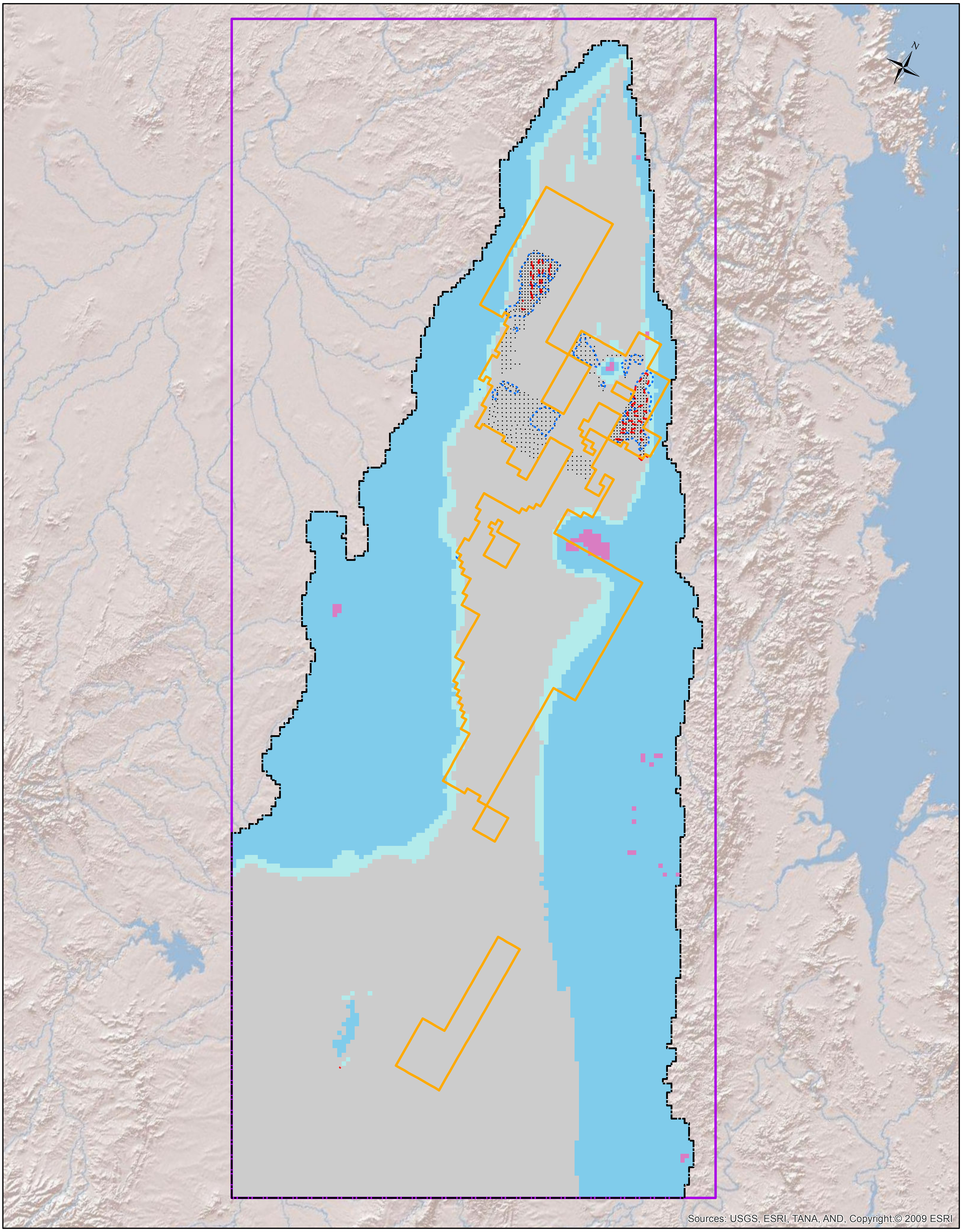
FIGURE B-2D

Modelled Drawdowns Layer 7 - BGP only Base Case at the end of CSG Production with Maximum 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:57:36 PM



Legend

· Future BGP Production Wells

Minimum 5m Drawdown

5

Layer 11 Drawdown (m)

5

EIS Project Area

Active Model Extent

GW Model Domain

Layer 11 Formations

Q Seam (MCM)

MCM

Back Creek

Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

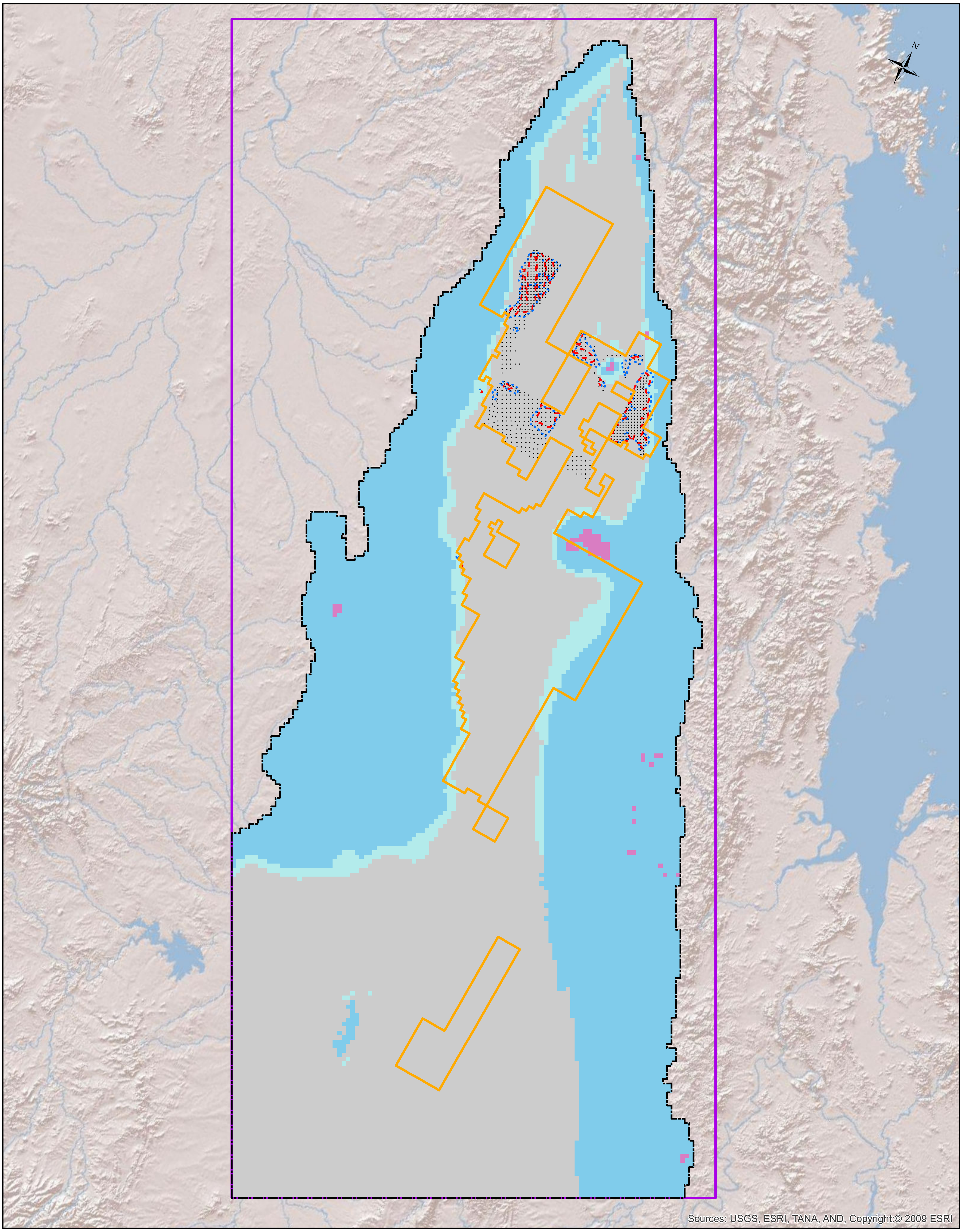
FIGURE B-3A

Modelled Drawdowns Layer 11 - BGP only Base Case at the end of CSG Production with Minimum 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 | Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:23:46 PM



Legend

· Future BGP Production Wells

Lower 95% confidence interval 5m drawdown

5

Layer 11 Drawdown (m)

5

EIS Project Area

Active Model Extent

GW Model Domain

Layer 11 Formations

Q Seam (MCM)

MCM

Back Creek

Intrusives

Data Source

EIS Area, Production Facility Areas: Arrow, 2012

Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100

Kilometers

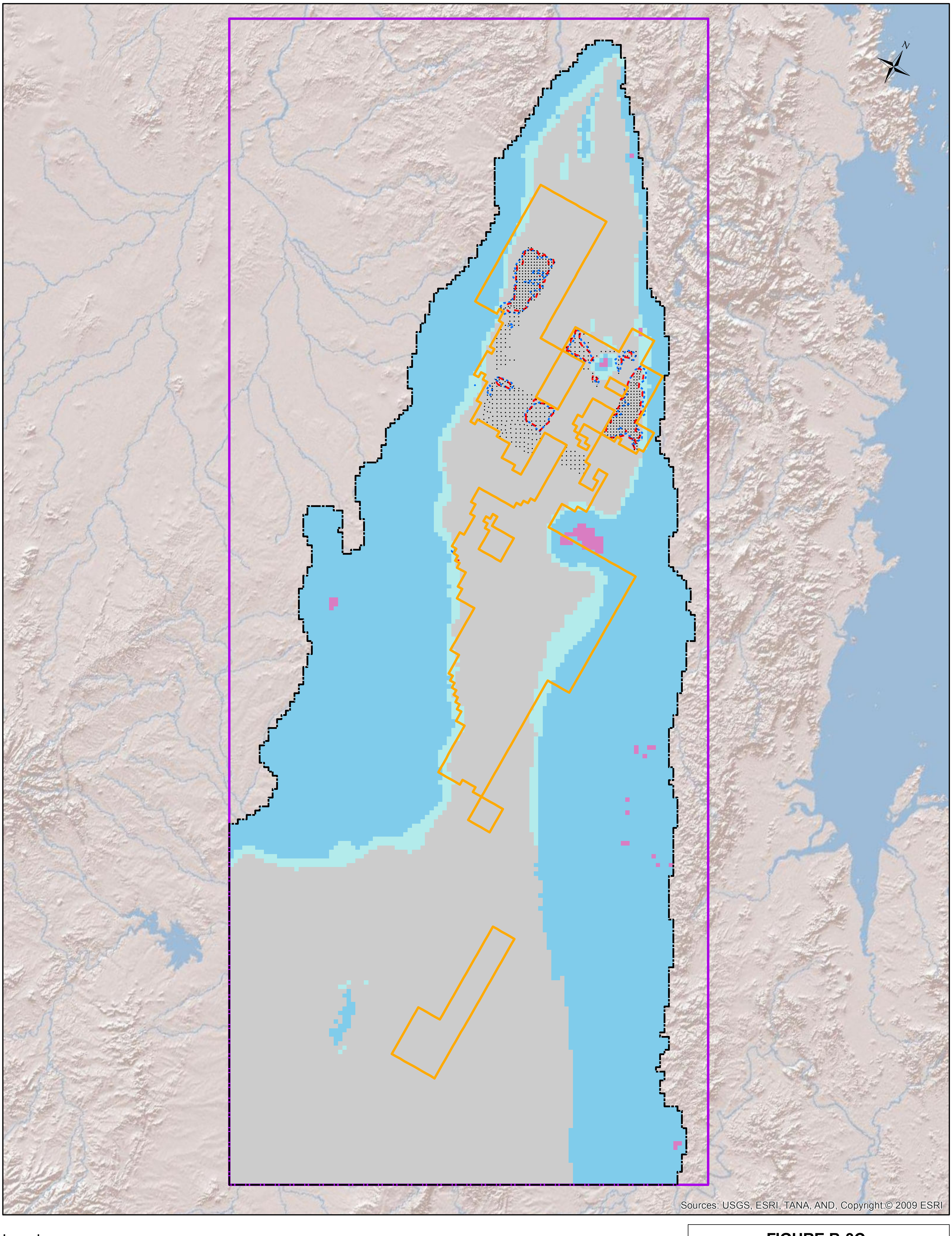
FIGURE B-3B

Modelled Drawdowns Layer 11 - BGP only Base Case at the end of CSG Production with Lower 95% Confidence Interval 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 | Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:38:56 PM



Legend

- Future BGP Production Wells

Upper 95% confidence interval 5m drawdown

- 5

Layer 11 Drawdown (m)

- 5
- EIS Project Area
- Active Model Extent
- GW Model Domain

Layer 11 Formations

- Q Seam (MCM)
- MCM
- Back Creek
- Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

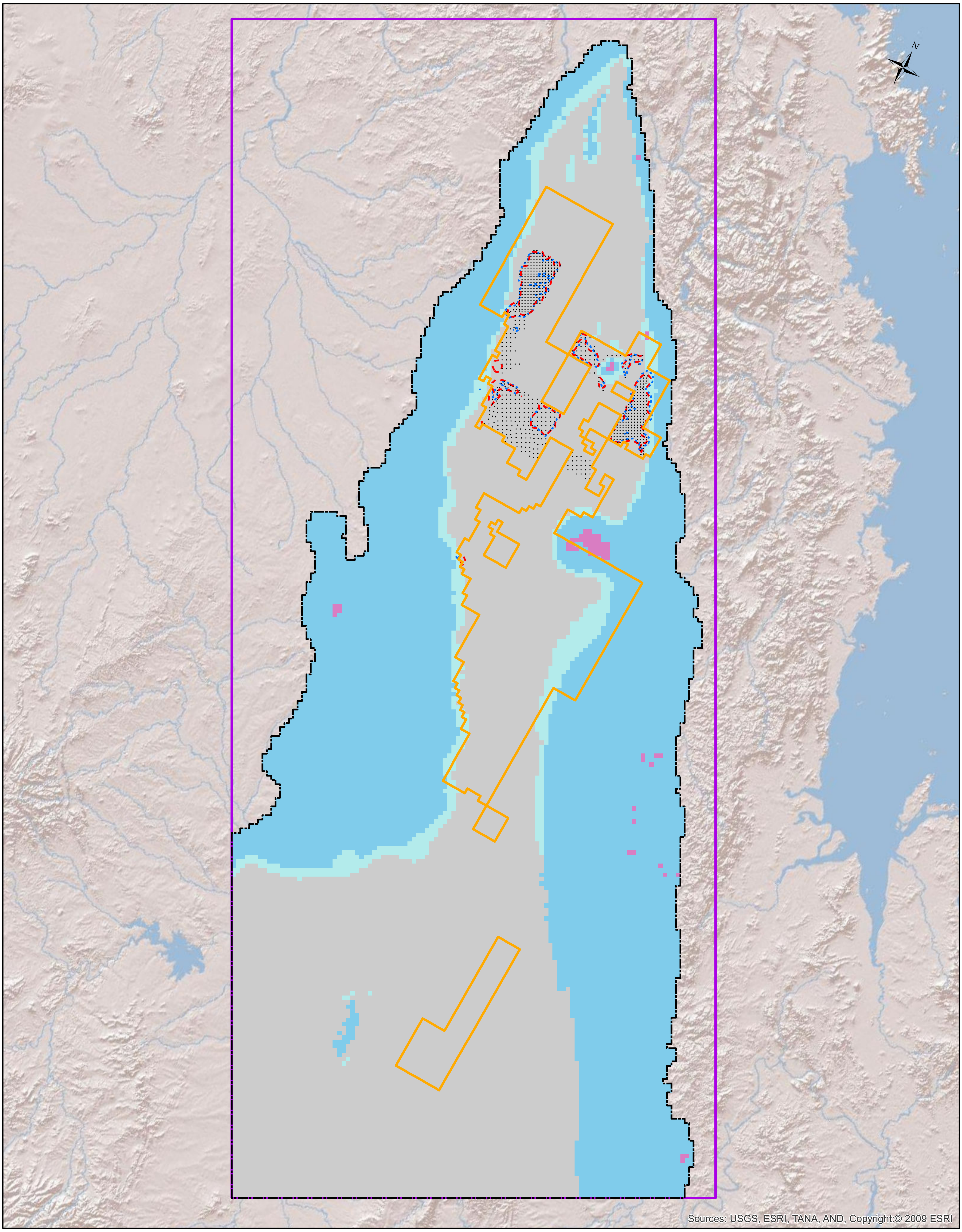
FIGURE B-3C

Modelled Drawdowns Layer 11 - BGP only Base Case at the end of CSG Production with Upper 95% Confidence Interval 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 | Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:45:34 PM



