Water Research Laboratory

Background Paper on Groundwater Resources in Relation to Coal Seam Gas Production

WRL Technical Report 2013/09
November 2013

by
D J Anderson, P F Rahman, E K Davey, B M Miller and W C Glamore

Prepared for the Office of the NSW Chief Scientist and Engineer
as part of the Independent Review of coal seam gas activities in NSW

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Water Research Laboratory
University of New South Wales
School of Civil and Environmental Engineering

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1. Introduction

This report was commissioned by the NSW Office of the Chief Scientist and Engineer. The report provides the reader with a background of NSW groundwater and CSG resources and NSW Water Management Practices, the science involved, a concise summary of consequences and risks, and methods for addressing these risks.

The Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at The University of New South Wales was provided with a scope of works to address the questions listed in Table 1 in a 50-page report. WRL have determined a report structure that allows the reader to progress through the arguments and evidence; the respective answers to these questions are not in the same order they were asked. As such, Table 1 provides a "map" to the sections of our report.

Table 1: Addressing Scope of Works – Document Map

Requirement	Relevant Sections
Definitions and explanations, including: Aquifers Aquitards Water table Recharge (how does water get into the ground?) Uses of groundwater Surface water Connections between surface and groundwater How is groundwater extracted?	 Section 2.1 Section 2.1 Section 2.1 Section 2.1 Section 6.0 Section 2.1 Section 2.3 Section 2.3
Describe the major groundwater bodies in NSW, including the Great Artesian Basin.	Section 6
What are the potential impacts on groundwater resources in relation to CSG exploration, production and abandonment? Including potential 'worst case scenarios' and the likelihood/risk of the scenarios occurring.	Section 4
What techniques and methodologies are used to measure/estimate the depth, extent and quantity of groundwater resources when planning CSG extraction? What techniques and methodologies are used to estimate/model and monitor the impacts on, and changes to, groundwater, the water table and pressure/head, as water is extracted through CSG?	Section 5
What techniques and methodologies are used to measure/estimate the quality and beneficial use category of groundwater resources when planning CSG extraction? What techniques and methodologies are used to estimate/model and monitor the changes in water quality and possible impact on beneficial use category of groundwater resources as water is extracted through CSG activities?	Section 5
How is hydraulic connectivity between aquifers and coal seams measured/assessed, and what are the uncertainties? Describe the situation with hydraulic connectivity between deep and shallow aquifers, how is this measured and assessed and what are the challenges? What characteristics of the geology or extraction activities can alter the hydraulic connectivity?	Section 5
What are the relative impacts of different water extraction activities on groundwater quality, quantity and the water table? For example, CSG extraction versus agricultural water bores versus town water supply versus drought impacts?	Section 6.5
What site/local/regional characteristics (e.g. coal permeability, coal seam depth) can influence the response of groundwater to CSG extraction activities including dewatering? (e.g. draw rate)	Section 3.2 Section 3.6 Section 3.7

Requirement	Relevant Sections
What are the mechanisms or solutions that can be used to minimise, address or remediate impacts and problems (quality or quantity) related to groundwater, including national or international examples?	Section 7
What water management, risk assessment and risk management practices are in place in NSW to manage water (including legislation and regulations)? How do these deal with cumulative impacts issues (including: many wells over a region; coincidence of CSG wells and other extractive activities; drought or flood regime over a coal measure)? How are the cumulative effects taken into account where there are numerous wells in place, or other industries such agriculture?	Section 7
What are the knowledge gaps/unknowns/research gaps in relation to CSG activities and groundwater?	All sections
What lessons (positive and negative) can be learnt from other jurisdictions (nationally and internationally) in relation to the management of groundwater and the water table in locations where unconventional gas extraction is planned or occurring?	Section 4.5 Section 7.4 Section 7.6 Section 7.7

The report is not biased in favour or against CSG extraction. The report finds that there are no potential groundwater risks that cannot be considered through careful site selection, resourced data collection programs, water balance assessments and numerical modelling, and carefully constructed wells. However, in order to quantify processes that may lead to depletion and contamination of the water resource aquifers, it is imperative to determine the inherently uncertain geological and hydrogeological conditions within and around a CSG lease.

This report is an expanded version of a background paper prepared for the Office of the NSW Chief Scientist and Engineer (OCSE) during May 2013. The original paper was prepared within three weeks of commissioning to help inform OCSE's initial report to NSW Government during July 2013. The draft report was based on an extensive review of publications (both journal and industry) supplemented by industry consultation where this was possible.

This final report contains 90-pages of text, tables and figures and approximately 390 references. It includes consideration of industry and consultant presentations at the 2013 IAH Conference held in Perth during September 2013 and edits to address three sets of comments provided by the Office of the NSW Chief Scientist and Engineer. Some of the updates to the report include the provision of maps and tables to summarise groundwater resources in relation to existing petroleum titles, and the provision of additional context regarding the bioregional assessment program. The revised report also includes a limited consideration of recent publications and public commentary. The report does not address material presented at the Unconventional Gas Thought Leadership Series conducted during June 2013 or the Queensland Gas Conference held during September 2013. For a synopsis of the Unconventional Gas Thought Leadership Series please see Volume 40(5) of the water journal published by the Australian Water Association.

2. Relevant Fundamental Groundwater Processes

The sediment and rocks below our feet are filled with small pores. In aquifers, these pores are filled with water, termed groundwater. This groundwater is typically transported at a slow rate controlled by vertical or lateral pressures. As the groundwater passes through the underlying layers, its chemical composition reflects these surrounding sediments. The quality, quantity, history, transport and extent of groundwater and its interaction with the substrate (often termed hydrogeology) is a complex field of science requiring a detailed understanding of small and large scale processes, timescales, chemistry and physics. This section provides a basic introduction to groundwater and related processes. Future sections will build upon this information to assess the risks and consequences of Coal Seam Gas (CSG) extraction. Additional references are provided at the end of this section.

2.1 Hydrogeological Setting

The sediments and rocks below the earth's surface can be classified as aquifers or aquitards. An **aquifer** is an underground (geologic) formation capable of holding water. The volume of water within the aquifer is primarily reliant on the volume of the pore spaces or **porosity**. While some aquifers have elevated concentrations of salts, metals or other contaminants, the term 'aquifer' is commonly used to refer to formations capable of yielding water which has some **beneficial use** such as for human consumption, irrigation or stock use (NWC, 2007). Alluvial deposits are sediments composed of gravel, sand, silt or clay deposited in river channels or on floodplains. They occur in most regions of Australia and are a major resource for irrigation, town, stock and domestic uses. About 20% of all bores in Australia are in alluvial systems and they account for 60% of Australia's groundwater extraction (GA, 2013b). **Alluvial aquifers** are generally shallower than sedimentary and fractured rock aquifers and water levels often fluctuate due to varying recharge and pumping rates. Due to their shallow and (usually) unconfined nature, alluvial aquifers are susceptible to contamination and pollution (GA, 2013b).

An **aquitard** is a geologic layer (or strata) through which water percolates extremely slowly (relative to adjacent geological strata). Due to the geologic nature of the rock or clay strata, an aquitard may contain water but this groundwater would be difficult to extract. Single or multiple aquitard layers may exist and these layers can be regionally continuous, segmented or angled. An example of an aquitard would be a saturated claystone layer overlying a saturated sandy layer (aquifer) (DPI, 2013). It is worth noting that the lateral extent, thickness and permeability of an aquitard may vary and that in many regions of NSW this information is not available because these properties can only be measured at boreholes or inferred between boreholes using geophysical survey.

Where groundwater is in direct contact with the atmosphere the aquifer is **unconfined.** The upper groundwater surface in an unconfined aquifer, which is always saturated, is called the **water table**. The thickness of strata between the water table and the ground surface (called the **vadose** zone) is a function of aquifer recharge and loss, which varies according to influences on the upper, lower and lateral boundaries of the aquifer. These factors include natural variables such as the topography, geology, season, weather patterns, evapotranspiration, tidal effects, and discharge from the aquifer to the surface and adjoining aquifers. Human induced factors such as aquifer pumping via bores, increased/decreased recharge zones, or impacts to the aquifer geology may also be important factors in controlling aquifer pressures, elevation and the extent of the water table.

In an unconfined aquifer the fluid pressure in the pores at the bottom of the vadose zone is equivalent to the atmosphere. These pore pressures increase with depth equivalent to the water density times gravity, which is approximately 1000 kPa per 100 m depth (so that a 400 m deep aquifer of static water has a hydrostatic pressure of approximately 4000 kPa). It is important to remember that this pressure is calculated using the water table depth and not the depth from the soil surface.

In regions where aquitards constrain water movement in an aquifer (by typically lying above the aquifer) the aquifer is **confined**. The fluid pressures in these systems can be complex with varying pressure mechanisms. The following section provides further detail on piezometric head and groundwater flow.

Recharge is the inflow of water to a groundwater reservoir from the surface (NWC, 2007). **Unconfined aquifers** are usually **recharged** by rain or stream water infiltrating directly through the overlying ground. Figure 1 displays a gaining surface waterbody (a) and a losing surface waterbody (b). Frame (c) represents pumping from a confined aquifer that is partly disconnected from the overlying aquifer by an aquitard.

Groundwater and **surface water** (water found in above ground water bodies such as streams, lakes and wetlands) form part of the total hydrologic cycle and are part of the same system. To manage both **groundwater and surface water** systems sustainably the **connection** between the two needs to be understood and quantified. For instance, rainwater drains into creeks and streams and may raise their levels but the baseflow in creeks and streams is a result of the water table being exposed at the ground surface. Quantifying the amount of recharge into unconfined aquifers, the loss of water from the aquifer to the environment or the volume of groundwater exchange across aquitards and between aquifers (**hydraulic connectivity**) is an area of ongoing research and investigation.

2.2 Permeability, Pressures and Groundwater Flow

While porosity can provide an indication of the volume of water stored, the permeability of an aquifer will indicate how groundwater moves. **Permeability** refers to the ease with which water or other fluids can move through soil or rock. It is a characteristic property of a material and fluid and is related to the geometry of the voids and surfaces of solid materials. Permeability is measured by calculating the discharge rate at which water (or another fluid) will be transported through the pore spaces of the material. This rate is controlled by the hydraulic conductivity of the saturated material (a function of soil properties for a given fluid density and viscosity) and the pressure gradient over an area (e.g. from one side of the aquifer to the other). The product of the hydraulic conductivity and formation thickness is called transmissivity.

In most aquifer systems, the permeability is calculated using laboratory and field techniques that utilise flow or flux equations derived from Darcy's Law. It is worth noting that Darcy's Law is only applicable in slow, viscous flows. Turbulent flows (i.e. Reynolds numbers > 10) and two phase gas-liquid flows, such as those that exist in the immediate vicinity of a CSG well, require more complex computations.