Legend

- Future BGP Production Wells
- Maximum 5 m Drawdown
  - 5
- Layer 11 Drawdown (m)
  - 5
- EIS Project Area
- Active Model Extent
- GW Model Domain

Layer 11 Formations

- Q Seam (MCM)
- MCM
- Back Creek
- Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

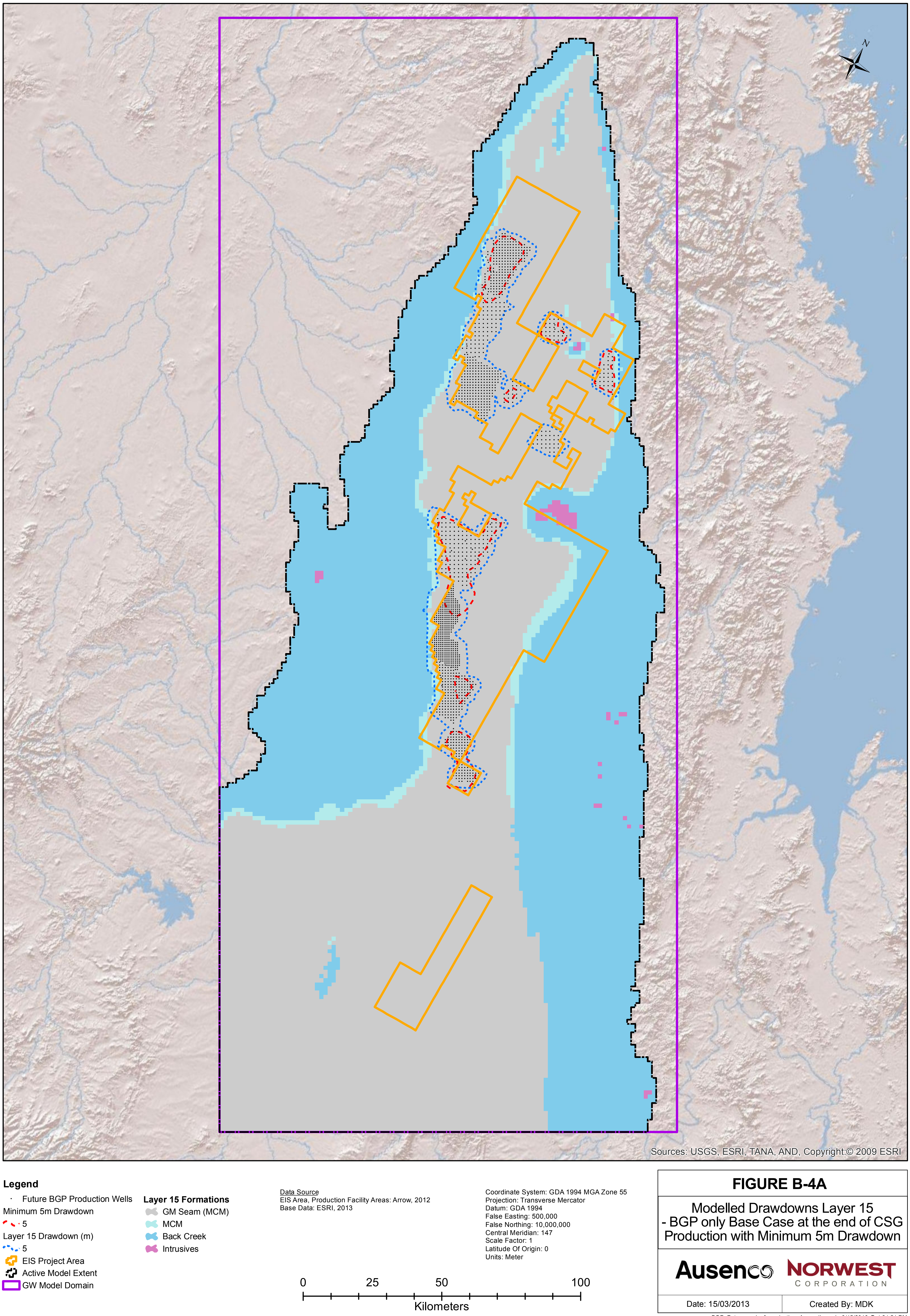
FIGURE B-3D

Modelled Drawdowns Layer 11 -
BGP only Base Case at the end of CSG
Production with Maximum 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 | Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:59:41 PM



Legend

- Future BGP Production Wells

Minimum 5m Drawdown

- 5

Layer 15 Drawdown (m)

- 5
- EIS Project Area
- Active Model Extent
- GW Model Domain

Layer 15 Formations

- GM Seam (MCM)
- MCM
- Back Creek
- Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

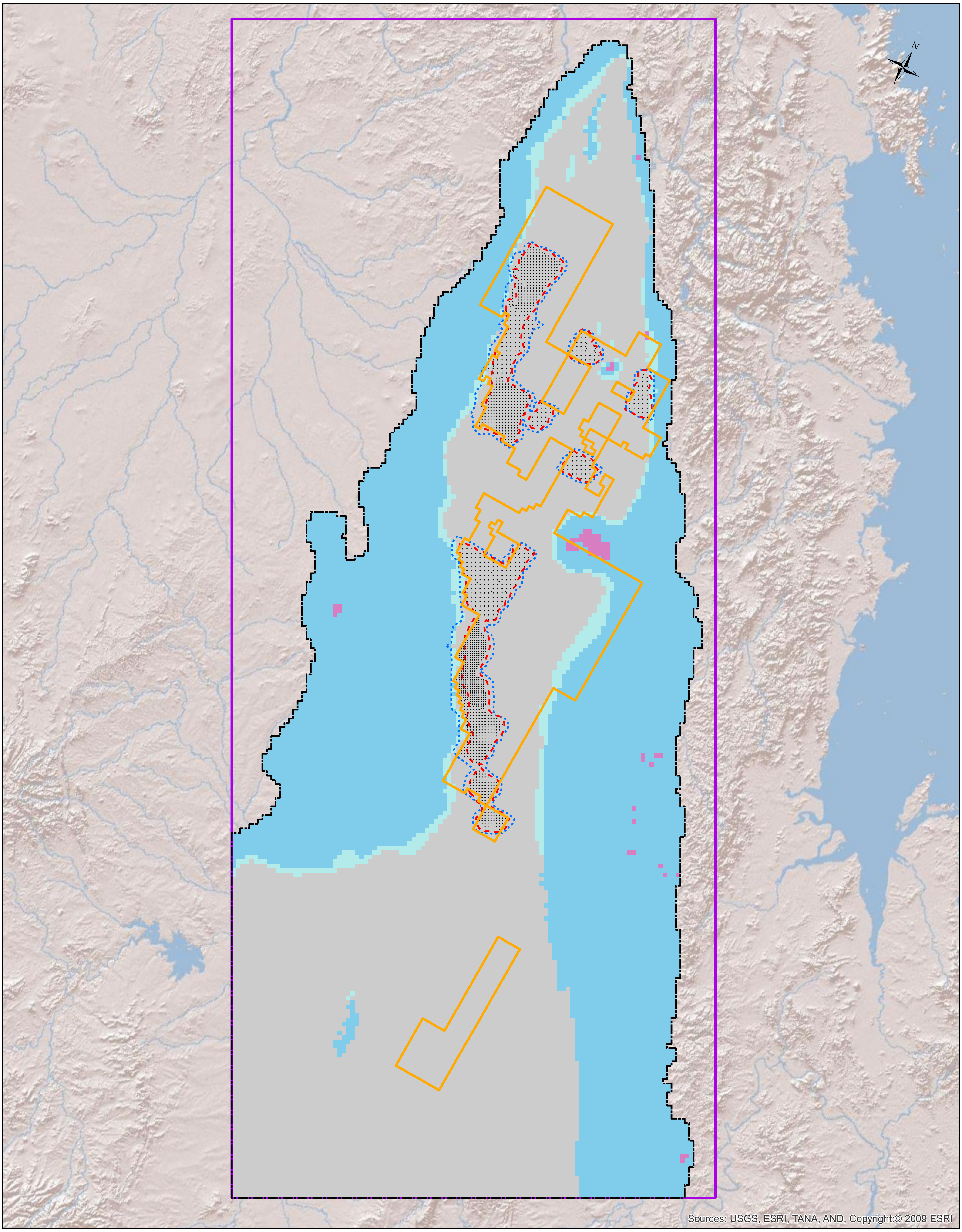
FIGURE B-4A

Modelled Drawdowns Layer 15 - BGP only Base Case at the end of CSG Production with Minimum 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 | Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:24:51 PM



Legend

- Future BGP Production Wells

Lower 95% confidence interval 5m drawdown

- 5

Layer 15 Drawdown (m)

- 5
- EIS Project Area
- Active Model Extent
- GW Model Domain

Layer 15 Formations

- GM Seam (MCM)
- MCM
- Back Creek
- Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

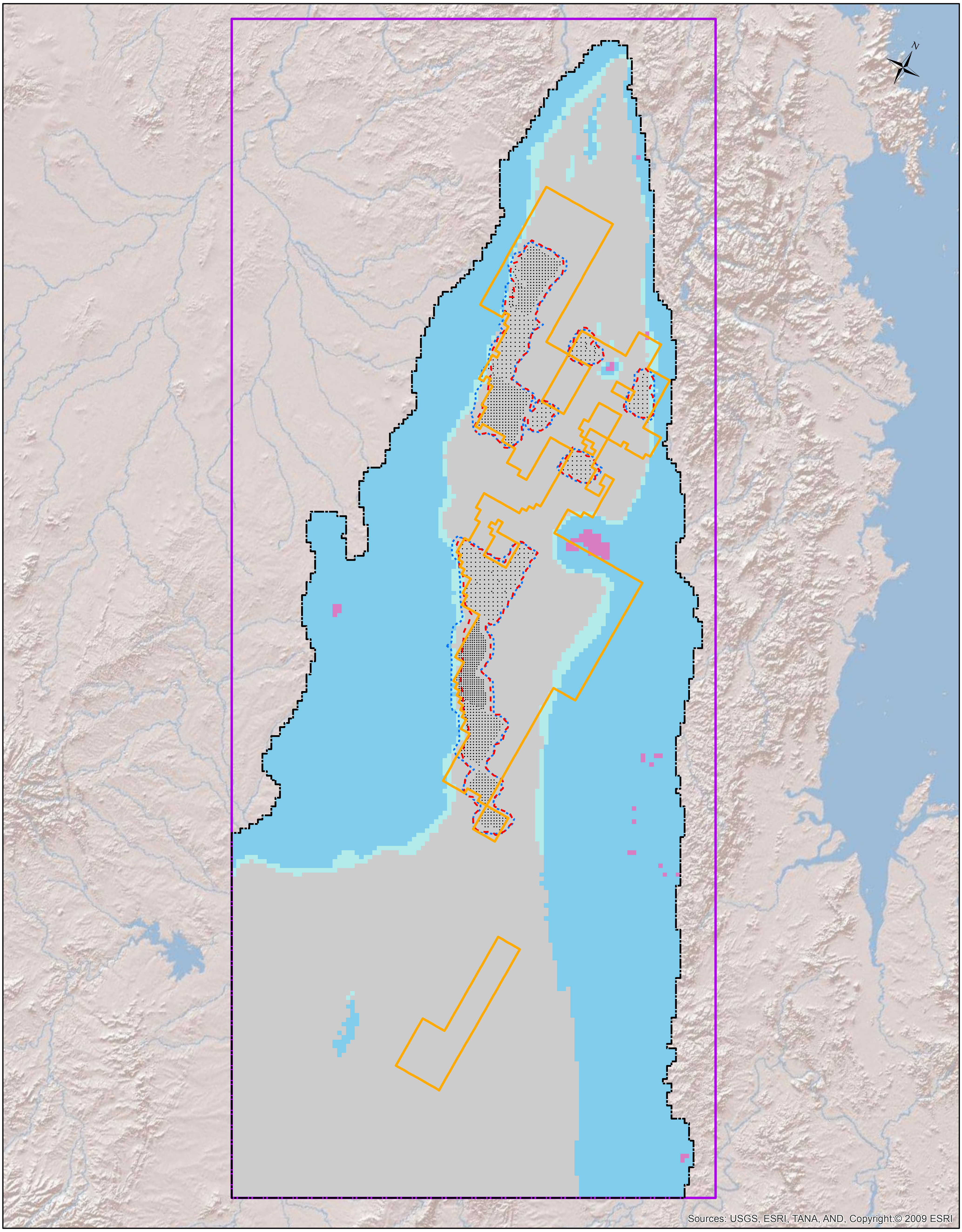
FIGURE B-4B

Modelled Drawdowns Layer 15 - BGP only Base Case at the end of CSG Production with Lower 95% Confidence Interval 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:40:02 PM



Legend

- Future BGP Production Wells
- Upper 95% confidence interval 5m drawdown
  - 5
- Layer 15 Drawdown (m)
  - 5
- EIS Project Area
- Active Model Extent
- GW Model Domain

Layer 15 Formations

- GM Seam (MCM)
- MCM
- Back Creek
- Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