Based on Darcy's Law, aquifer pressures are important because they control water movements. Figure 2 shows different pressure levels within a series of aquifers. In Figure 2, the top aquifer (referred to as Aquifer A) is unconfined, with the groundwater surface represented by the top of the water table. As water flows into and out of this aquifer the groundwater level can rise and fall accordingly. If the inflow or loss of water within the system is greater in one area than another a pressure gradient would be created. Due to the unconfined nature of the aquifer this pressure gradient would result in the entire groundwater table rising or falling.

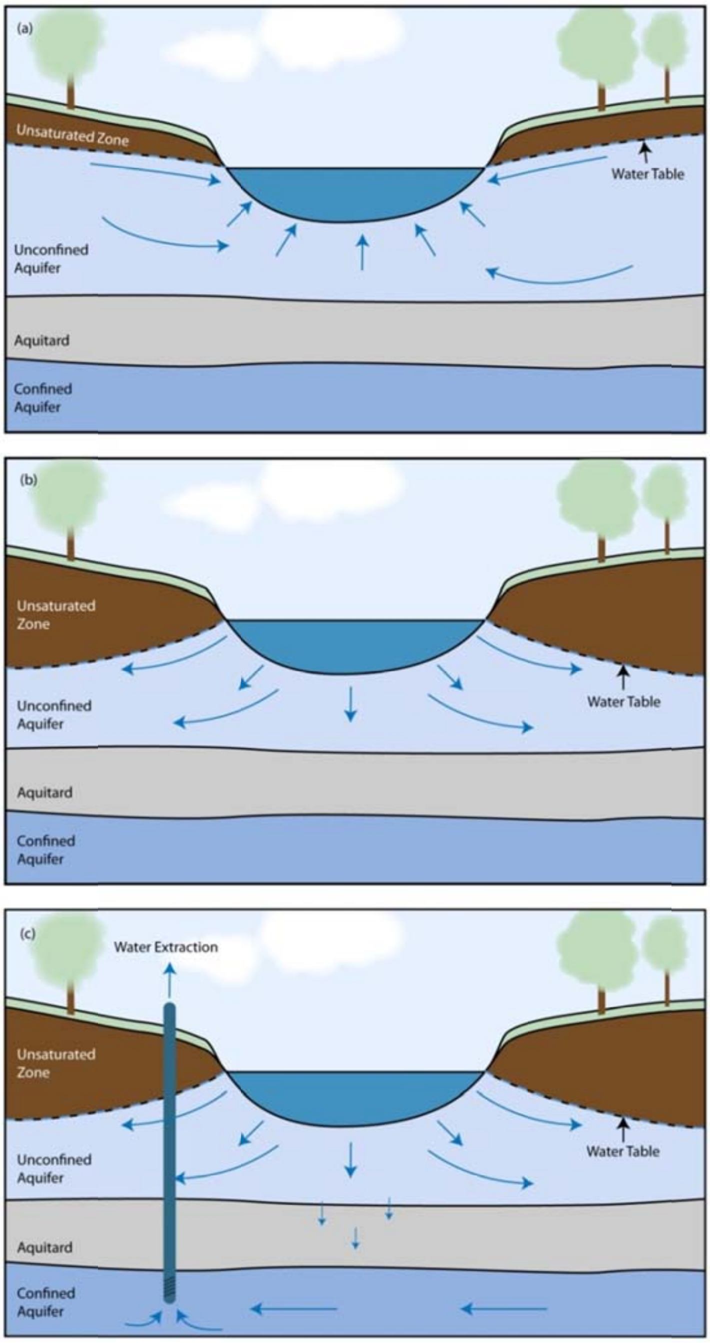


Figure 1: Aquifers, Groundwater and Surface Water Interaction. (a) Gaining Waterbody; (b) Losing Waterbody; (c) Losing Waterbody with Additional Water Extraction (not to scale)

In confined systems, such as Aquifer B and C, aquifer recharge increases pressure, but due to the confined layer above, it does not raise the water table. This is largely because recharge of confined aquifers occurs at a significant distance from the main body of the aquifer. If a water bore is inserted into these systems (Figure 2) the pressure will raise the water inside the bore to the height equivalent of the hydrostatic equilibrium (such as with Aquifer C in Figure 2, panel (b)). The elevation of the water within the bore (or piezometer) is called the potentiometric, or piezometric surface. The pressure of the water within a confined aquifer is also referred to as 'head'. If the water reaches the ground surface (Figure 2, panel (b)), it is known as a flowing artesian well.

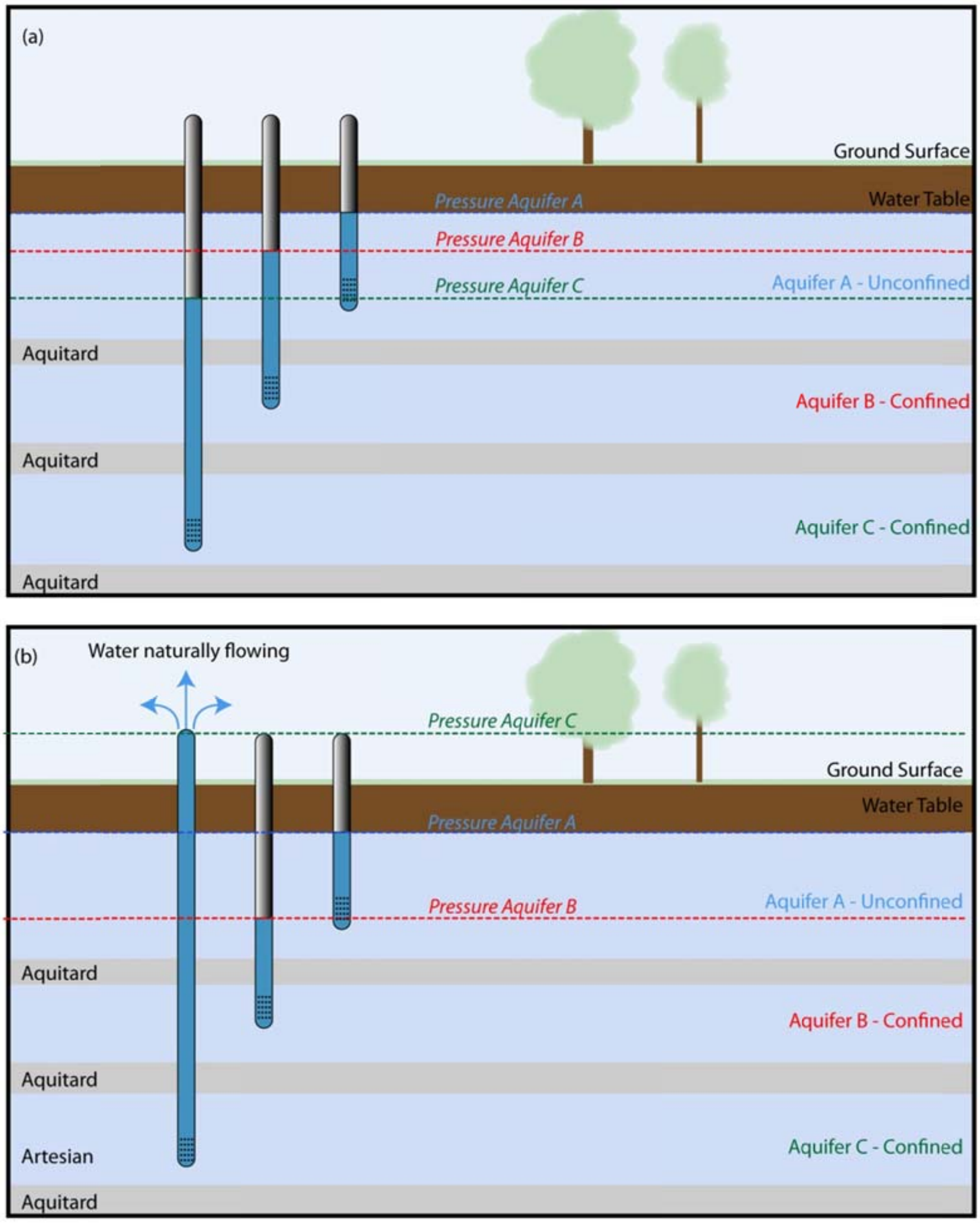


Figure 2: Pressure Levels within Aquifers

Confined aquifers are not always perfectly sealed. The aquitard may be 'leaky' due to (i) cracks (or fractures) in the aquitard which are more prevalent under overburden pressure or in response to geological stress; (ii) discontinuities in the aquitard conductivity or geological strata; (iii) poorly installed bores which allow leakage between aquifers; or (iv) naturally occurring flow in accordance with Darcy's Law. The spatial extent of these leaks and the response of aquitard layers to fluctuations in pressure is an important area of ongoing research and investigation.

Figure 3 provides an example of how a leaky aquitard will influence surrounding aquifers. As shown in Figure 3 water is being extracted from Confined Aquifer C. In Figure 3 (a), the aquitard between B and C is highly impermeable, so there is negligible connectivity between the aquifers B and C. Subsequently, there is negligible impact from the water extraction on Aquifers A and B. However, in Figure 3 (b) the aquitard between Aquifers B and C is more permeable. Whether this is due to fractures in the aquitard layer or a just a more permeable zone within the strata, water extraction from Aquifer C has led to an observable lowering of the pressure level in Aquifer B. The implications of aquifer connectivity are further explored below.

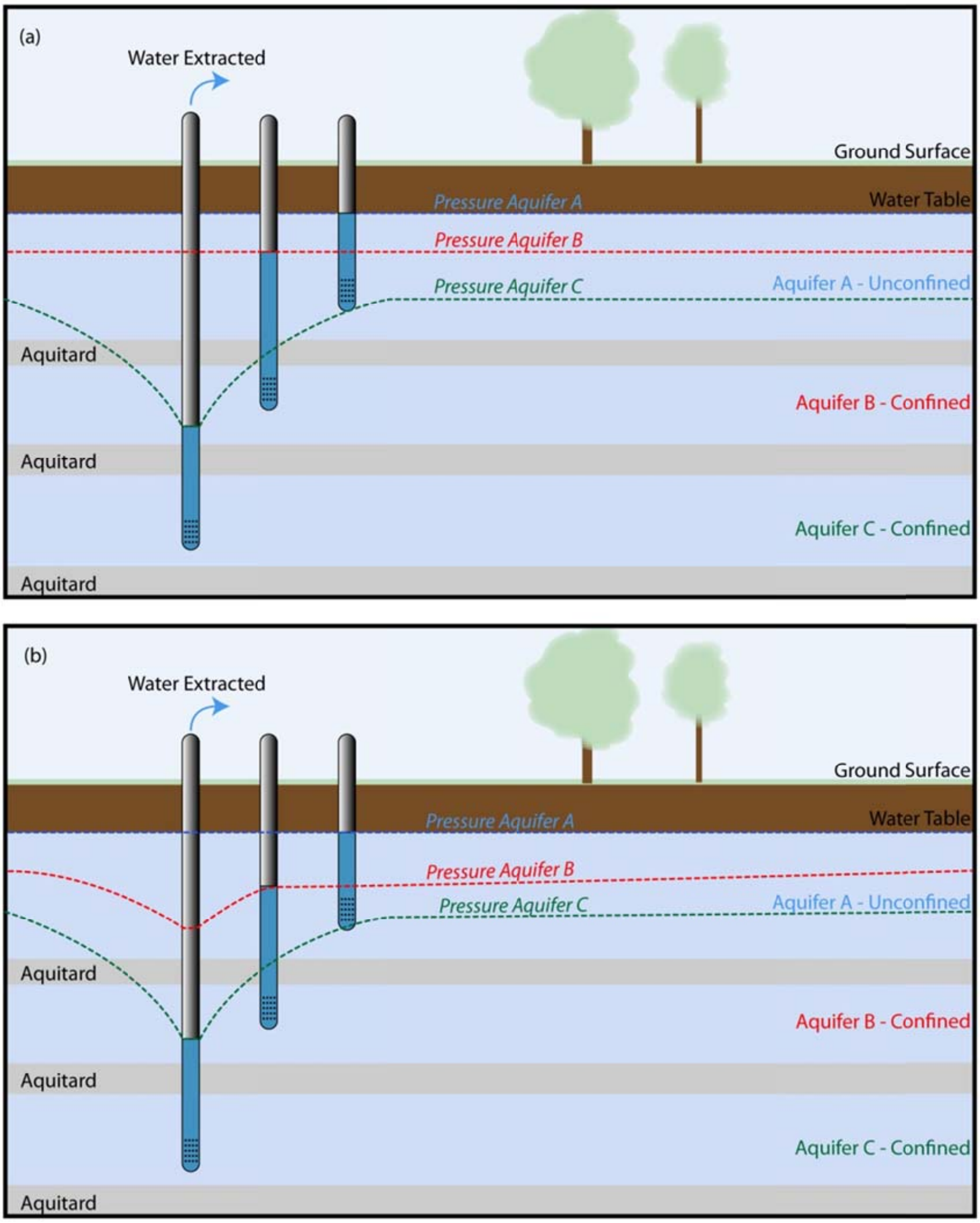


Figure 3: Pressure Levels within Aquifers Following Water Extraction

2.3 Groundwater Extraction, Recharge and Connectivity

Groundwater bores (or wells) are required to extract water and/or resources within an aquifer to the surface. A wide range of bore types exist, with each design customised to the measurement or activity required. A production well is drilled to the depth and bore size required using a drill rig. During this process bore casings are installed to minimise aquifer contamination. The gap between the hole and drill or production casing is typically encased in concrete and other surface casings may be installed to limit cross-contamination between different strata. A screened section extends beyond the casing to allow inflow of groundwater from the desired seams (or plays). A downhole pump is then inserted into the well and groundwater is extracted at a predetermined rate. In CSG operations the extracted water and methane gas are then pumped separately to a treatment facility (water) or to the main trunk pipeline (gas). Further information on CSG bore and operations is provided in Section 3.

The extraction of water from the confined aquifer results in a zone of depressurisation. The size and extent of the area depressurised is of fundamental importance to the hydrogeologist. In brief, the pressure within the aquifer reacts as soon as the bore is installed. The extent of depressurisation is reliant on several factors including the size of the aquifer, the water storage capacity (storativity), the pumping rate, the initial pressure, the aquifer recharge rates, the aquifer geology and the flow of water through the aquifer.

Pressure changes within a confined aquifer can be complex, can travel large distances and can change the prevailing direction of groundwater flow. The difference between the pressure and water particle movement is similar to opening a garden tap. Initially there is a rapid pulse of pressure moving through a full garden hose. The near immediate flow of water at the end of the hose is not due to the instant arrival of water molecules from the tap but the transfer of pressure through the hose so the molecules nearest the end of the hose are forced out. In the case of an aquifer, the groundwater flow is further influenced by the soil and water characteristics (hydraulic conductivity and storativity) and the change in pressure gradients (as calculated using Darcy's Law). **Storativity** defines the amount of water released from a unit of aquifer in response to a unit decline in water pressure. **Specific Storage** defines the amount of water released from a unit of confined aquifer in response to a unit decline in water pressure. It is a function of the compressibility of the formation and the fluid, in addition to the porosity.

The recharge of confined aquifers is dependent on where water can flow into the aquifer. Two main mechanisms control confined aquifer recharge; (i) natural recharge through the aquifer from recharge zones, and (ii) vertical water movement from overlying aquifers (Figure 4). Confined aquifers, including coal beds such as displayed in Figure 4, may be recharged by rain or stream water infiltrating into the rock at some considerable distance where the formation or a connected formation outcrops at ground surface. Groundwater in these aquifers can sometimes be thousands or even millions of years old due to the low flow rates through the aquifer and the long distances. Subsequently, natural recharge of deep, confined aquifers following water extraction takes substantially longer than recharge of shallow, unconfined aquifers.

Vertical water movement from overlying aquifers into confined aquifers is an area of ongoing research. The volumes of water moving from the overlying aquifer depend on the hydraulic conductivity of the aquitard and the connectivity between the aquifers. Water may not flow directly, or may flow extremely slowly through the aquitard due to low hydraulic conductivity values or gradients, however preferential flow paths through the aquitard may be possible via joints, fractures and conductive faults. Small quantities of vertical water movement might be significant over large areas, or over long time periods.

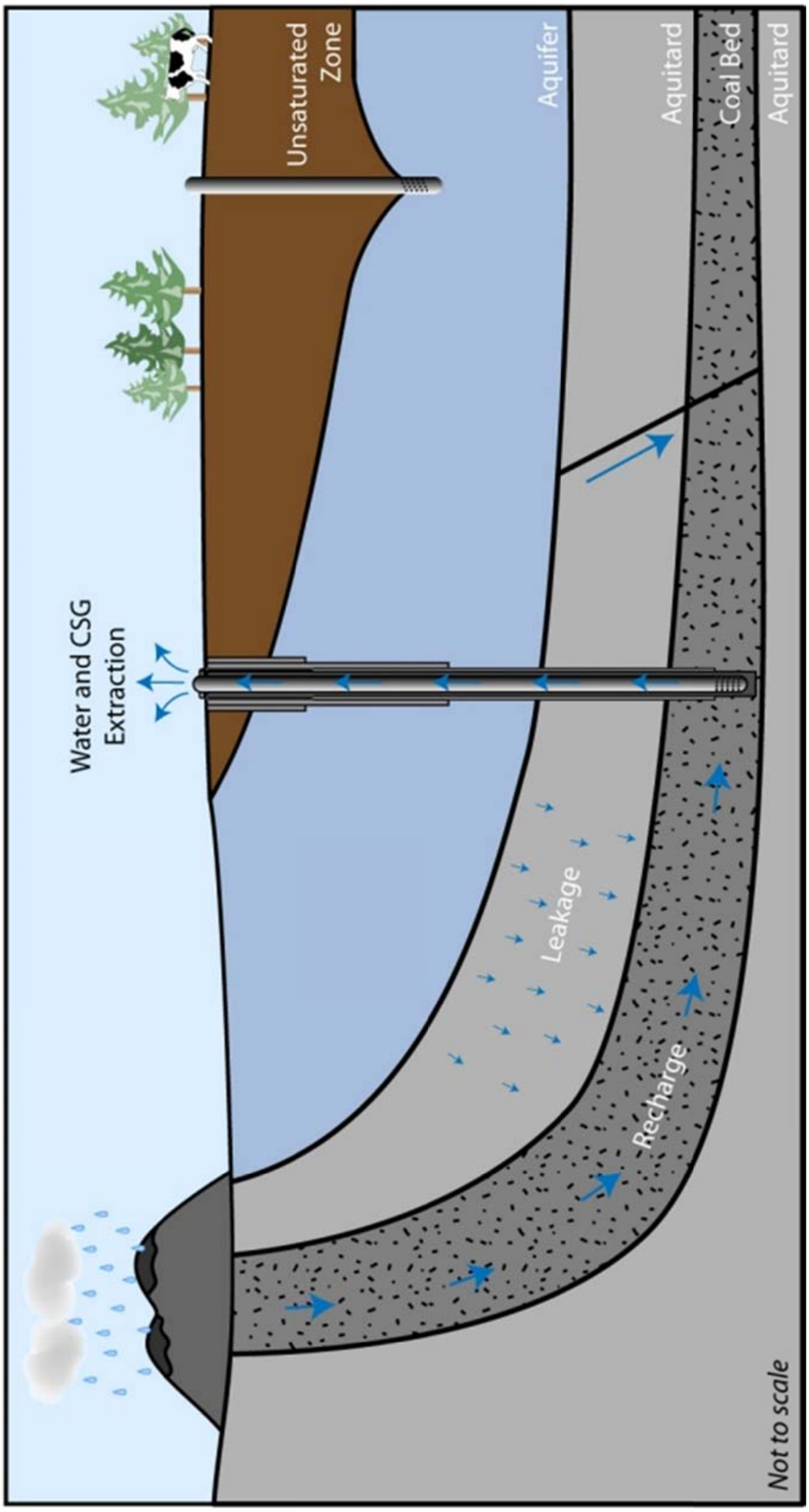


Figure 4: Mechanisms for Water to Re-enter the Coal Seam

3. Coal Seam Gas

3.1 Characteristics of Coal Seam Gas

Coal seam gas (CSG) is generated within a coal seam via biogenic and thermogenic processes. While the majority of the gas is expelled and migrates to conventional traps or escapes to the atmosphere, some is sorbed (adsorbed and absorbed) into the coal's micropores. The coal matrix is characterised by a natural fracture, or cleat system, which is generally saturated with water. Coal seams have moderate intrinsic porosity, yet they can store up to six times more gas than an equivalent volume of sandstone at similar pressures (Schlumberger, 2013). CSG is categorised as an unconventional gas along with shale gas and tight gas as they are produced in complex geological systems that prevent or limit the migration of gas without physical intervention. The difference between conventional and unconventional gas is explained in Figure 5.

CSG in Australia is predominantly methane (typically 95 - 97%, mixed with carbon dioxide, other hydrocarbons and nitrogen from the coal formation) and therefore is often referred to as Coal Bed Methane (CBM). The gas is attached by sorption to the chemistry in the coal matrix which is held under the pressure from the over laying formations and the water in cleats. Gas-storage capacity can vary extensively (1 to 25 m^3/tonne), and is primarily related to the coal's rank. Higher-rank coals, bituminous and anthracite, have the greatest potential for methane storage (Al-Jubori *et al.*, 2009). The 'depth of cover', a term used by industry, provides an indication of the depth of the coal seam and thickness of overburden strata that can provide important hydraulic barriers to vertical flow. It is important to recognise that the geology is different for each site specific coal seam aquifer. In general more fraccing is required if the permeability of the coal seam is low.