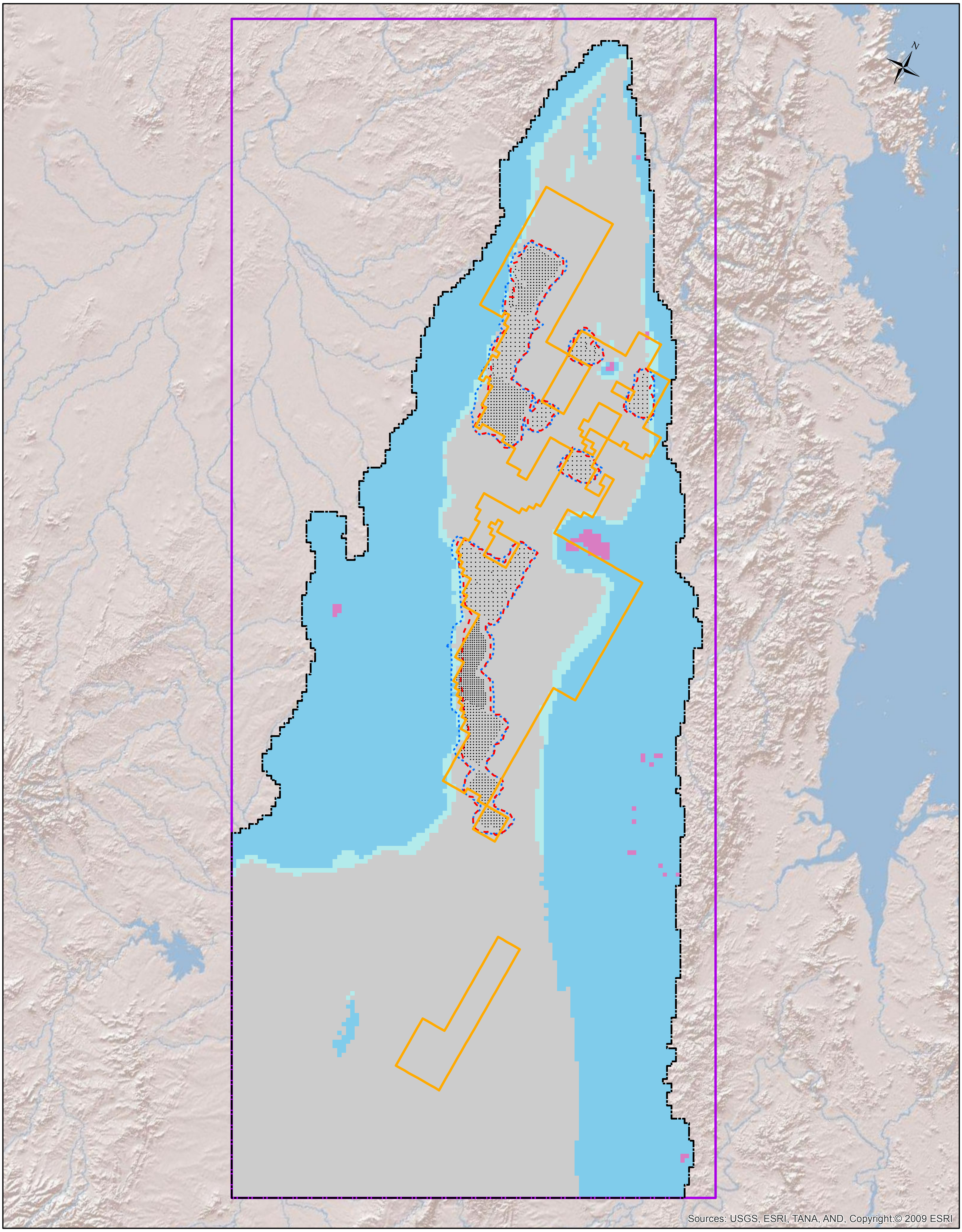
FIGURE B-4C

Modelled Drawdowns Layer 15 - BGP only Base Case at the end of CSG Production with Upper 95% Confidence Interval 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 | Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:46:40 PM



Legend

- Future BGP Production Wells

Upper 95% confidence interval 5m drawdown

- 5

Layer 15 Drawdown (m)

- 5
- EIS Project Area
- Active Model Extent
- GW Model Domain

Layer 15 Formations

- GM Seam (MCM)
- MCM
- Back Creek
- Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

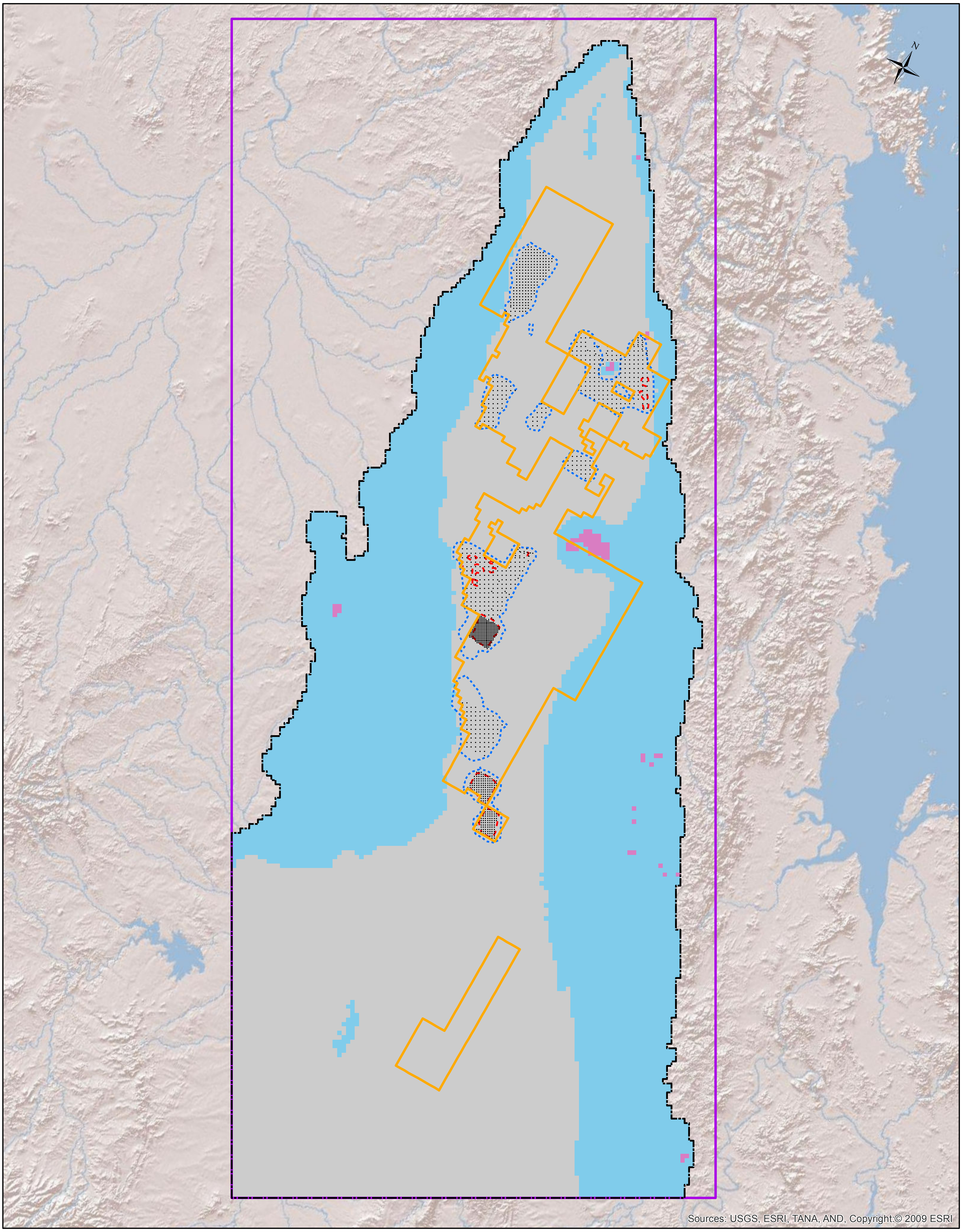
FIGURE B-4D

Modelled Drawdowns Layer 15 -
BGP only Base Case at the end of CSG
Production with Maximum 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 5:00:48 PM



Legend

· Future BGP Production Wells

Minimum 5m Drawdown

5

Layer 17 Drawdown (m)

5

EIS Project Area

Active Model Extent

GW Model Domain

Layer 17 Formations

GML (MCM)

Back Creek

Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

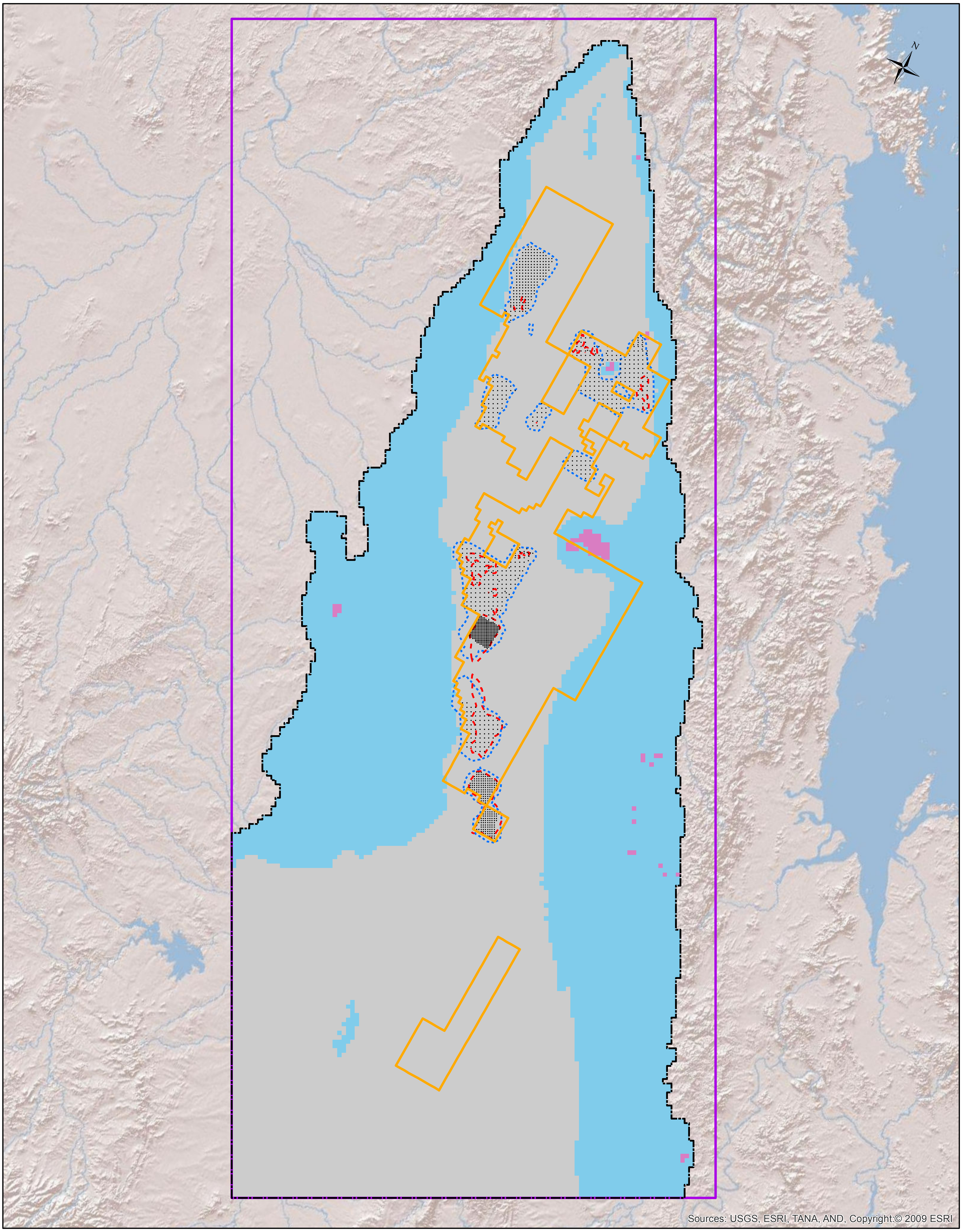
FIGURE B-5A

Modelled Drawdowns Layer 17 - BGP only Base Case at the end of CSG Production with Minimum 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 | Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:26:20 PM



Legend

· Future BGP Production Wells

Lower 95% confidence interval 5m drawdown

5

Layer 17 Drawdown (m)

5

EIS Project Area

Active Model Extent

GW Model Domain

Layer 17 Formations

GML (MCM)

Back Creek

Intrusives

Data Source

EIS Area, Production Facility Areas: Arrow, 2012

Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55

Projection: Transverse Mercator

Datum: GDA 1994

False Easting: 500,000

False Northing: 10,000,000

Central Meridian: 147

Scale Factor: 1

Latitude Of Origin: 0

Units: Meter

0 25 50 100

Kilometers

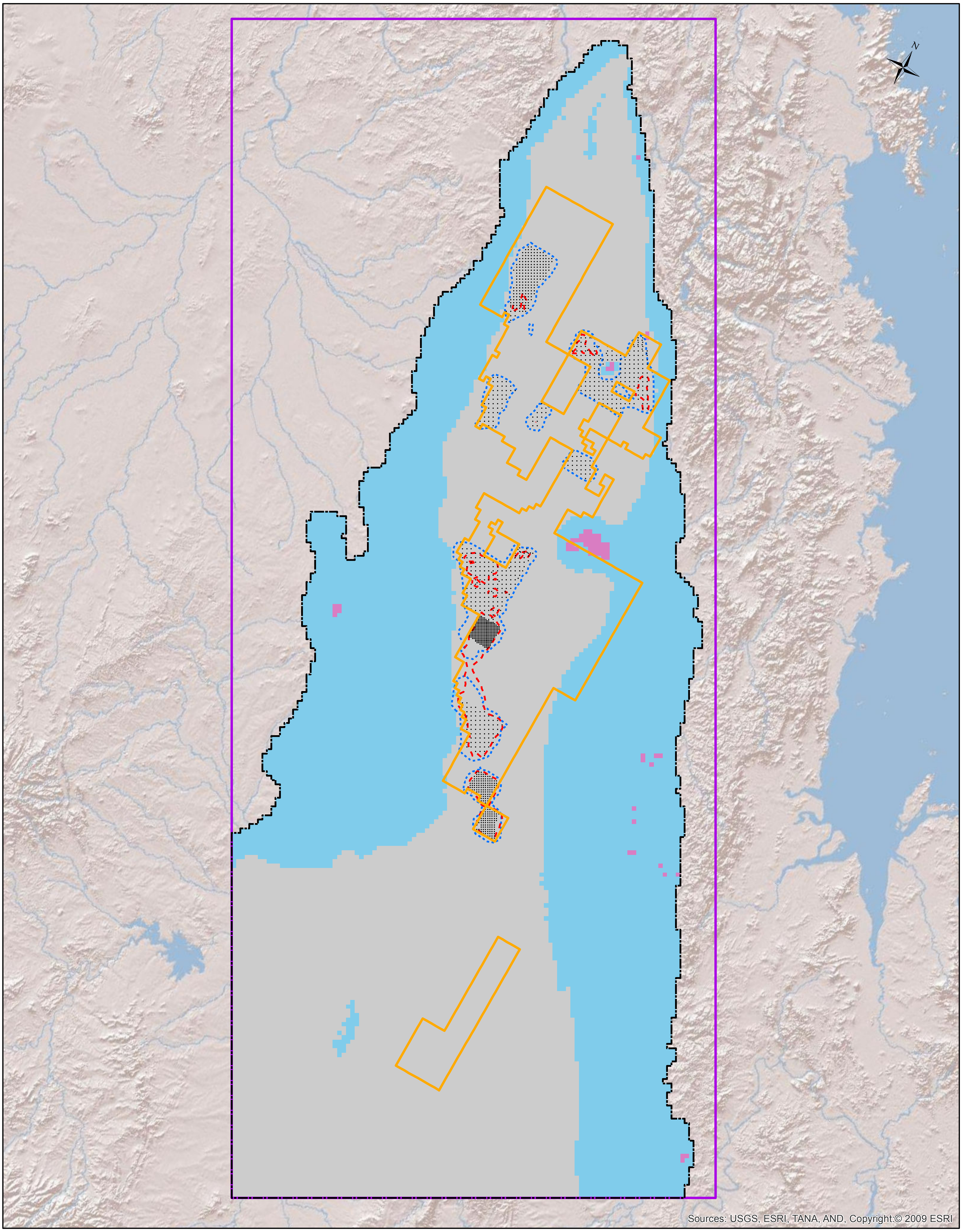
FIGURE B-5B

Modelled Drawdowns Layer 17 - BGP only Base Case at the end of CSG Production with Lower 95% Confidence Interval 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 | Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:41:01 PM



Legend

- Future BGP Production Wells

Upper 95% confidence interval 5m drawdown

- 5

Layer 17 Drawdown (m)

- 5
- EIS Project Area
- Active Model Extent
- GW Model Domain

Layer 17 Formations

- GML (MCM)
- Back Creek
- Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

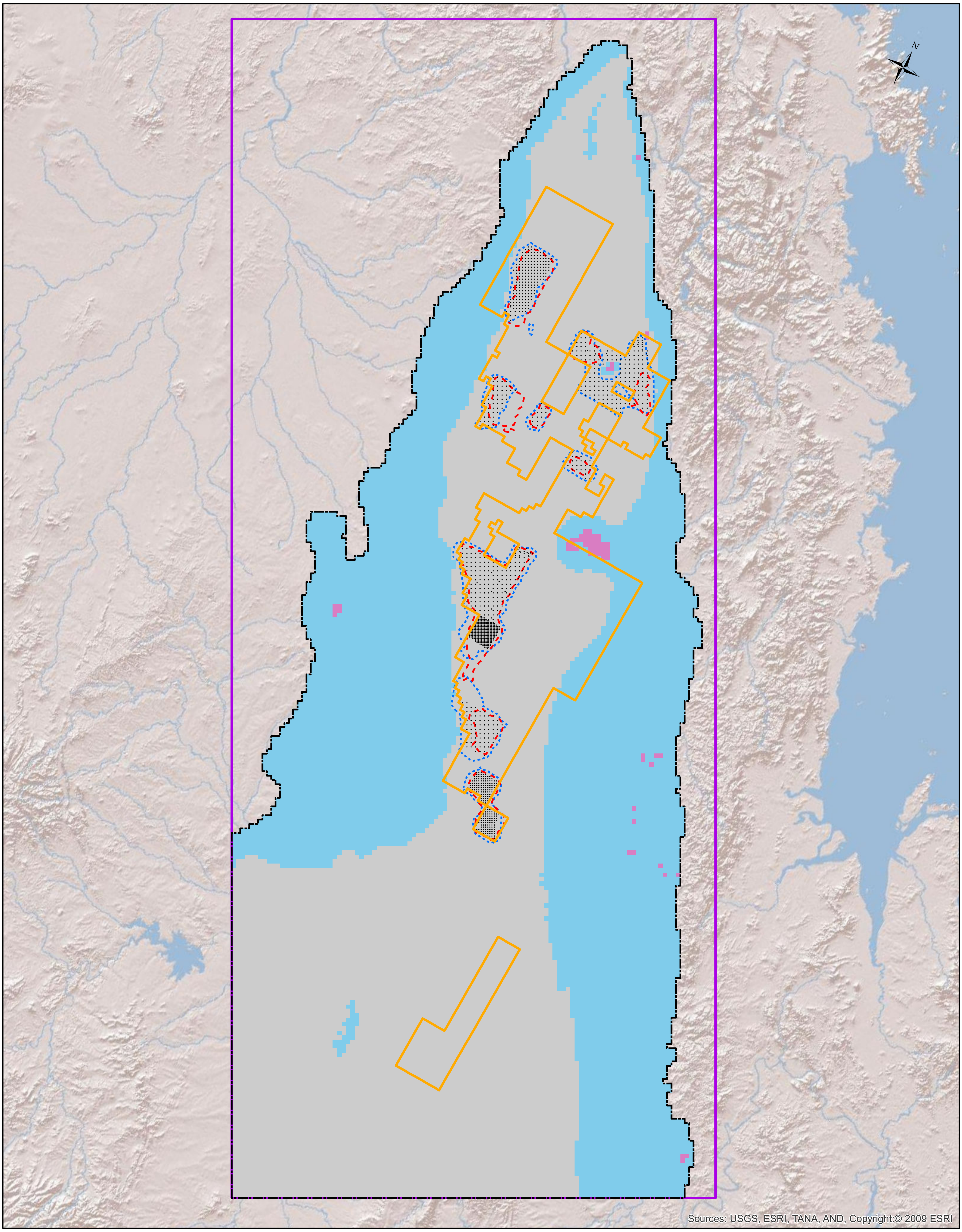
FIGURE B-5C

Modelled Drawdowns Layer 17 - BGP only Base Case at the end of CSG Production with Upper 95% Confidence Interval 5m Drawdown

Ausenco NORWEST CORPORATION

Date: 15/03/2013 Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 4:50:20 PM



Legend

· Future BGP Production Wells

Maximum 5m Drawdown

5

Layer 17 Drawdown (m)

5

EIS Project Area

Active Model Extent

GW Model Domain

Layer 17 Formations

GML (MCM)

Back Creek

Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2013

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

FIGURE B-5D

Modelled Drawdowns Layer 17 -
BGP only Base Case at the end of CSG
Production with Maximum 5m Drawdown

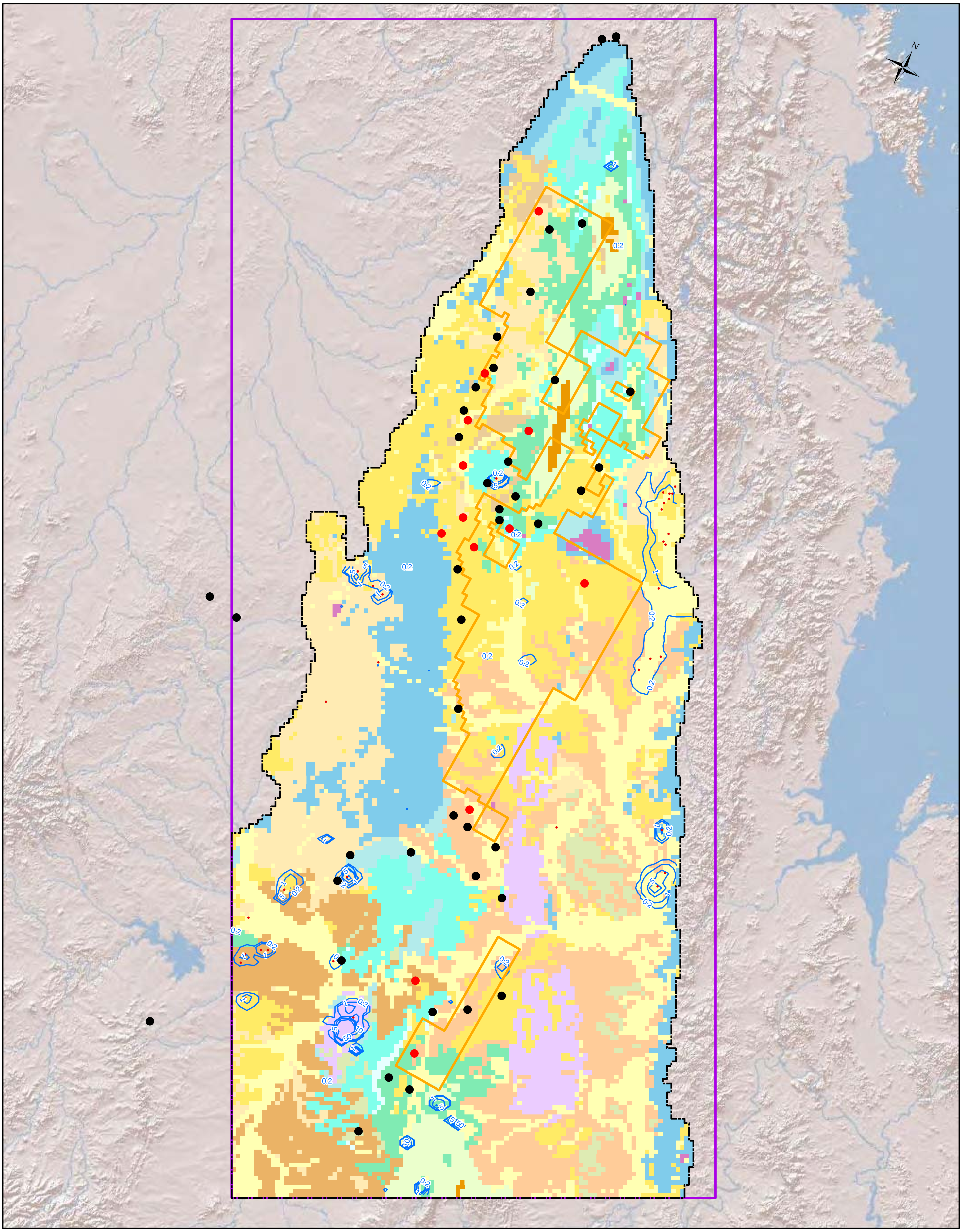
Ausenco NORWEST CORPORATION

Date: 15/03/2013 | Created By: MDK

BGP_Future_end_of_production_Appendix.mxd - 3/15/2013 @ 5:01:58 PM

Appendix F
Arrow Energy Bowen Gas Project
Modelled Cumulative Impact Drawdown
Figures

Supplementary Groundwater Assessment
Arrow Energy Bowen Gas Project
Supplementary Report to the EIS



Legend

- WERD Production
- GW Model Domain
- EIS Project Area
- Layer 1 Drawdown (m)
- Active Model Extent

Layer 1 Formations

- Alluvium
- Colluvium
- Basalt Flows
- Duaringa Fm
- Suttor Fm
- Emerald Fm
- Moolayember Fm
- Clematis Fm
- Rewan Fm
- RCM
- FCM
- MCM
- Back Creek
- Black Water
- Ferricrete
- Intrusives

- Operational coal mine
- Proposed coal mine

Note: Operational coal mines (DNRM) and proposed coal mines (URS) added to figure by Coffey (Dec 2013), locations indicative only

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2012

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

FIGURE 7-21

Modeled Drawdowns Layer 1 - BGP, MGP, and WERD wells at the end of CSG Production

Ausenco NORWEST CORPORATION

Date: 02/12/2013	Created By: MDK

BGP_Cumulative_production_Dec2013.mxd - 12/2/2013 @ 5:25:37 PM
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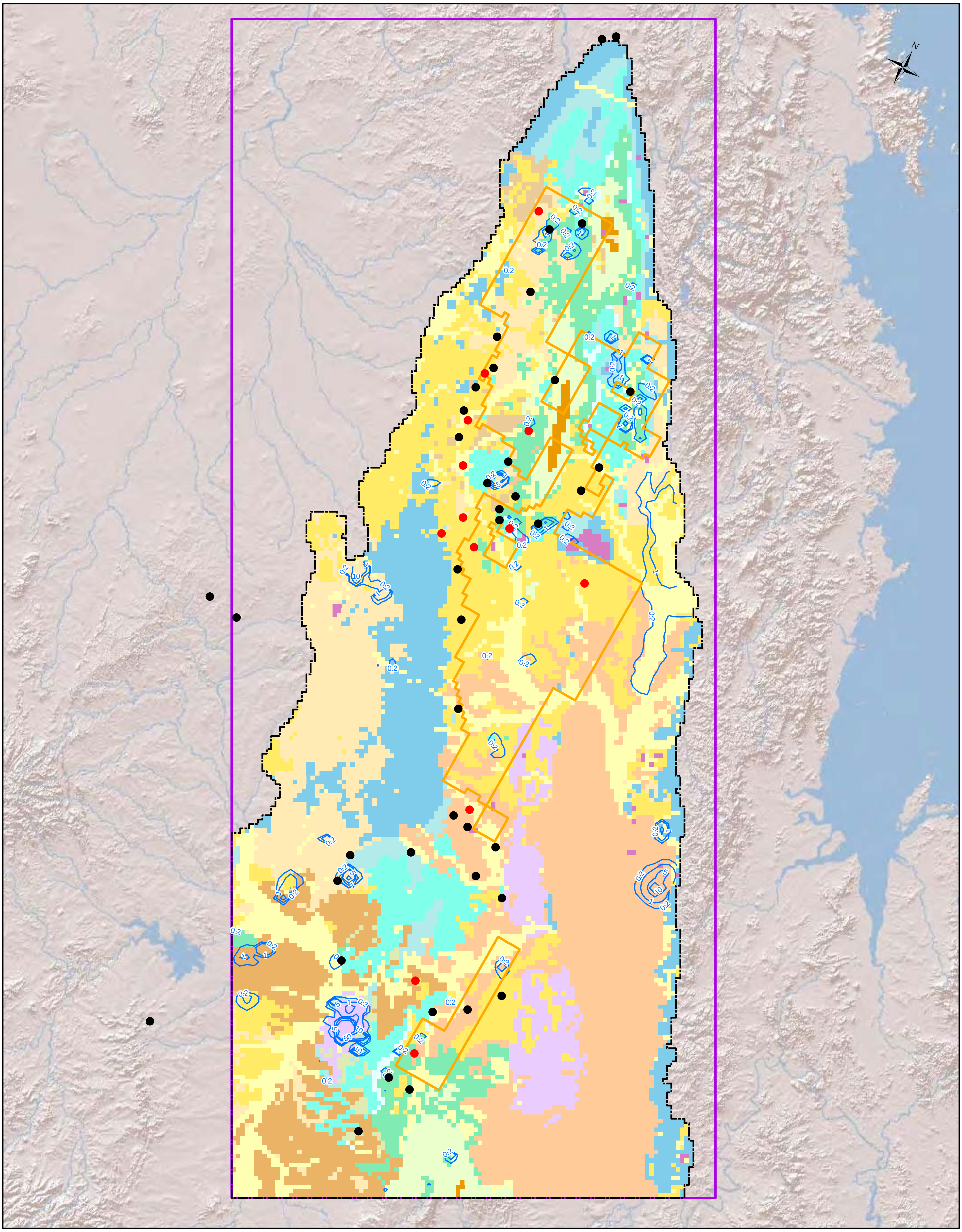


Legend

- GW Model Domain
- EIS Project Area
- Layer 2 Drawdown (m)
- Active Model Extent

Layer 2 Formations

- Alluvium
- Colluvium
- Basalt Flows
- Duaringa Fm
- Suttor Fm
- Emerald Fm
- Moolayember Fm
- Clematis Fm
- Rewan Fm
- RCM
- FCM
- MCM
- Back Creek
- Black Water
- Ferricrete
- Intrusives

- Operational coal mine
- Proposed coal mine

Note: Operational coal mines (DNRM) and proposed coal mines (URS) added to figure by Coffey (Dec 2013), locations indicative only

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2012

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

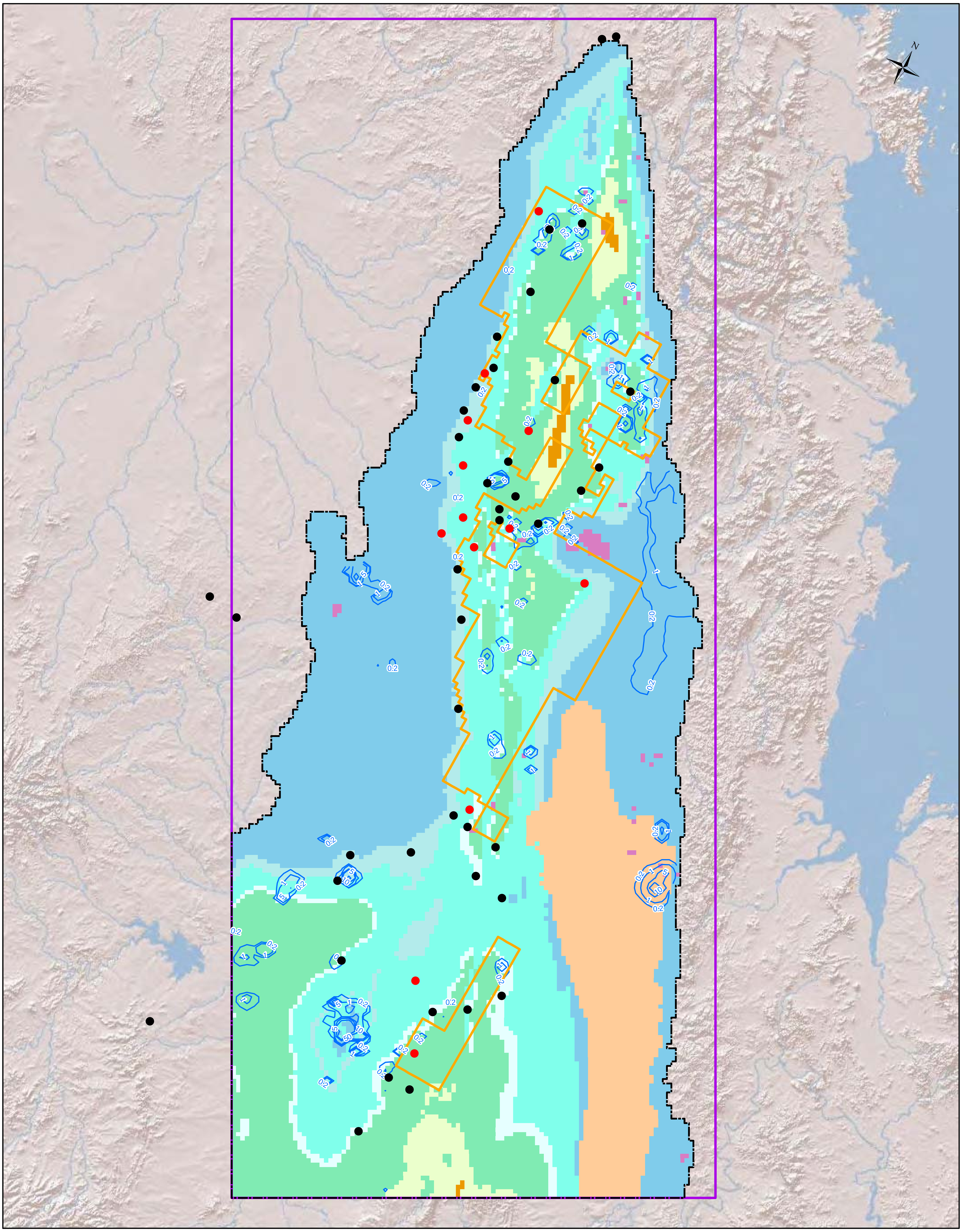
FIGURE 7-22

Modeled Drawdowns Layer 2 - BGP, MGP, and WERD wells at the end of CSG Production