3.2 Releasing Coal Seam Gas from Coal Seams

At the micro level, the molecular structure of the coal acts as a virtual chemical cage, capable of storing methane molecules. The gas remains in the micropores as long as there is enough pressure confining it to the coal. In coal seams this is possible via two mechanisms. Either the coal seam saturates and groundwater flows through the cleat system to build up reservoir pressure, thus preventing the gas from escaping the coal microstructure, or there exists (paleo) water that has been trapped underground (fossil water). Aquitards immediately above or below the coal seam effectively act as confining layers and therefore coal seams can be conceptualised as a type of confined aquifer.

Pressure at the given point in the aquifer can be expressed as a function of the hydraulic head. When the pressure drops the methane gas desorbs from the internal surfaces of the coal. Methane gas then diffuses through the micropores of the coal until it reaches a cleat. At that point the gas has reached the coal macro structure (large pores and fractures or cleats) and it can be transported (Figure 6). The migration of CSG is directly related to the flow of water in the coal seams, and the physical and chemical structure of the coal. In time, the rate of desorption decreases due to the reduction of the pore size in the coal matrix and thereby reduces potential flow.

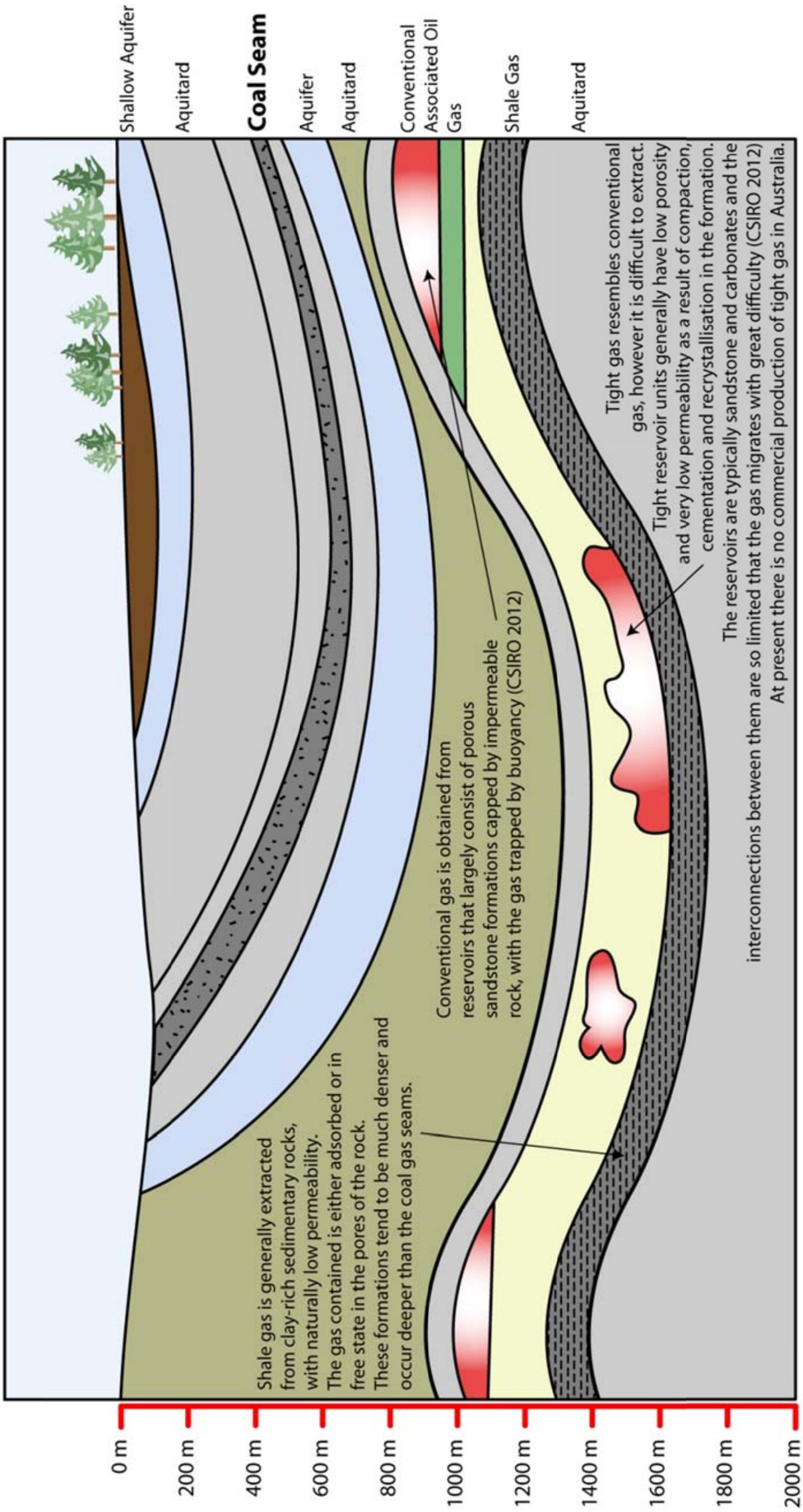


Figure 5: Characterisation of Natural Gas

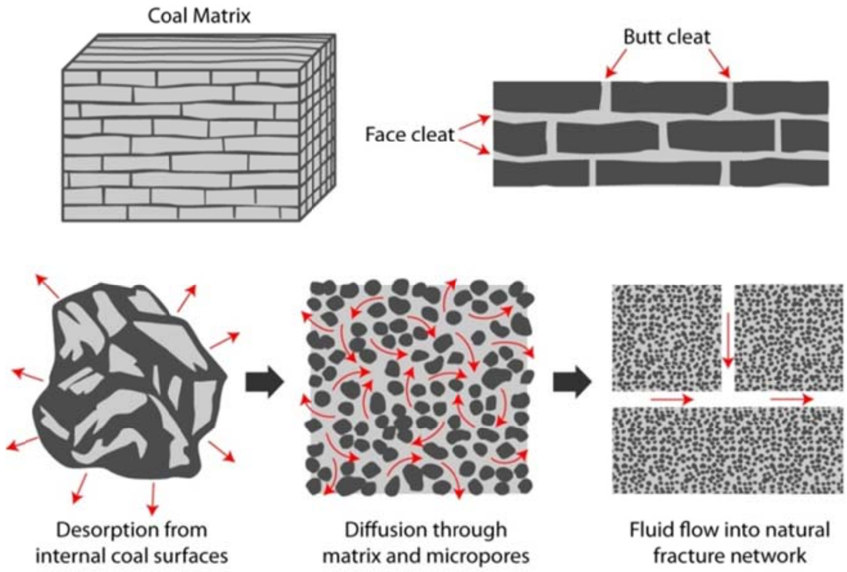


Figure 6: Desorption and Diffusion of CSG within the Coal Matrix

The reduction in pressure on the internal coal surface can take place naturally over geological time if there is tectonic movement or uplifting of gas bearing coal strata. This natural depressurisation can induce natural leakages (of gas and water) from the coal seam aquifer into overlaying aquifers. This concept is used for CSG extraction whereby the coal seam aquifer is depressurised to allow desorption to take place so that the gas can be collected. After the coal seam has been depressurised, in situ production rates can be estimated using conventional techniques such as material balance and decline-curve analysis. The storage characteristics of sorbed-gas reservoirs mean that larger volumes of gas are liberated at lower reservoir pressures (Jenkins and Boyer, 2008). Figure 7 shows for coals of various maturities, that if the average reservoir pressure is reduced from 100 to 50 psia (psi atmospheric) much more gas is liberated than with a comparable 50 psia reduction in pressure from 200 to 150 psia.

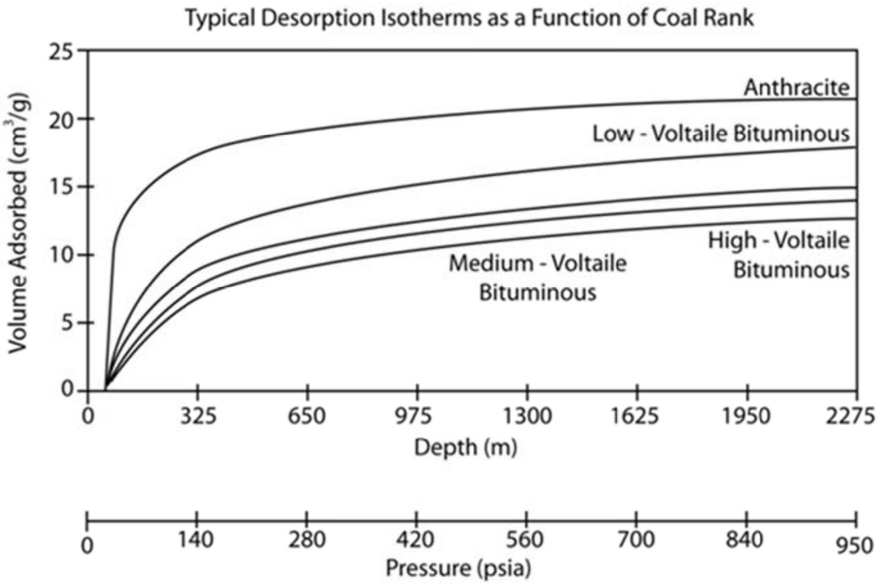


Figure 7: Typical Desorption Isotherms (Adopted from Kim, 1977)

3.3 Bores

Various types of bores are required to be drilled during the life of a CSG operation. Wells are bores or excavations which produce water (Sharp, 2007). Bores are drilled during exploration and production of CSG, and to undertake monitoring activities in different stratigraphical layers/aquifers either to demonstrate regulatory compliance or to aid producing hydrogeological models. The following sections introduce the concepts behind CSG well construction from drilling through to decommissioning.

3.3.1 Drilling Methods

A variety of drilling methods are available for the drilling of CSG wells. These include vertical, directional horizontal and multilateral drilling (Figure 8). The geological conditions and fracture patterns in coal and adjacent rock will dictate which borehole type, stimulation and completion techniques will succeed (Sydney Catchment Authority, 2012).