Ausenco NORWEST CORPORATION

Date: 02/12/2013 | Created By: MDK

BGP_Cumulative_production_Dec2013.mxd - 12/2/2013 @ 5:26:26 PM
Coffey reference: 7043_02_AppB_F07.22_HU



Legend

- GW Model Domain
- EIS Project Area
- Layer 3 Drawdown (m)
- Active Model Extent

Layer 3 Formations

- Duaringa Fm
- Moolayember Fm
- Clematis Fm
- Rewan Fm
- RCM
- FCM
- MCM
- Back Creek
- Intrusives

- Operational coal mine
- Proposed coal mine

Note: Operational coal mines (DNRM) and proposed coal mines (URS) added to figure by Coffey (Dec 2013), locations indicative only

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2012

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

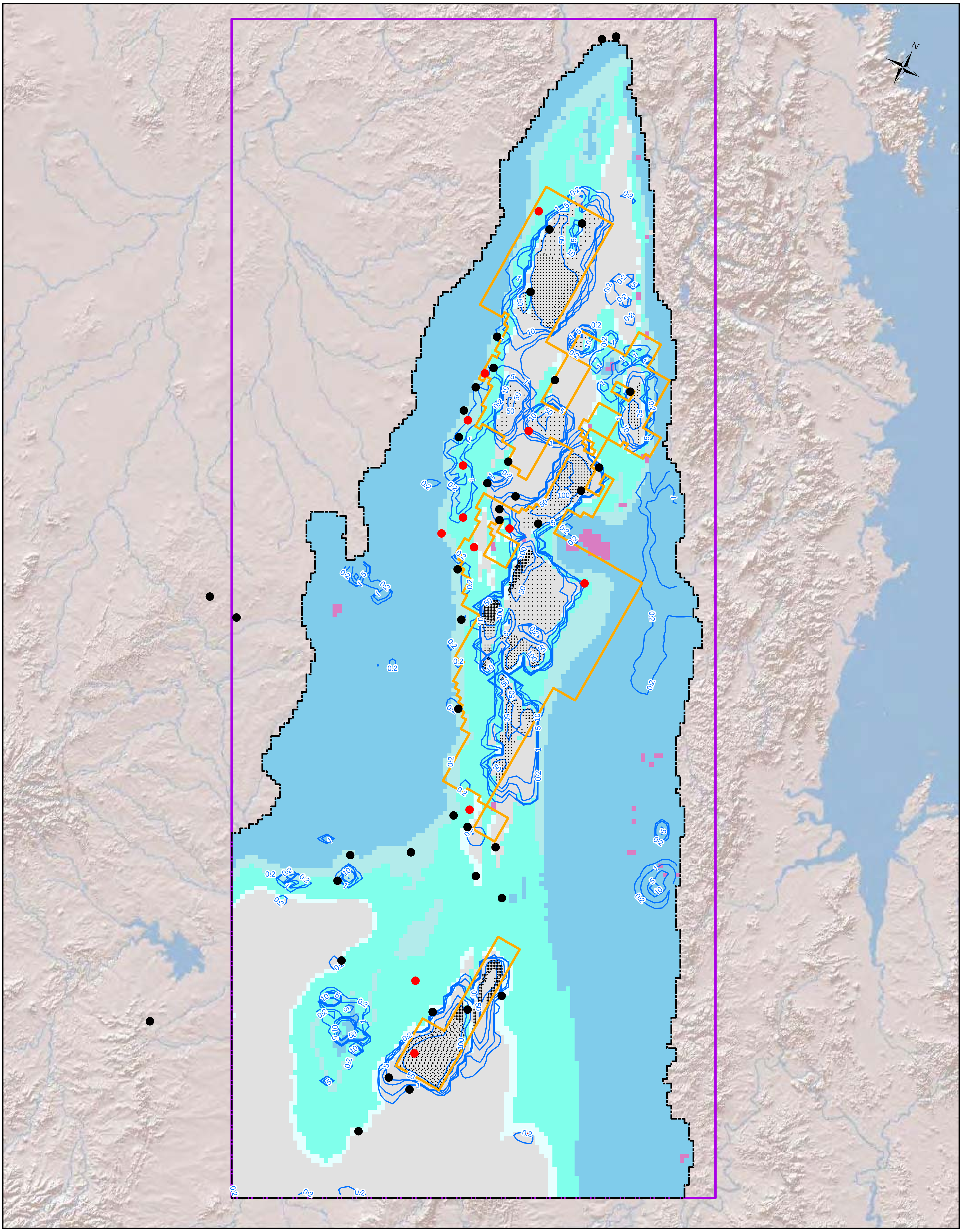
FIGURE 7-23

Modeled Drawdowns Layer 3 - BGP, MGP, and WERD wells at the end of CSG Production

Ausenco NORWEST CORPORATION

Date: 02/12/2013 | Created By: MDK

BGP_Cumulative_production_Dec2013.mxd - 12/2/2013 @ 5:27:20 PM
Coffey reference: 7043_02_AppB_F07.23_HU



Legend
· Future BGP Production Wells
• WERD Production
GW Model Domain
EIS Project Area
Layer 5 Drawdown (m)
Active Model Extent

Layer 5 Formations
Leichhardt
RCM
FCM
MCM
Back Creek
Intrusives

● Operational coal mine
● Proposed coal mine

Note: Operational coal mines (DNRM) and proposed coal mines (URS) added to figure by Coffey (Dec 2013), locations indicative only

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2012

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

FIGURE 7-24

Modeled Drawdowns Layer 5 - BGP, MGP, and WERD wells at the end of CSG Production

Ausenco NORWEST CORPORATION

Date: 02/12/2013 | Created By: MDK

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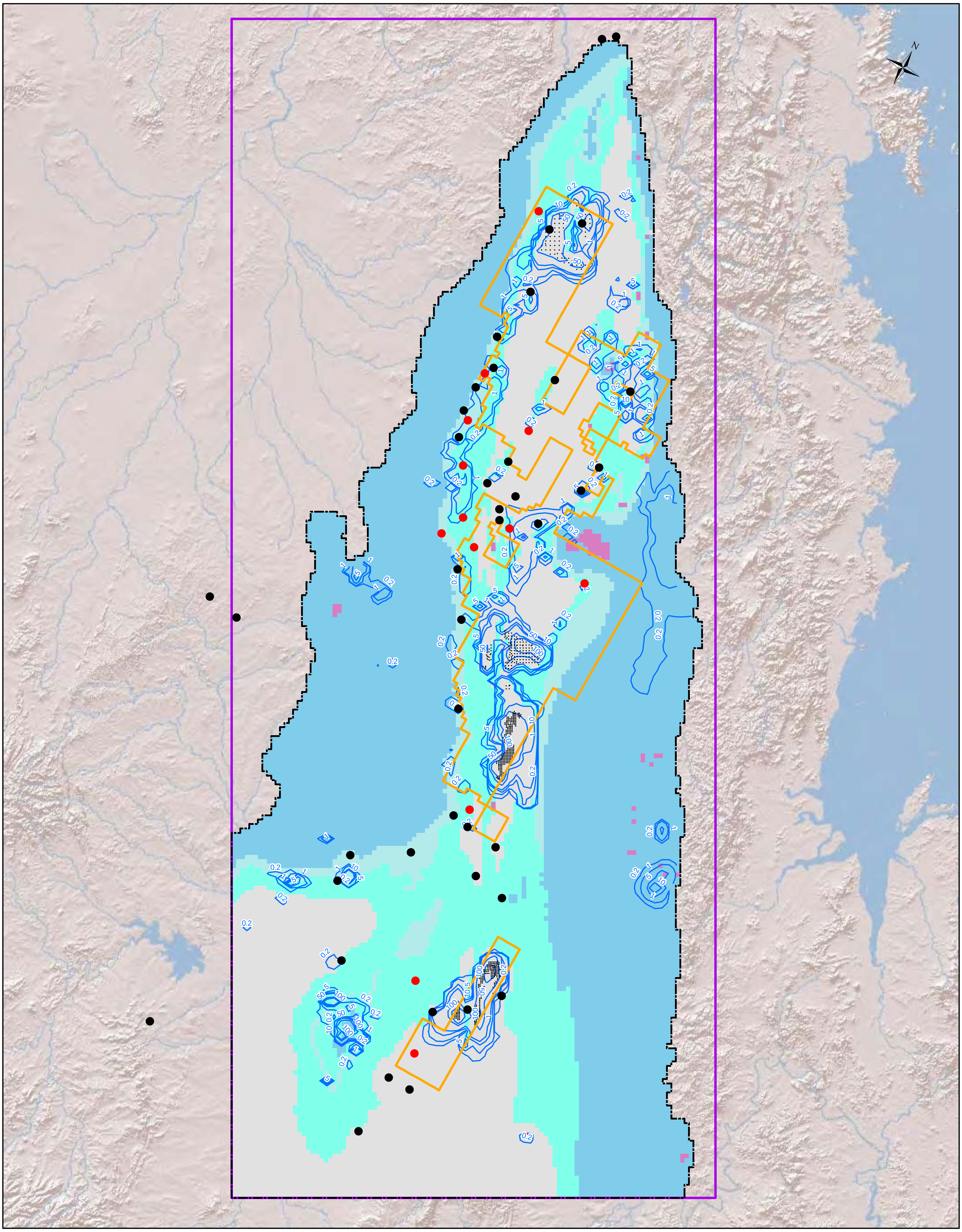

Legend

- WERD Production
- Future BGP Production Wells
- GW Model Domain
- EIS Project Area
- Active Model Extent
- Layer 7 Drawdown (m)

Layer 7 Formations

- Vermont (RCM)
- FCM
- MCM
- Back Creek
- Intrusives

- Operational coal mine
- Proposed coal mine

Note: Operational coal mines (DNRM) and proposed coal mines (URS) added to figure by Coffey (Dec 2013), locations indicative only

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2012

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

FIGURE 7-25

Modeled Drawdowns Layer 7 - BGP, MGP, and WERD wells at the end of CSG Production

Ausenco NORWEST CORPORATION

Date: 02/12/2013 Created By: MDK

BGP_Cumulative_production_Dec2013.mxd - 12/2/2013 @ 5:32:29 PM
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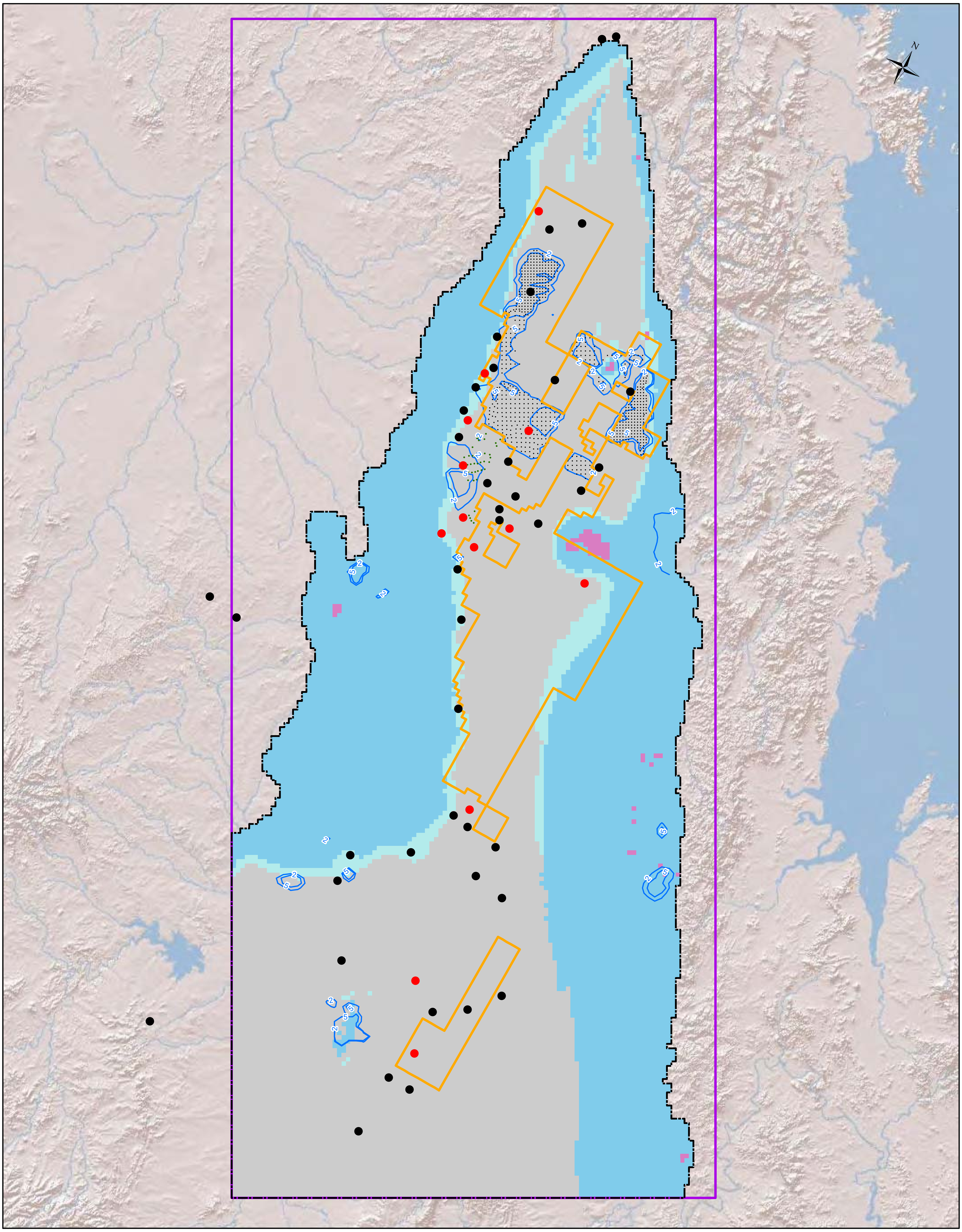


Legend

- Future MGP Production Wells
- Future BGP Production Wells
- GW Model Domain
- EIS Project Area
- Active Model Extent
- Layer 11 Drawdown (m)

Layer 11 Formations

- Q Seam (MCM)
- MCM
- Back Creek
- Intrusives

- Operational coal mine
- Proposed coal mine

Note: Operational coal mines (DNRM) and proposed coal mines (URS) added to figure by Coffey (Dec 2013), locations indicative only