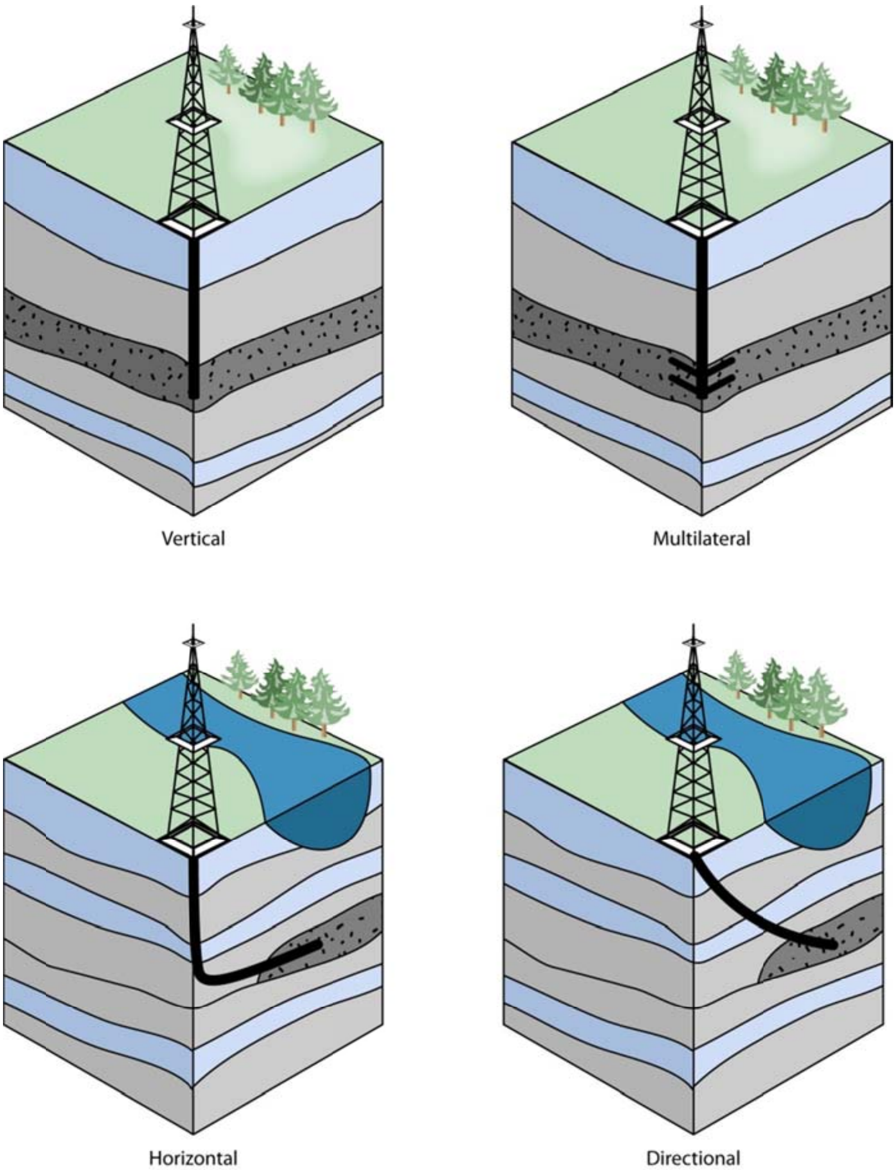


Figure 8: Characterisation of Various Drilling Methods

3.3.2 Well Construction

Wells are required to be isolated from the geological strata and shallower aquifers by steel and cement casings. This is done to achieve a non-porous barrier which aims to prevent cross-contamination for coal seam fluids with overlying aquifers. A typical section of a CSG well is shown in Figure 9.

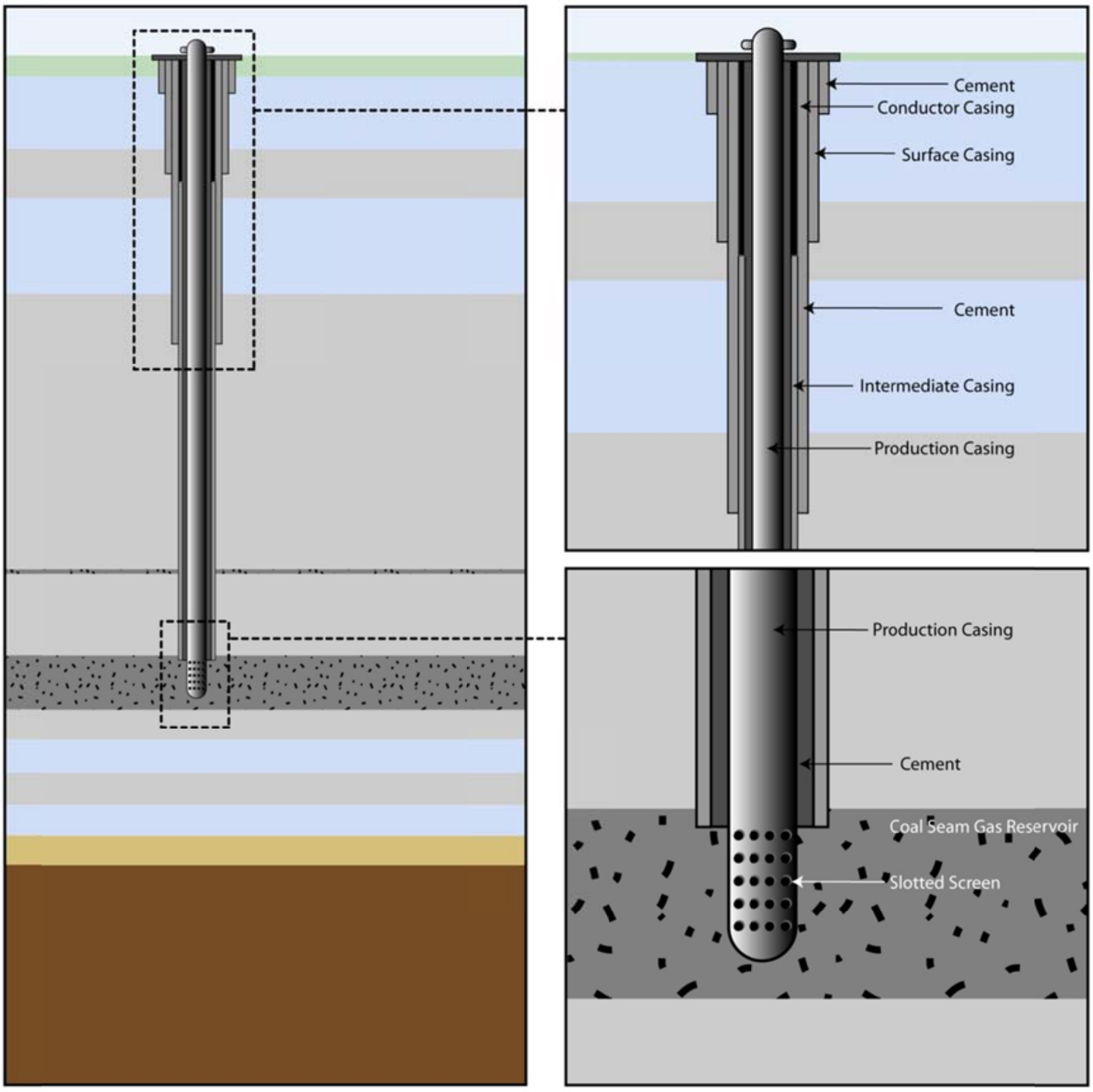


Figure 9: Typical CSG Well

3.3.3 Well Logging

Well logging techniques are often the only means of evaluating the condition of some of the well barrier elements such as the cement, casing and tubing (OGP, 2012) following construction. Well logging methods can include; corrosion calliper, acoustic, sonic and ultra-sonic, magnetic eddy current, magnetic flux leakage, tracer tests, pressure tests and video camera surveys.

Wells require monitoring for:

- Leakage;
- Erosion;
- Cathodic protection (if in contact with saline water);
- Structural integrity (metal corrosion, metal fatigue, degradation of soil strength due to climatic and thermal loads, sideways squeezing formation or earthquakes); and
- Annular pressure.

Cement bond logs (a type of sonic log) are produced using down hole geophysics tools to examine the integrity of the cement used to complete the well. These logs can be used to identify areas of low cement density and any fractures or cracks that may exist. Well pressure tests can be undertaken by injecting water and examining the pressure response to ensure that the well can withstand pressures expected during the life cycle.

More information on best practices and guidelines regulating well development and construction in NSW can be sourced from the NSW Code of Practice for Coal Seam Gas Well Integrity (DTIRIS, 2012b).

3.3.4 Well Decommissioning

The well decommissioning process requires shutting down well activities and rehabilitating the site. In the NSW Government Code of Practice for Coal Seam Gas Exploration it is suggested that the outcomes of the well abandonment are to:

- Maintain isolation of beneficial aquifers within the well from each other and hydrocarbon zones;
- Maintain isolation of hydrocarbon zones within the well from each other, from aquifers, water bearing zones or from zones of different pressure; and
- Minimise risk to possible future coal mining by isolating the surface casing or production casing from open hole and placing a surface cement plug in the top of the casing as well as recovering and removing the wellhead.

These objectives are difficult to validate over the longer term even with continued monitoring regimes. NSW has mandatory requirements in place that require abandoned wells are sealed by filling the total depth of the well with at least a concrete strength of 500 psi (3.5 MPa). In instances where fraccing techniques (as detailed in Section 3.6) were employed, squeezed cementation is required to seal the fractures.

3.4 Monitoring

An essential over-arching activity for all stages of CSG operations is the ongoing monitoring, analysis and modelling of environmental variables. This includes groundwater, surface water, land and air. At the beginning of a CSG operation there can be considerable uncertainty in the geological and hydrogeological structure and properties of the subsurface. For each stage and step of a CSG operation monitoring provides valuable information about the structure, properties and behaviour of the system in response to external stresses. Analysis, modelling and review of the monitoring data reduces the uncertainty and helps practitioners better understand the system in the context of their activity.

Monitoring programs need to incorporate both quantity and quality elements. Monitoring regimes must commence at the very beginning of a CSG operation (prior to drilling) and must continue for many years well after the completion of the activity. Hydrogeologists call monitoring data collected prior to drilling and pilot testing a 'baseline'. Further information on groundwater monitoring can be found in Section 5.3.

3.5 Stages in CSG Operations:

There are four stages in CSG operations: exploration, assessment, production and abandonment. The first two stages exist to: (a) characterise the subsurface gas and water resources; (b) assess the integrity of the intervening geological structures and the connectivity between aquifers; (c) measure gas production and water impacts, and (d) test remediation strategies. The last two stages involve the economic production of gas and the subsequent decommissioning of the site. The following sections aim to describe the techniques and processes in each of these stages with the purpose of assessing the potential impact to groundwater resources.

3.5.1 Exploration

The purpose of CSG exploration drilling is to obtain information on geology - depth and thickness of coal seams, gas content and composition, gas saturation, coal seam permeability and geological structures that may influence production. The exploration stage determines whether production of gas is economical for a given formation and if exploration should proceed to field development. Activities in this stage include desktop studies (no impact on groundwater), monitoring program (no impact on groundwater), and sampling of existing bores and wells (no impact on groundwater), drilling (potential impact on groundwater) and field geophysics (no impact on groundwater).

The bulk physical properties of the subsurface during the planning stages are primarily collected using geophysics. Seismic methods are the most commonly used for CSG explorations. There are three types: Seismic Refraction (shallow investigations), Seismic Reflection (depths greater than 50 m) and borehole seismic.

Seismic methods are based on the theory that rocks of very low porosity (including most igneous and metamorphic rocks, and evaporites) have seismic velocities which are controlled mainly by their compositions, and can be predicted from prior knowledge of their component minerals. In rocks of medium to high porosity, the velocity will depend on the nature of the fluid filling the pore space. In general seismic velocities:

- Increase as the saturation increases;
- Increase with consolidation of sediments;
- Are similar in saturated unconsolidated sediments;
- Decrease as weathering increases; and
- Decrease as fracturing increases.

The results of an example seismic survey are shown in the right hand panel of Figure 10. The left hand panel shows an illustration of the seismic method. In this case, a seismic signal is transmitted into the subsurface by vibroseis trucks and reflections of the seismic energy from density contrasts in the subsurface are detected and recorded by a geophone cable connected to an instrumented truck.

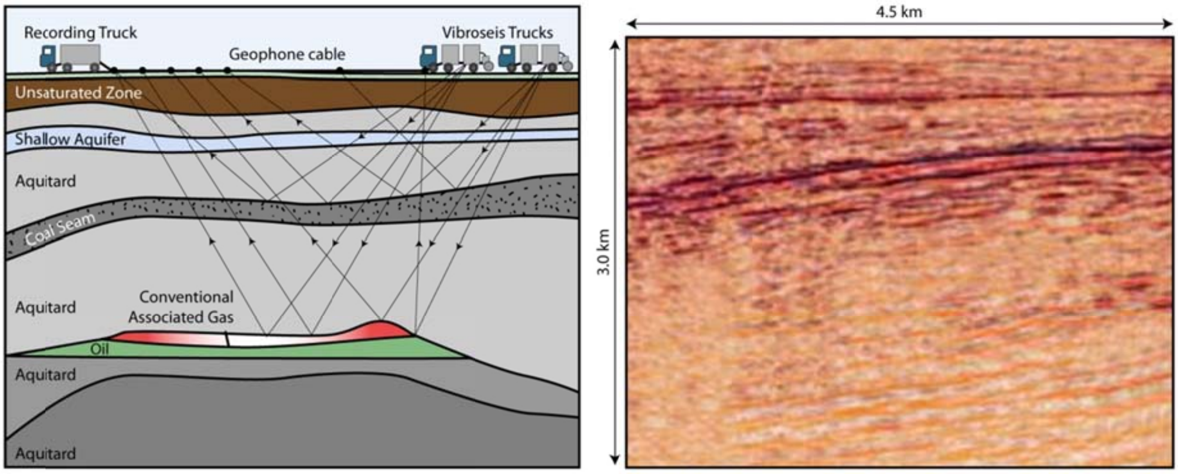


Figure 10: Representation of Geophysical Surveys

Geophysical surveys such as seismic surveys may be particularly useful for identifying geological structures that may influence CSG production. For example, faults may intersect coal seams with upwards or downwards displacement of strata. The faults may be conductive for water flows interconnecting adjacent strata, or may be barriers to groundwater flow.

It is important to realise the limitations of seismic surveys, with interpretations that may not be unique or uncertain with increasing depth. Geophysical surveys should always be used in conjunction with all available knowledge and data to enhance the reliability of interpretations.

3.5.2 Pilot Testing

If initial exploration indicates the potential for gas production, pilot wells may be drilled or completed to confirm production performance and to further define reservoir properties and potential gas reserves. A pilot test (or appraisal test) is essentially a small scale production trial, with associated infrastructure (Keogh *et al.*, 2011).

The purpose of pilot/appraisal testing is to:

- Confirm gas and water production volumes;
- Compute duration of dewatering and rate decline;
- Confirm commercial gas rates can be achieved and full-scale development will be economic; and
- Assess potential environmental impacts, including those to groundwater, by confirming or updating conditions and impacts predicted in the exploration stage.

Most multi-well pilot tests consist of closely spaced wells drilled as part of a five or nine spot configuration and are typically produced for a minimum of 6 to 12 months to collect necessary information (Jenkins and Boyer, 2008). Licenses for assessment can be granted for up to six years under current legislations and regulatory frameworks. If it is determined that production is not economical pilot wells are often abandoned. Decommissioned wells developed for pilot testing have similar consequences to groundwater interference as those related to production wells. The decommissioning of pilot wells should be treated in a similar fashion.

3.5.3 Production

If exploration and pilot testing confirm viability of commercial production and a low risk of no more than minimal impact to water resources (see Section 7), a coal seam gas field may be developed. Figure 11, demonstrates the typical production curve for a coal seam gas reservoir.

The shape of the production curves are explained by considering theory of desorption of coal seam gas in section 3.2, which requires larger volumes of water to be extracted in the initial stages to depressurise the coal bed and allow for desorption and gas flow. The movement of the two fluids (multiphase flow) is defined by their effective permeability (GRI, 1996) and lower volumes of water are required to be removed during later stages of production to sustain the desorption. Volumes of produced waters reported by AGL for current activities are relatively small for NSW (coastal) Permian Basins (Camden < 30ML pa, Hunter < 1ML pa, Gloucester < 4ML pa) (Roy, 2012).

In addition to the permeability, the degree of gas saturation is considered to be the second most important parameter in characterising production (Moore, 2012). Figure 12 demonstrates the significant increase in the amount of hypothetically producible gas based on initial level of gas saturation (in addition to the rank, as described in Section 3.2). The maximum level of saturation for a given coal rank is demonstrated by the black lines. Figure 12 shows that the state of saturation of the coal seam formation at a given location can have huge implications on coal seam aquifer extraction rates, as low rank coal may be less sensitive to changes in the level of gas saturation than the high rank coal.

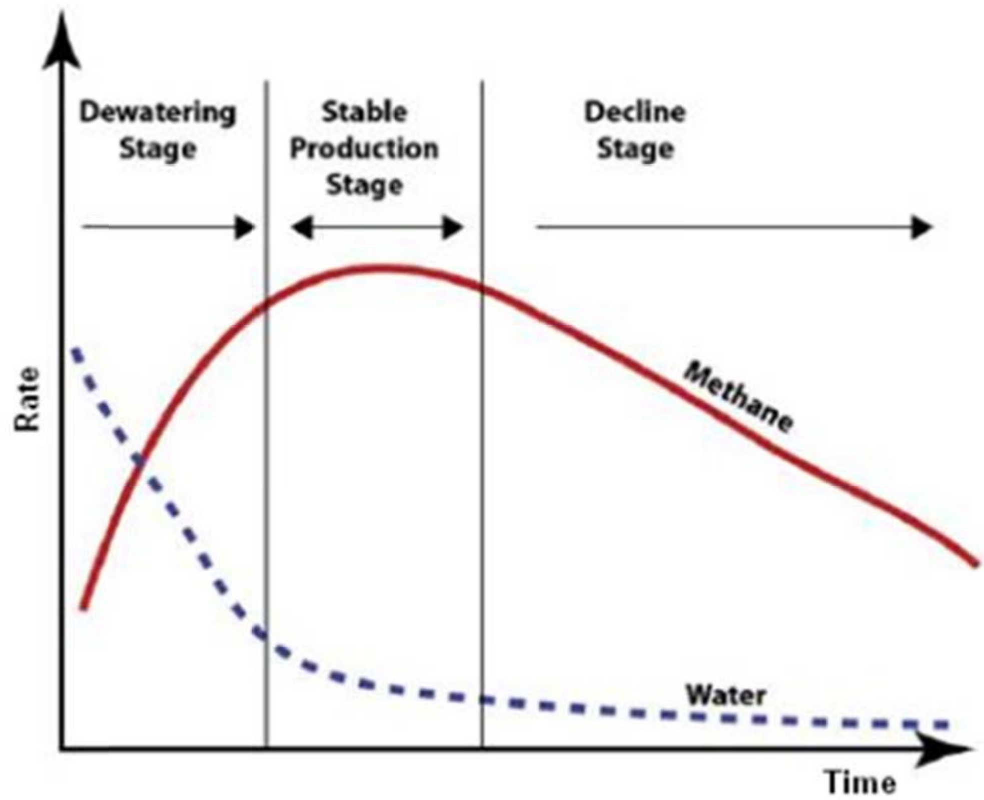


Figure 11: Schematic Production Profile (Williams, 2012)

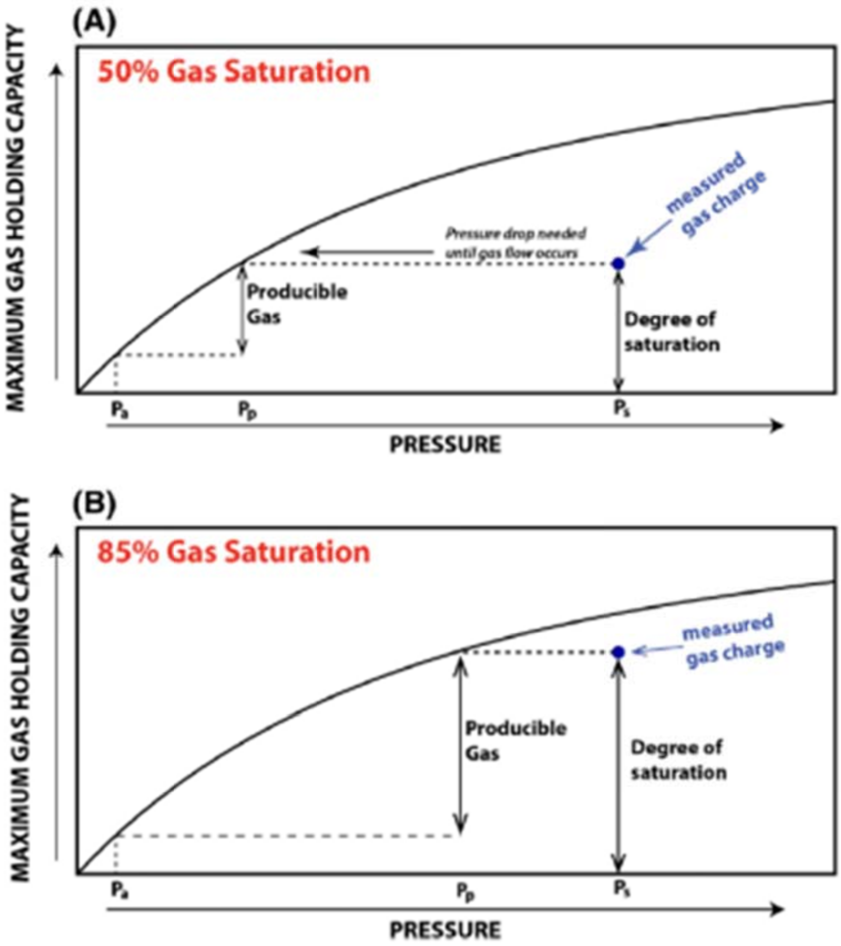


Figure 12: Comparison of the Effects of Two Different Gas Saturations on De-pressurisation (Moore, 2012)

3.5.4 Abandonment

Well abandonment occurs when the well is no longer commercially productive, or required due to exogenous factors (such as end of lease of regulatory requirements). The life of a well is generally around 20 to 30 years. To limit the drawdown of overlying aquifers associated with depressurisation caused from abandoned wells, it is necessary to consider the repressurisation processes and associated time frames. There are two main ways that repressurisation of a coal seam can take place; naturally or artificially.