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2012

0 25 50 100
Kilometers

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

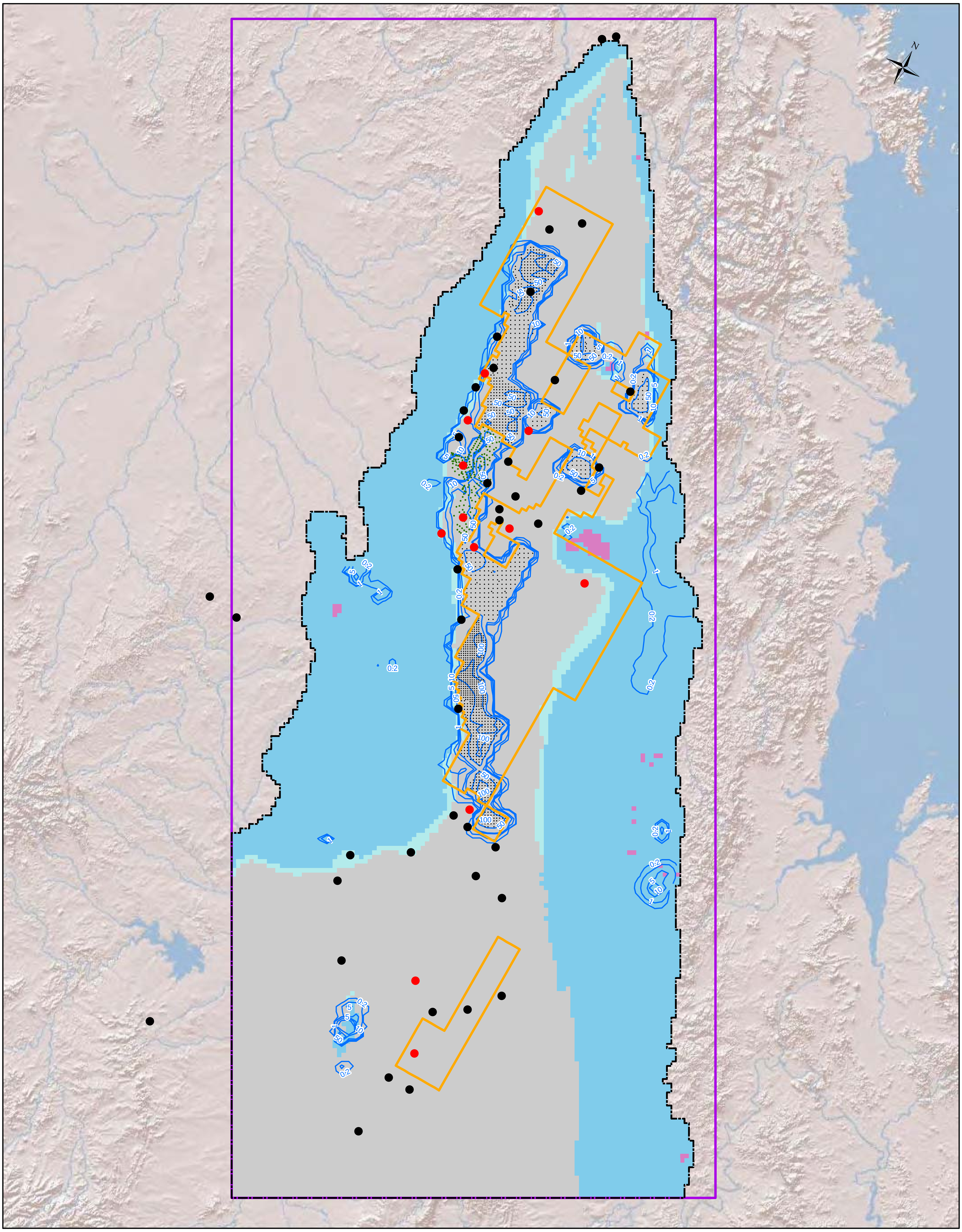
FIGURE 7-26

Modeled Drawdowns Layer 11 - BGP, MGP, and WERD wells at the end of CSG Production

Ausenco NORWEST CORPORATION

Date: 02/12/2013 Created By: MDK

BGP_Cumulative_production_Dec2013.mxd - 12/2/2013 @ 5:33:31 PM
Coffey reference: 7043_02_AppB_F07.26_HU



Legend

- Future MGP Production Wells
- Future BGP Production Wells
- GW Model Domain
- EIS Project Area
- Active Model Extent
- Layer 15 Drawdown (m)

Layer 15 Formations

- GM Seam (MCM)
- MCM
- Back Creek
- Intrusives

- Operational coal mine
- Proposed coal mine

Note: Operational coal mines (DNRM) and proposed coal mines (URS) added to figure by Coffey (Dec 2013), locations indicative only

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2012

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

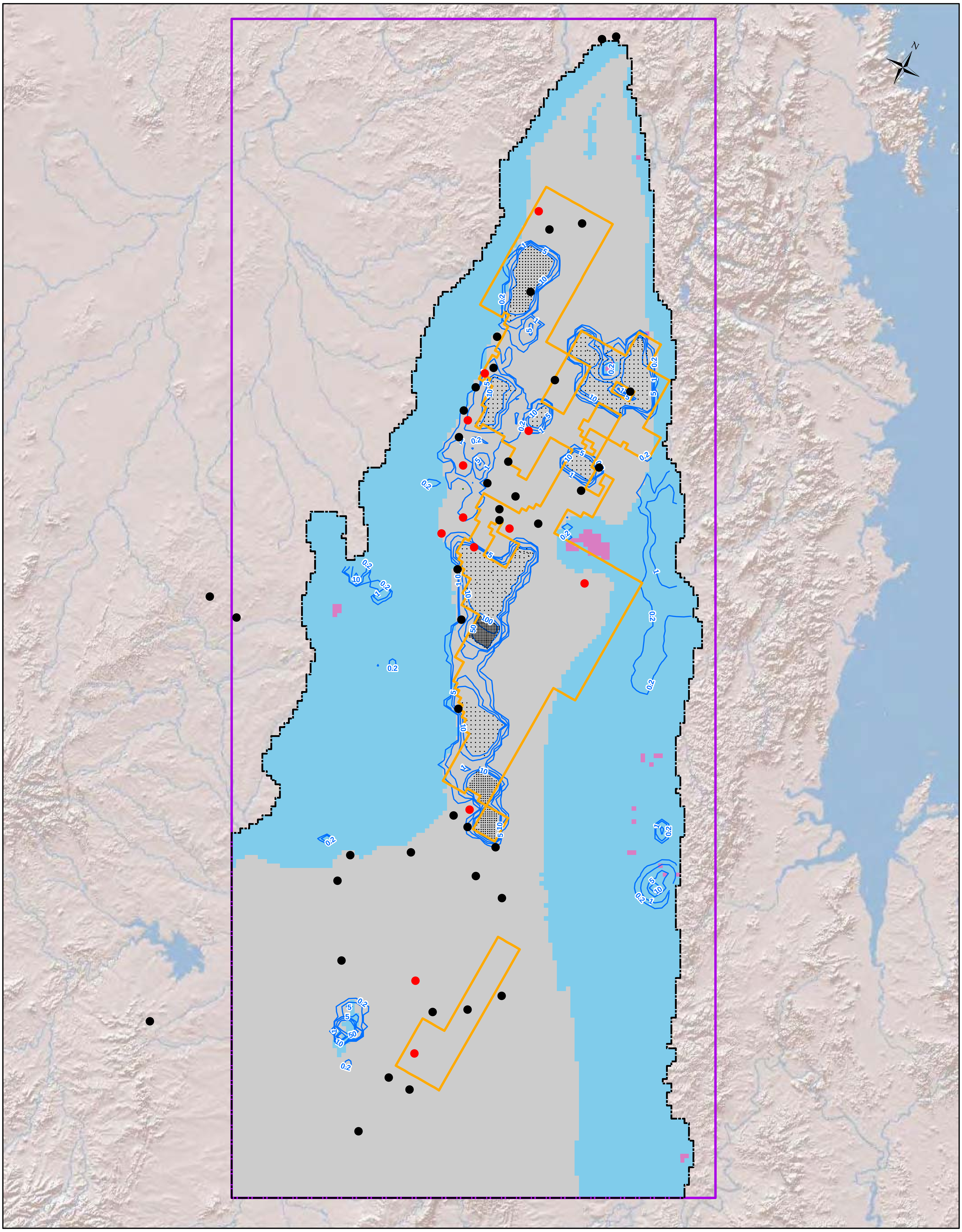
FIGURE 7-27

Modeled Drawdowns Layer 15 - BGP, MGP, and WERD wells at the end of CSG Production

Ausenco NORWEST CORPORATION

Date: 02/12/2013 | Created By: MDK

BGP_Cumulative_production_Dec2013.mxd - 12/2/2013 @ 5:34:32 PM
Coffey reference: 7043_02_AppB_F07.27_HU



Legend

- Future MGP Production Wells
- Future BGP Production Wells
- GW Model Domain
- EIS Project Area
- Active Model Extent
- Layer 17 Drawdown (m)

Layer 17 Formations

- GML (MCM)
- Back Creek
- Intrusives

- Operational coal mine
- Proposed coal mine

Note: Operational coal mines (DNRM) and proposed coal mines (URS) added to figure by Coffey (Dec 2013), locations indicative only

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2012

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

FIGURE 7-28

Modeled Drawdowns Layer 17 - BGP, MGP, and WERD wells at the end of CSG Production

Ausenco NORWEST CORPORATION

Date: 02/12/2013 | Created By: MDK

BGP_Cumulative_production_Dec2013.mxd - 12/2/2013 @ 5:35:16 PM
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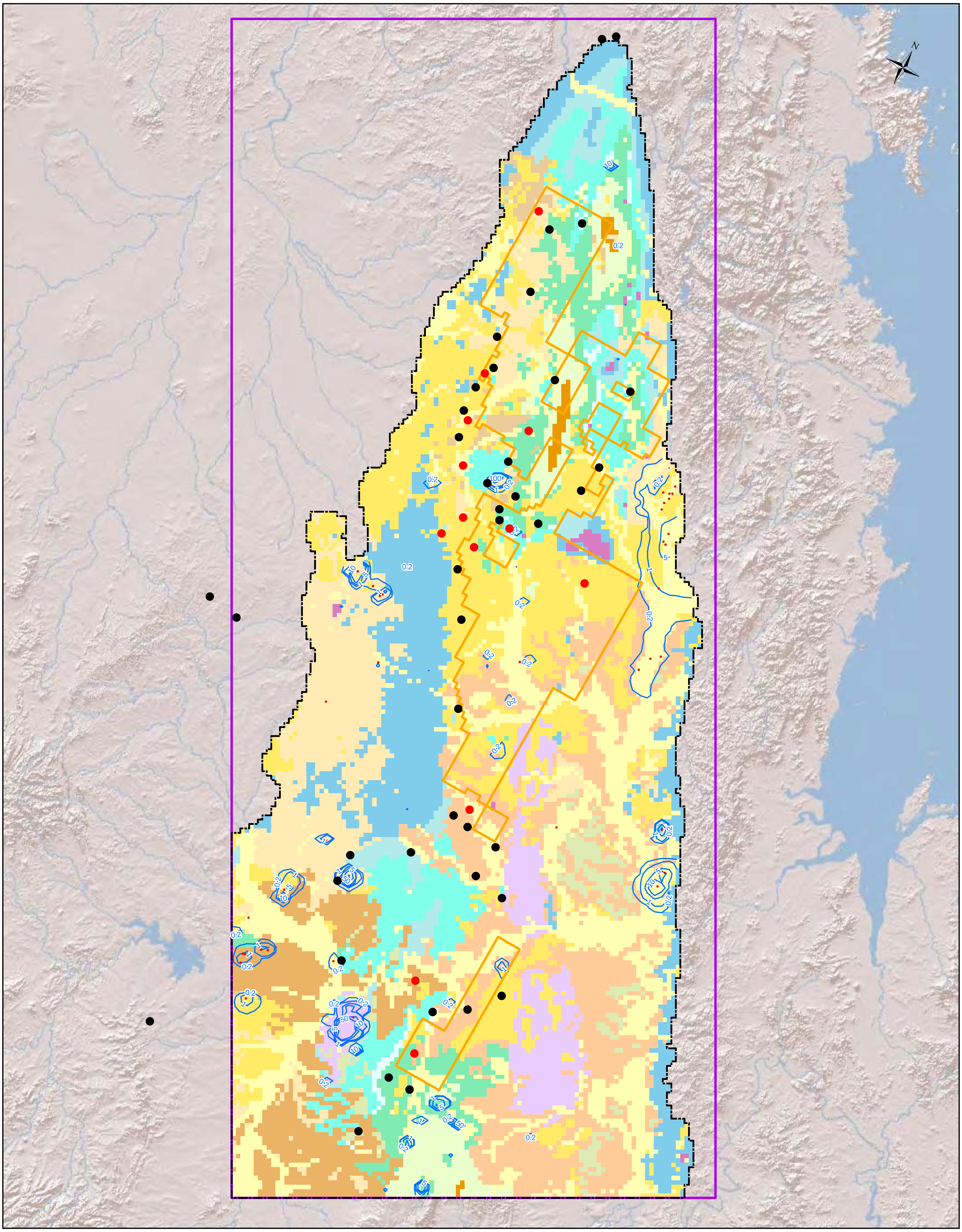


Legend

- WERD Production
- Layer 1 Drawdown (m)
- GW Model Domain
- EIS Project Area
- Active Model Extent

Layer 1 Formations

- Alluvium
- Colluvium
- Basalt Flows
- Duaringa Fm
- Suttor Fm
- Emerald Fm
- Moolayember Fm
- Clematis Fm
- Rewan Fm
- RCM
- FCM
- MCM
- Back Creek
- Black Water
- Ferricrete
- Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2012

- Operational coal mine
- Proposed coal mine

Note: Operational coal mines (DNRM) and proposed coal mines (URS) added to figure by Coffey (Dec 2013), locations indicative only

0 25 50 100
Kilometers

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

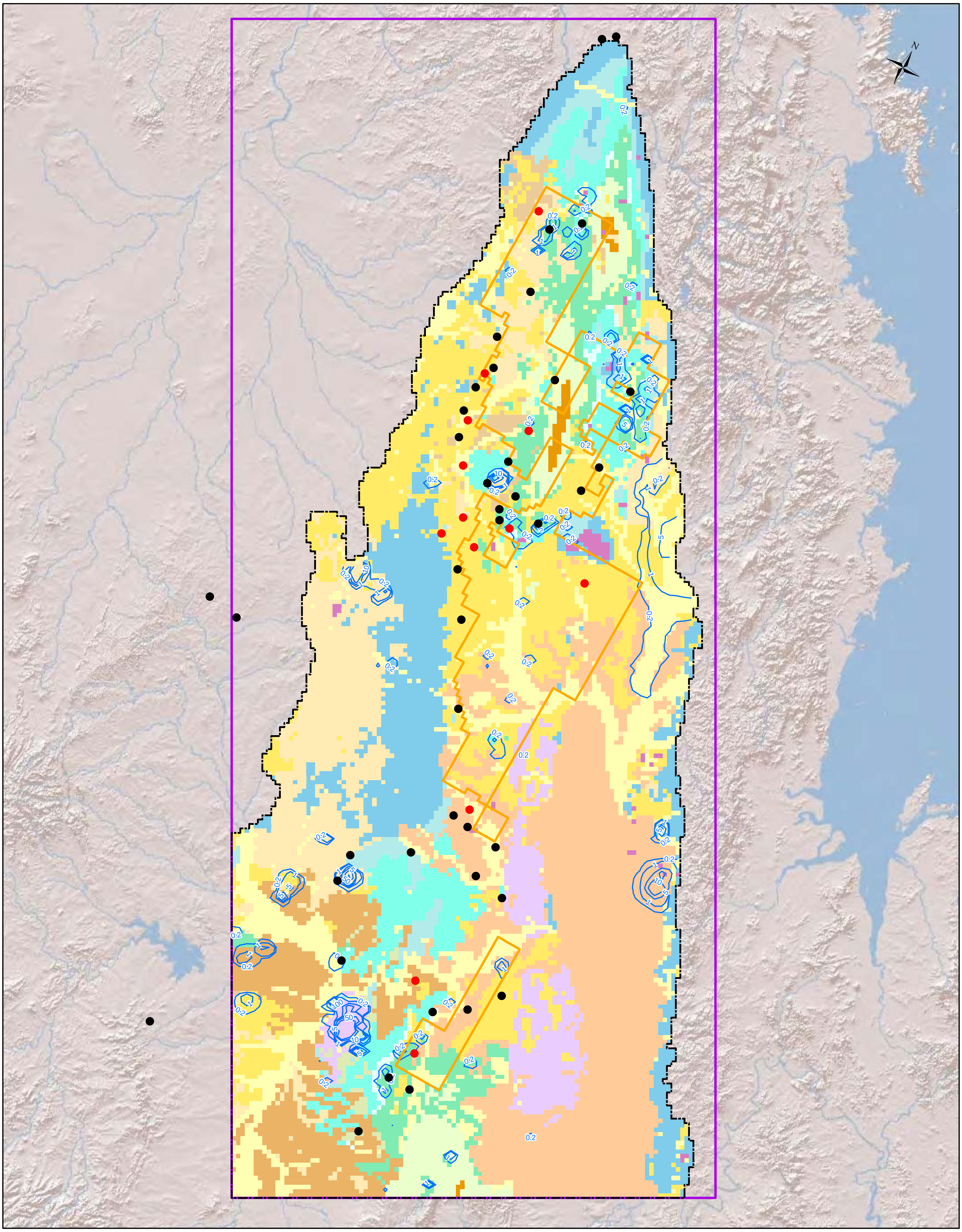
FIGURE 7-29

Modeled Drawdowns Layer 1 - BGP, MGP, and WERD wells 50 years after CSG Production

Ausenco NORWEST CORPORATION

Date: 02/12/2013	Created By: MDK

BGP_Cumulative_production_Dec2013.mxd - 12/2/2013 @ 4:44:15 PM
Coffey reference: 7043_02_AppB_F07.29_HU



Legend

- Layer 2 Drawdown (m)
- GW Model Domain
- EIS Project Area
- Active Model Extent

Layer 2 Formations

- Alluvium
- Colluvium
- Basalt Flows
- Duaringa Fm
- Suttor Fm
- Emerald Fm
- Moolayember Fm
- Clematis Fm
- Rewan Fm
- RCM
- FCM
- MCM
- Back Creek
- Black Water
- Ferricrete
- Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2012

- Operational coal mine
- Proposed coal mine

Note: Operational coal mines (DNRM) and proposed coal mines (URS) added to figure by Coffey (Dec 2013), locations indicative only

0 25 50 100
Kilometers

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

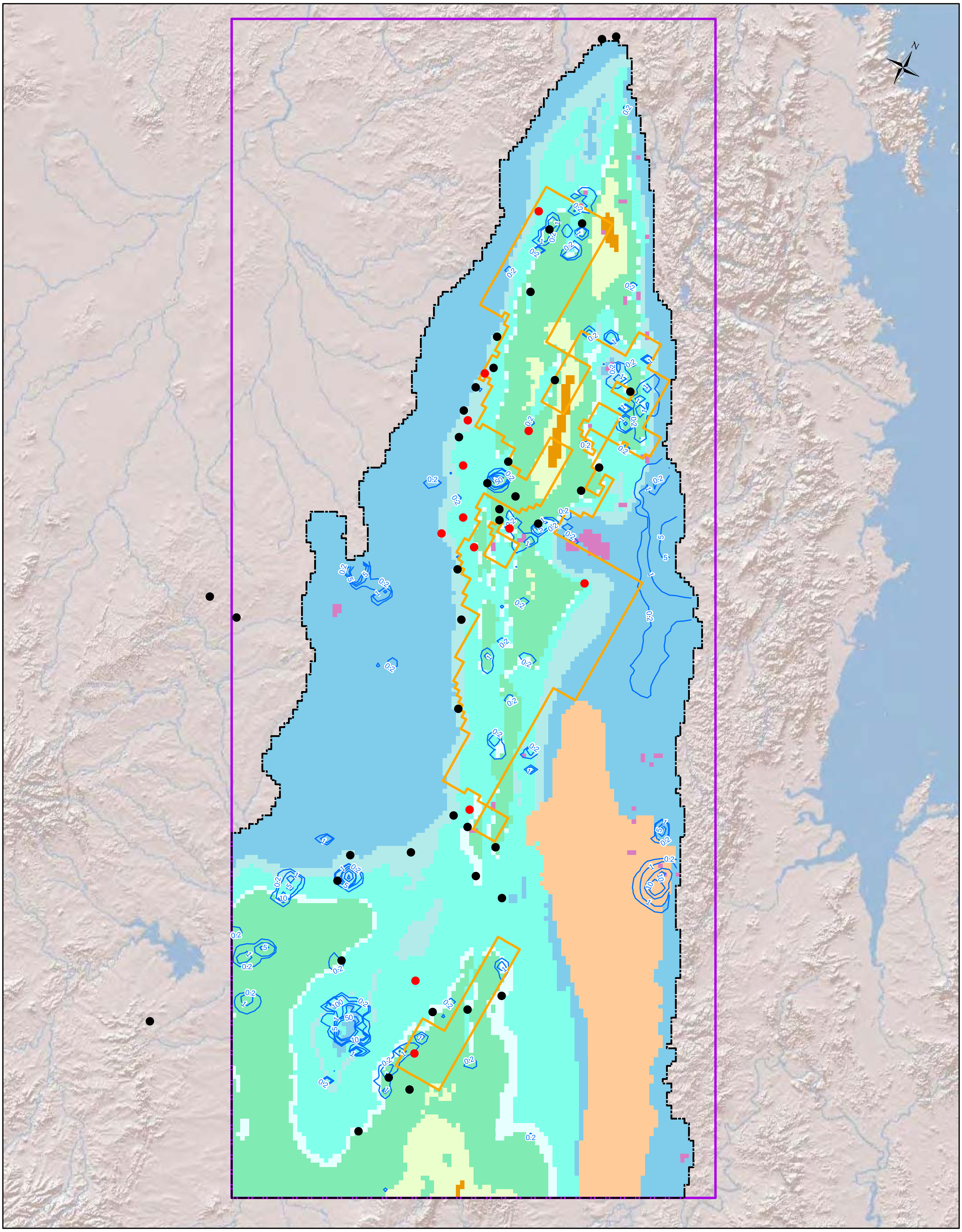
FIGURE 7-30

Modeled Drawdowns Layer 2 - BGP, MGP, and WERD wells 50 years after CSG Production

Ausenco NORWEST CORPORATION

Date: 02/12/2013
Created By: MDK

BGP_Cumulative_production_Dec2013.mxd - 12/2/2013 @ 4:47:18 PM
Coffey reference: 7043_02_AppB_F07.30_HU



Legend

- Future BGP Production Wells
- Layer 3 Drawdown (m)
- GW Model Domain
- EIS Project Area
- Active Model Extent
- Operational coal mine
- Proposed coal mine

Note: Operational coal mines (DNRM) and proposed coal mines (URS) added to figure by Coffey (Dec 2013), locations indicative only

Layer 3 Formations

- Duaringa Fm
- Moolayember Fm
- Clematis Fm
- Rewan Fm
- RCM
- FCM
- MCM
- Back Creek
- Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2012

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

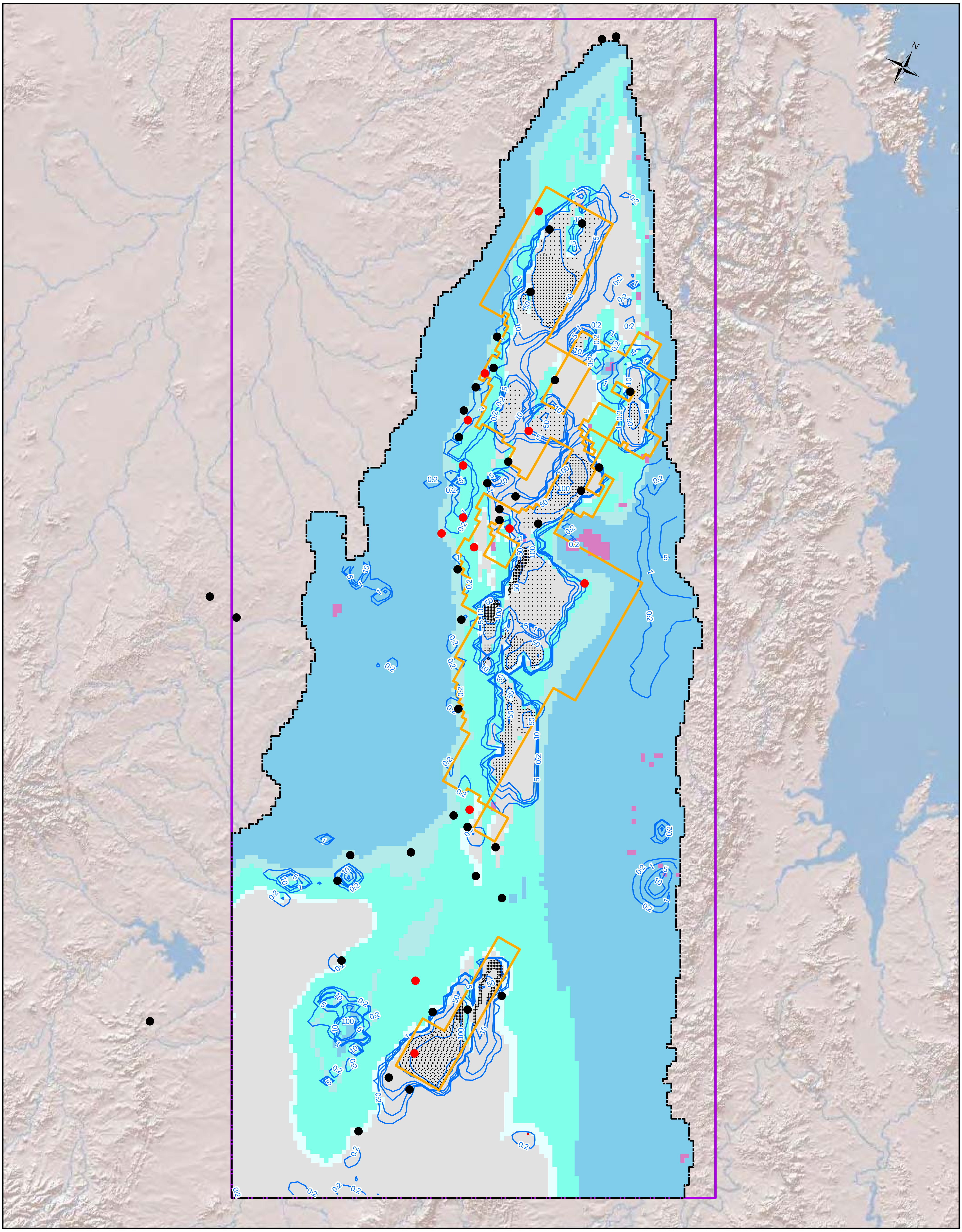
FIGURE 7-31

Modeled Drawdowns Layer 3 - BGP, MGP, and WERD wells 50 years after CSG Production

Ausenco NORWEST CORPORATION

Date: 02/12/2013
Created By: MDK

BGP_Cumulative_production_Dec2013.mxd - 12/2/2013 @ 4:48:55 PM
Coffey reference: 7043_02_AppB_F07.31_HU



Legend

- Future BGP Production Wells
- WERD Production
- Layer 5 Drawdown (m)
- GW Model Domain
- EIS Project Area
- Active Model Extent

Layer 5 Formations

- Leichhardt
- RCM
- FCM
- MCM
- Back Creek
- Intrusives

- Operational coal mine
- Proposed coal mine

Note: Operational coal mines (DNRM) and proposed coal mines (URS) added to figure by Coffey (Dec 2013), locations indicative only

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2012

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

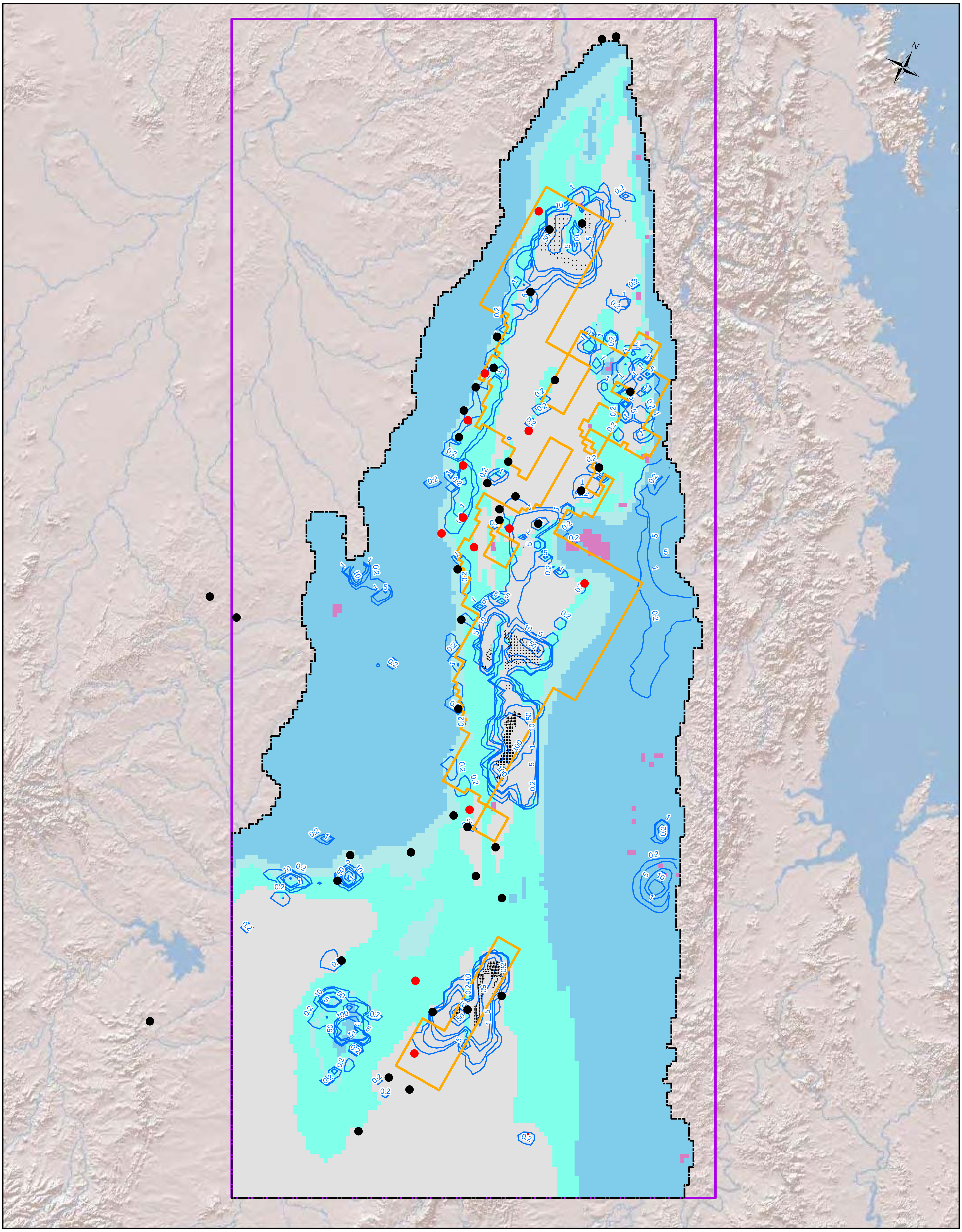
FIGURE 7-32

Modeled Drawdowns Layer 5 - BGP, MGP, and WERD wells 50 years after CSG Production