If left to natural processes, depressurised coal seams will repressurise with time. However, this is likely to take an extensive period of time (potentially in the order of 1000s of years) due to the distance the water has to travel from the surface to repressurise the system and the rate at which rainfall infiltration and recharge occurs in natural systems. There is an additional potential problem with allowing natural recharge and repressurisation; the water has to come from somewhere, subsequently it is likely to result in reduced water volumes in surface water bodies and/or shallow aquifers or in the soils where coal seams outcrop. Essentially, natural recharge of these water systems could result in taking water that other water users including vegetation, could be relying on. Conversely, depressurised coal seams can be recharged artificially through re-injection of the extracted groundwater.

3.6 Increasing Hydraulic Connectivity

Production of CSG can employ hydraulic fracturing (fraccing) techniques to increase the connectivity within the coal seam. "*Fraccing involves pumping a fluid, mostly comprised of water and sand, under pressure through a steel and cement-cased gas well into coal seams*" (NSW Government, 2013). The flow of fluid into the coal seam under pressure promotes fracturing of the coal matrix which increases the connectivity between the coal and the CSG well. The sand infiltrates the cleats and fractures and helps to maintain a flow path in the coal seam to release the water within (CSIRO, 2012e).

Subsequent pumping of water from the CSG well depressurises the gas from the pores of the coal seam allowing it to be extracted from the well. The Code of Practice for Coal Seam Gas Fracture Stimulation (DTIRIS, 2012a) establishes a best practice framework which covers; the fracturing process, chemicals in fracturing fluid, the sourcing of the water used in fracturing; protection of aquifers from the fracturing fluid and a review process to reconsider the codes every two years. A schematisation of a fracced well is represented in Figure 13.

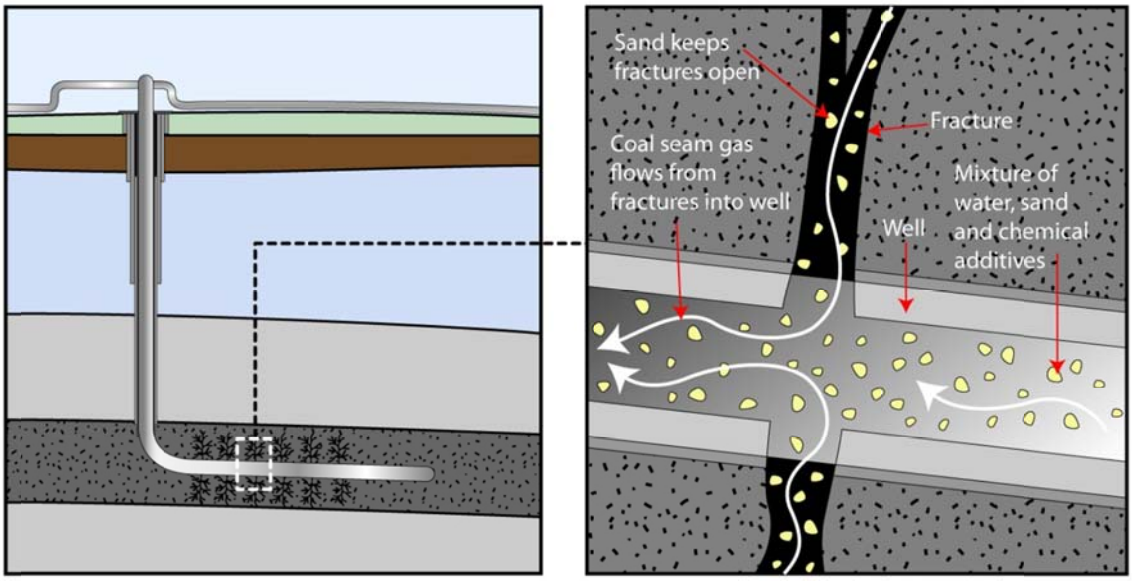


Figure 13: Example of Hydraulic Fractured Horizontal Well

Fraccing is more likely to be used in coal seams with low permeability, coal seams of lower ranks, or coal beds which are large, thick and continuous and more often in vertical wells. Fraccing techniques are infrequently used in NSW because in the majority of cases, the geology allows gas to be extracted productively without fracturing (NSW CSG 2013).

3.7 Groundwater Response to CSG Activity

Groundwater responds to any activity that interferes with the subsurface. Remote sensing activities such as exploration geophysics (e.g. seismic survey) do not interfere with the subsurface. Drilling, fraccing and pumping water are examples of aquifer interference activities.

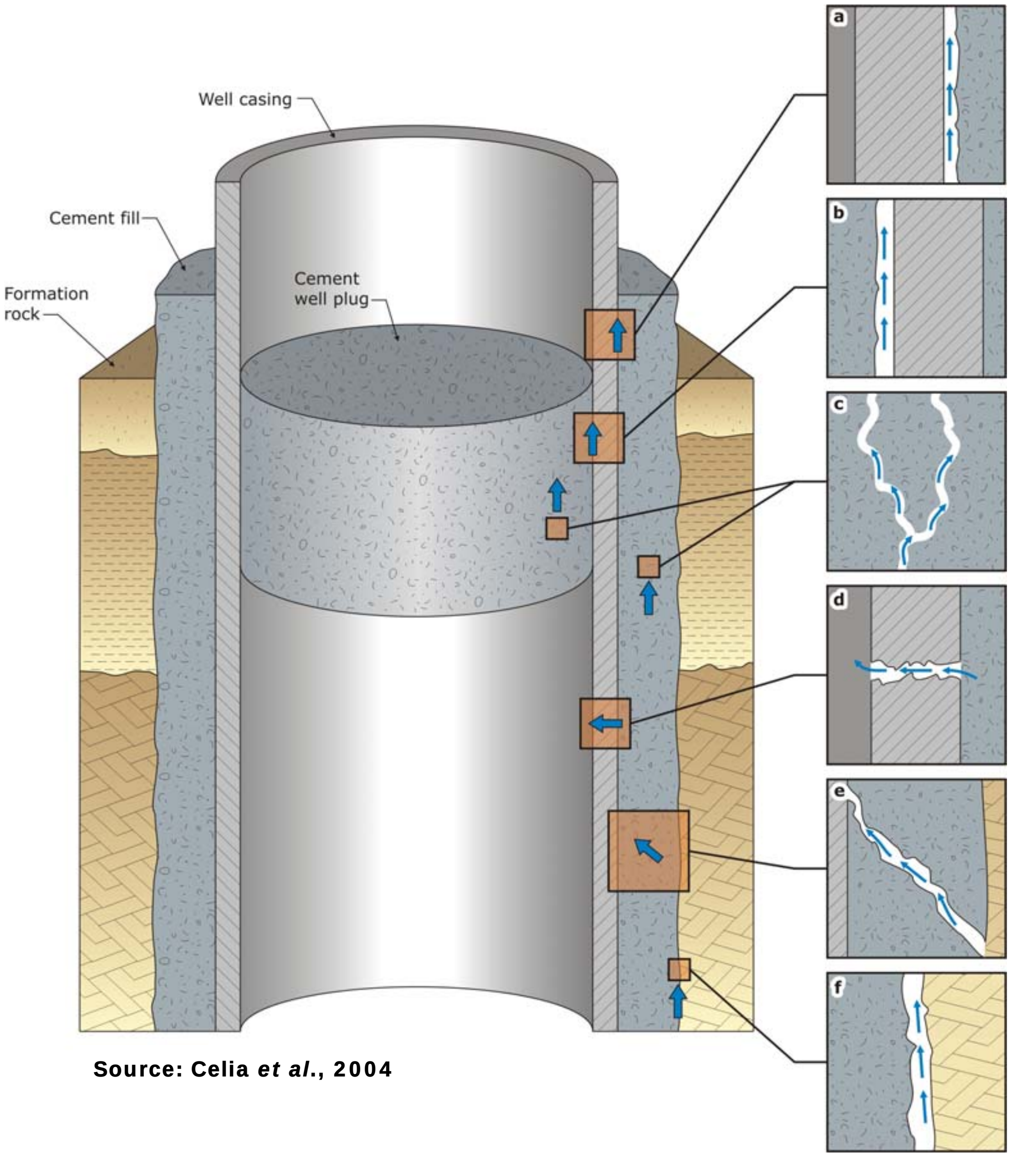
Drilling and fraccing of wells and pumping of groundwater are activities that currently take place during CSG exploration. Drilling and fraccing of wells and pumping of groundwater also take place during CSG assessment and production. This is discussed further in Section 7.

3.7.1 Response to Drilling and Well Completion (Exploration)

A groundwater response to drilling can occur if drilling fluids move from the drill hole into the formation during drilling (this is normal for any water well) or if the well casing or cement fill (concrete or other) allows water to move between or along the formation and the well.

A well casing may allow water movement to occur if:

- The cement shrinks with time – water may flow along the contact edge between the well and formation or around the well-plug, and hence to different aquifers (Figure 14a,b,f);
- The cement fill is permeable –water may flow very slowly (Figure 14c);
- The well casing fractures or corrodes –water can be exchanged between the formation and the well-bore (Figure 14d); or
- The cement cracks with time – water may leak to or from the well (Figure 14e).



Source: Celia *et al.*, 2004

Figure 14: Potential Leakage Pathways for a Decommissioned Well

The amount of water leaking into, out of, or along a defective well is proportional to the extent of well damage and the pressure differences between the formations intersected by the well. In old agricultural wells with failed casings WRL engineers have heard water cascading through the well from one beneficial aquifer to another. To reduce the likelihood of such outcomes new regulations will require CSG operators to commit to adhering to codes of practice for well decommissioning (see Section 7).

3.7.2 Response to Fraccing (Exploration, Assessment and Production)

The groundwater response to fraccing activity is summarised in Section 3.6 above. Groundwater does not respond directly to fraccing. Fraccing increases the hydraulic conductivity of the coal seam allowing a greater response to pumping (Section 3.7.3).

3.7.3 Response to Pumping (Exploration, Assessment and Production)

With the exception of the risk surrounding well failure or any surface excavation works, the groundwater response of CSG activities is technically limited to groundwater pumping. At the present time pumping occurs during CSG exploration, assessment and production. Groundwater pumping that occurs during CSG exploration and assessment is called pilot testing.