Ausenco
NORWEST CORPORATION

Date: 02/12/2013
Created By: MDK

BGP_Cumulative_production_Dec2013.mxd - 12/2/2013 @ 4:54:54 PM
Coffey reference: 7043_02_AppB_F07.32_HU



Legend

- WERD Production
- Future BGP Production Wells
- Layer 7 Drawdown (m)
- GW Model Domain
- EIS Project Area
- Active Model Extent

Layer 7 Formations

- Vermont (RCM)
- FCM
- MCM
- Back Creek
- Intrusives

- Operational coal mine
- Proposed coal mine

Note: Operational coal mines (DNRM) and proposed coal mines (URS) added to figure by Coffey (Dec 2013), locations indicative only

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2012

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

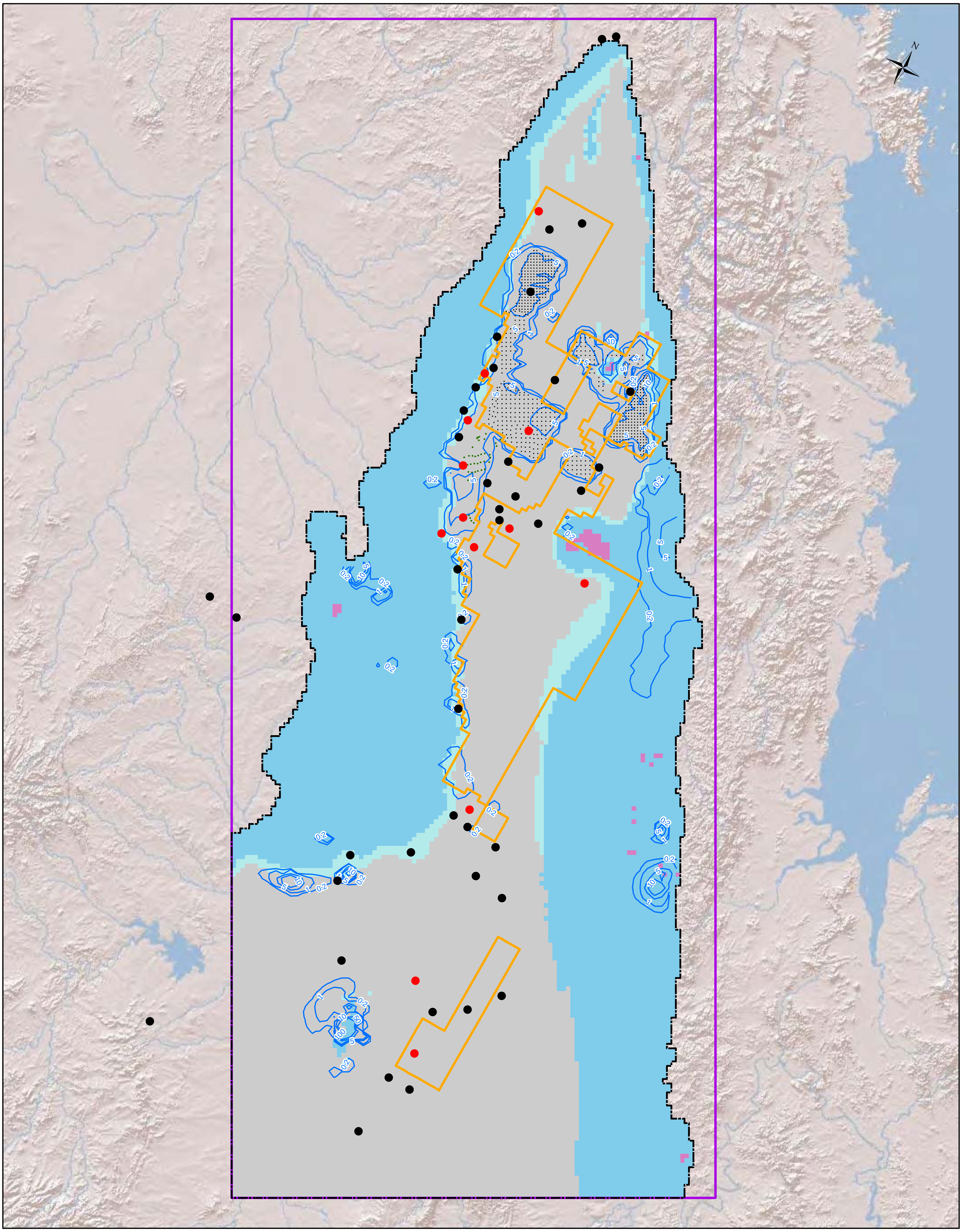
FIGURE 7-33

Modeled Drawdowns Layer 7 - BGP, MGP, and WERD wells 50 years after CSG Production

Ausenco NORWEST CORPORATION

Date: 02/12/2013	Created By: MDK

BGP_Cumulative_production_Dec2013.mxd - 12/2/2013 @ 4:57:21 PM
Coffey reference: 7043_02_AppB_F07.33_HU



Legend

- Future MGP Production Wells
- Future BGP Production Wells
- Layer 11 Drawdown (m)
- GW Model Domain
- EIS Project Area
- Active Model Extent

Layer 11 Formations

- Q Seam (MCM)
- MCM
- Back Creek
- Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2012

- Operational coal mine
- Proposed coal mine

Note: Operational coal mines (DNRM) and proposed coal mines (URS) added to figure by Coffey (Dec 2013), locations indicative only

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

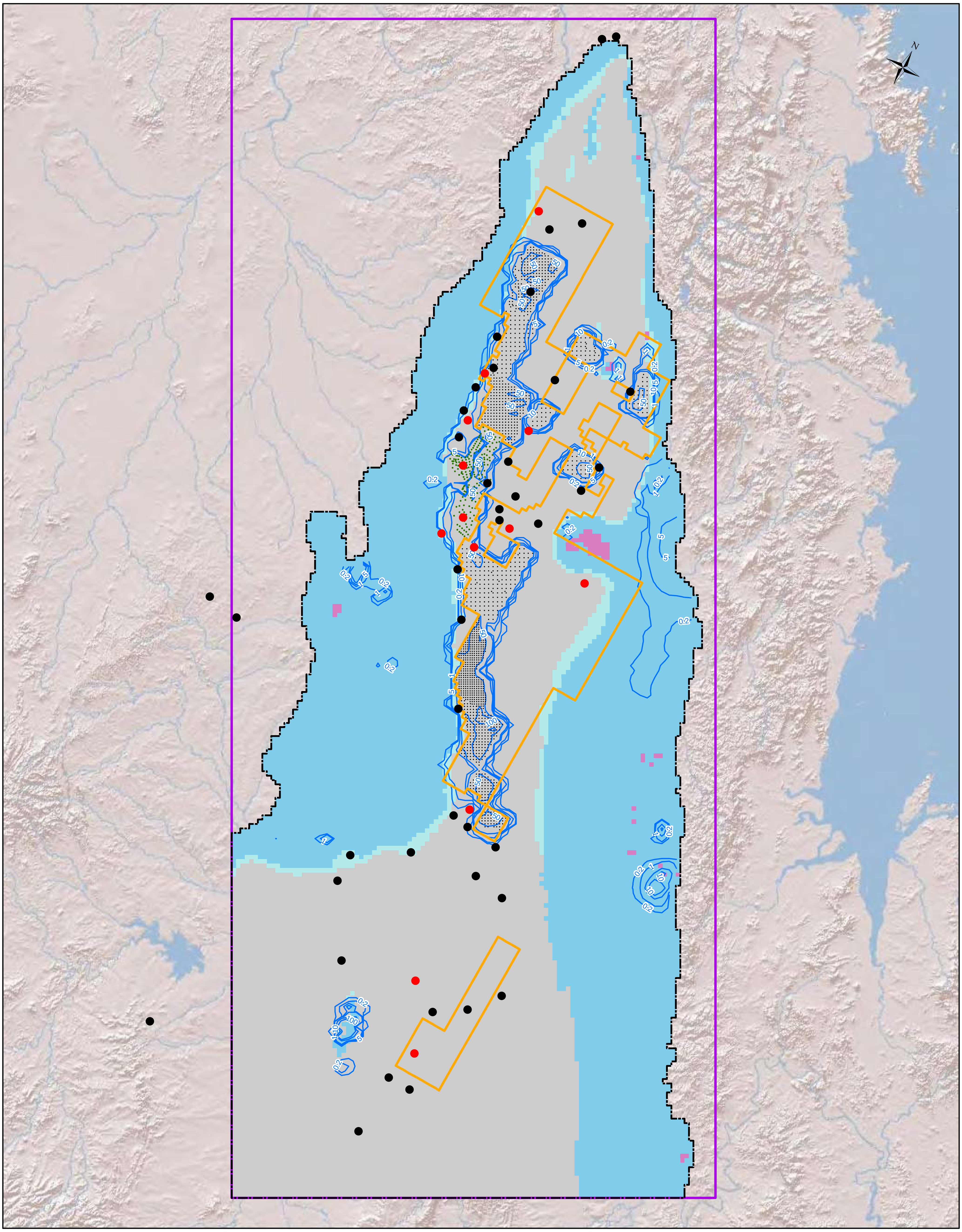
FIGURE 7-34

Modeled Drawdowns Layer 11 - BGP, MGP, and WERD wells 50 years after CSG Production

Ausenco NORWEST CORPORATION

Date: 02/12/2013 | Created By: MDK

BGP_Cumulative_production_Dec2013.mxd - 12/2/2013 @ 5:00:25 PM
Coffey reference: 7043_02_AppB_F07.34_HU



Legend

- Future MGP Production Wells
- Future BGP Production Wells
- Layer 15 Drawdown (m)
- GW Model Domain
- EIS Project Area
- Active Model Extent

Layer 15 Formations

- GM Seam (MCM)
- MCM
- Back Creek
- Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2012

- Operational coal mine
- Proposed coal mine

Note: Operational coal mines (DNRM) and proposed coal mines (URS) added to figure by Coffey (Dec 2013), locations indicative only

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

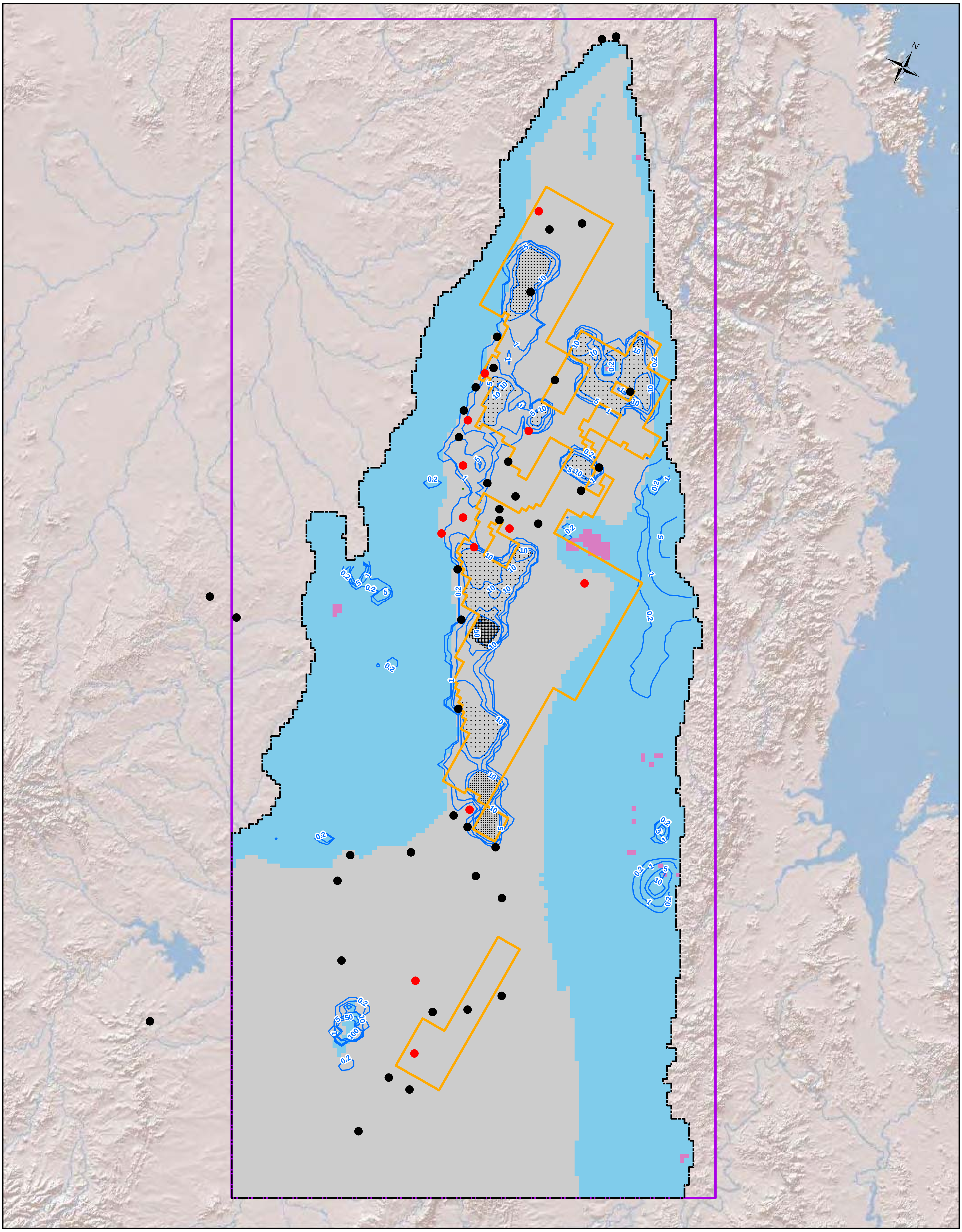
FIGURE 7-35

Modeled Drawdowns Layer 15 - BGP, MGP, and WERD wells 50 years after CSG Production

Ausenco NORWEST CORPORATION

Date: 02/12/2013 | Created By: MDK

BGP_Cumulative_production_Dec2013.mxd - 12/2/2013 @ 5:22:47 PM
Coffey reference: 7043_02_AppB_F07.35_HU



Legend
- Future MGP Production Wells
- Future BGP Production Wells
- Layer 17 Drawdown (m)
- GW Model Domain
- EIS Project Area
- Active Model Extent

Layer 17 Formations
- GML (MCM)
- Back Creek
- Intrusives

Data Source
EIS Area, Production Facility Areas: Arrow, 2012
Base Data: ESRI, 2012

- Operational coal mine
- Proposed coal mine

Note: Operational coal mines (DNRM) and proposed coal mines (URS) added to figure by Coffey (Dec 2013), locations indicative only

Coordinate System: GDA 1994 MGA Zone 55
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000
False Northing: 10,000,000
Central Meridian: 147
Scale Factor: 1
Latitude Of Origin: 0
Units: Meter

0 25 50 100
Kilometers

FIGURE 7-36

Modeled Drawdowns Layer 17 - BGP, MGP, and WERD wells 50 years after CSG Production

Ausenco NORWEST CORPORATION

Date: 02/12/2013 | Created By: MDK

BGP_Cumulative_production_Dec2013.mxd - 12/2/2013 @ 5:23:53 PM
Coffey reference: 7043_02_AppB_F07.36_HU