Groundwater systems respond to pumping as follows:

1. There is a decrease (drop) in water pressure in the coal seam at the pumping well;
2. The pressure drop propagates away from the pumping well in all directions creating a pressure gradient towards the well;
3. Groundwater flows towards the pumping well in response to the pressure gradient;
4. As pumping continues groundwater levels or pressure heads continue to fall and the pressure drop continues to propagate outwards to new sources of water until such time as an equilibrium is achieved; and
5. Pumping is stopped and groundwater levels and pressures begin to recover.

The following “rules” govern the groundwater response:

- The pressure drop at the well is proportional to the volume rate of water removed;
- The speed of the pressure “wave” is proportional to magnitude of the pressure drop at the well, and the hydraulic diffusivity of the coal seam and the surrounding geological formations. (The hydraulic diffusivity is equal to hydraulic conductivity divided by the specific storage of the formation and has no relation to molecular diffusion);
- The rate of groundwater flow is proportional to the hydraulic conductivity of the formation, which may have been modified by fraccing, and the pressure gradient (Darcy’s Law); and
- The amount of water removed from every cubic metre of aquifer or aquitard for every one metre decline in the groundwater head is given by the storativity coefficient of the formations. The storativity coefficient is a function of the formation porosity and compressibility, and to a lesser extent the compressibility of water.

3.7.4 Factors Influencing the Groundwater Response

When considering the magnitude of the groundwater response the following aspects of geology, hydrogeology and hydrology must be considered:

- **Water Saturation in the Coal Seam:** Coal seams containing large volumes of water will require significantly more pumping to lower the pressure in the coal seam to release methane. If the coal seam contains little water the volumes of water produced to create an equivalent pressure drop will be smaller. Coal seams in some geological basins may have low permeability and contain very little water.
- **Hydraulic Conductivity and Storativity:** These geological and fluid properties control the groundwater flow, level and pressure response to groundwater pumping. The values of these parameters can vary significantly across a site and from one site to another. Making confident assessments of these parameters requires detailed characterisation with a range of different methods and techniques.

  The potential variability of the hydraulic conductivity and storativity parameters can be better understood by considering the physical properties that define these hydrogeological parameters. Structural properties include fracture aperture, roughness and connectivity, and fault locations, dip and strike. Formation properties include compressibility, porosity, grain size, grain size distribution, sorting, packing, and pore interconnectivity. Fluid properties include compressibility, density and viscosity. The interplay between all these physical parameters is complex.

  There is no one measurement method that can adequately define the hydraulic conductivity and storage parameters of a hydrogeological system. The best answers are achieved using a combination of techniques.
- **Aquitard Thickness and Continuity:** There will be more groundwater flow from beneficial aquifers into coal seams when aquitards separating aquifers and coal seams are thin, fractured, permeable, or non-existent. There will be less flow when the aquitards are thick, continuous, consolidated and have ultra-low conductivity.
- **Proximity to Surface Water Bodies:** Large water bodies and rivers effectively limit the extent of pressure propagation from a pumping groundwater well. This is because the water body supplies water to the pumping well. It may take many days, months or years for a pressure response to reach a distant water body and many decades for groundwater to flow from the water body to the pumping well, in response to the pressure gradient and the above factors.
- **Water Saturation in Aquifers and Aquitards:** The hydraulic conductivity of soils is widely recognised as being a function of pore-water saturation (van Genuchten, 1980). As a soil becomes unsaturated the flow rate through the material will decrease. This concept, and the need for more research concerning the unsaturated hydraulic conductivity of jointed rock mass, is discussed further in Pells and Pells (2012a; 2012b).

3.8 Further Reading

Life Cycle of Coal Seam Gas Projects: Technologies and Potential Impacts (Cook, 2013)
http://www.chiefscientist.nsw.gov.au/__data/assets/pdf_file/0010/31321/Life-Cycle-of-Coal-Seam-Gas-Report_FINAL_PJC.pdf

NSW Background Paper on Horizontal Drilling (Carter, 2013)
http://www.chiefscientist.nsw.gov.au/__data/assets/pdf_file/0014/35330/Horizontal-Drilling_John-Carter.pdf

NSW Government Exploration and Production Fact Sheet (DTIRIS, 2013a)
(http://www.csg.nsw.gov.au/the-facts/exploration-and-production)

NSW Draft Code of Practice for CSG Explorations (DTIRIS, 2012c)
(http://engage.haveyoursay.nsw.gov.au/document/show/194)

NSW Code of Practice for Coal Seam Gas Well Integrity (DTIRIS, 2012b)
(http://www.csg.nsw.gov.au/protections/codes-of-practice-well-integrity-standards)

NSW Code of Practice for Coal Seam Gas Fracture Stimulation Activities (DTIRIS, 2012a)
https://www.nsw.gov.au/sites/default/files/uploads/common/CSG-fracturestimulation_SD_v01.pdf

From Mud to Cement—Building Gas Wells – Schlumberger
http://www.slb.com/~/media/Files/resources/oilfield_review/ors03/aut03/p62_76.ashx

Minimum Construction Requirements for Water Bores in Australia, 3rd Edition (NWC, 2012b)
http://www.nrm.qld.gov.au/water/management/pdf/minimum-const-req.pdf

UK Onshore Shale Gas Well Guidelines (UKOOG, 2013)
http://www.ukoog.org.uk/elements/pdfs/ShaleGasWellGuidelines.pdf

Shale gas extraction in the UK: a review of hydraulic fracturing (UKOOG, 2013)
http://royalsociety.org/uploadedFiles/Royal_Society_Content/policy/projects/shale-gas/2012-06-28-Shale-gas.pdf

4. Consequences and Risks

With any activity, there are potential adverse consequences. This section raises the potential adverse consequences for groundwater associated with CSG extraction and discusses the relative risk of occurrences that would lead to these consequences being realised.

4.1 Identified Consequences

The consequences to groundwater systems associated with CSG extraction (raised to date) are all associated with water resources and environment. The potential effects on water resources can be grouped into contamination of water resource aquifers or depletion of water resource aquifers and surface waters.

WRL have categorised potential consequences associated with water resources in Table 2. For clarity, this table presents the consequences without the occurrences that may lead to these consequences. The possible occurrences are discussed in Section 4.2.

Table 2: Potential Adverse Consequences to Water Resource Aquifers Associated with CSG Extraction

Group	Potential Adverse Consequence
Depletion	After depressurisation of the CSG Aquifer, water from adjacent Water Resource Aquifers are depleted due to flows to the CSG Aquifer. Groundwater dependent ecosystems could be effected.
Depletion	Surface Water Resources are depleted by either directly recharging the CSG aquifer or flowing into a depleted surface groundwater aquifer.
Contamination	Chemicals used during drilling or fraccing escape into Water Resource Aquifers.
Contamination	Poor quality CSG Aquifer water leaks or discharged to a Water Resource Aquifer.
Contamination	Methane Gas (and/or other constituents) released from the depressurised coal seam matrix, leak into a Water Resource Aquifer or surface waters.
Contamination	Produce water from the CSG Aquifer is released into a Water Resource Aquifer.
Contamination	Operational spills or leaks at the surface leak into a Water Resource Aquifer or surface waters.

4.2 Occurrences Leading to Depletion

This section describes occurrences that may lead to aquifer depletion and associated consequences. The discussion relies on an understanding of the groundwater processes described in Section 2 of this report.

After depressurising the CSG aquifer, pressure potentials may drive flow towards the CSG aquifer. The rate of flow is determined by the three dimensional geometry of the strata, the hydraulic conductivity of the various materials and any preferential flow paths (such as joints, fractures or faults). An aquitard may not be spatially consistent due to geological discontinuities, or thinner aquitard strata between some aquifers in the system.

The maximum total volume of flow into the CSG aquifer (possibly over a very long period of time) will not be greater than the volume of water extracted from the CSG aquifer. In other words, the volume of water that may flow into a CSG aquifer will be the same or less than the volume of water that was extracted. Managed Aquifer recharge (MAR) is a technique to minimise the volume of beneficial groundwater flowing into a CSG aquifer following CSG production.

Under ideal conditions minimal depletion will occur vertically if the aquitards above and below the CSG aquifer are continuous and have ultra-low hydraulic conductivity and are not faulted, fractured or jointed. **However, *there is always potential for some depletion by water flowing through the aquitard*** if the vertical pressure difference is large enough and the hydraulic conductivity of the aquitard allows a slow rate of leakage.

If depletion occurs, ***the rate of depletion will be proportional to the rate and volumes of water removed from the coal seam***, regardless of whether the activity involves pilot testing or production.

Preferential flow paths may allow water to move more rapidly than through the aquitard matrix. In this case, the water resource aquifer above may be subject to storage depletion. The rate of depletion will be relative to the nature of the preferential flow paths and the pressure difference between the aquifers. Preferential flow paths may also increase after depressurisation of the CSG aquifer due to differential subsidence. This geological process is a potential risk but has been outside the scope of works of this review See Pineda and Sheng (2013) for further information.

Wells should be considered as potential leakage points through aquitards. Codes of practise (DTIRIS, 2012; 2012a; 2012b and 2012c) have been established to reduce the possibility of this occurring. However, "leaky" wells are not unheard of and uncertainty exists over the viability of both newly installed and decommissioned wells. This may be due to factors such as concrete corrosion or fractures caused by in situ stresses.

Fraccing (as described in Section 3) is the process of opening up the cleats and flow paths within the CSG aquifer. ***There is a potential for the fraccing process to compromise aquitard integrity*** of the aquitard and hence increase the rate of depletion of water resource aquifers above (Davies *et al.*, 2012). While this risk exists, fraccing is an established process, and can be designed and controlled in a manner that minimises the risks of unexpected fractures. Any increase in inflow to the CSG aquifer is detrimental to the extraction process as it will increase the required rate of extraction. Hence, it is greatly in the interests of the CSG operators not to cause large inflows of water to the CSG aquifer. Monitoring of the fraccing operation, for example, using micro-seismic techniques, can assist in determining its effectiveness and the length and spacing of new fractures.

Lateral recharge within the CSG aquifer may deplete other water resources. This water may come from great distances away and recharge may occur at very slow rates potentially over centuries. The volume of water to recharge the CSG aquifer may also be a depletion of a water resource aquifer or surface waters.

All water resource aquifers have variability in the pressure and storage resulting from variations in recharge (rainfall), extractions and natural flows. Depletion of these aquifers from flows into depressurised CSG aquifers will be a net loss of water, but the rates of depletion may not be discernible if they are relatively small.

Methods for determining and assessing the relative risks of these occurrences and quantifying the scale of the processes are discussed in Section 5.

4.3 Operational Occurrences Leading to Contamination

Contamination issues have been separated into those associated with operations (i.e. extraction) and those associated with changes in groundwater processes. Operational risks are largely influenced by the diligence, professionalism and resources applied to the operation. Industry codes exist (Refer to Section 7) to promote best practice in CSG Operations.

Chemicals used during drilling may escape into Water Resource Aquifers. These chemicals can include drilling water from a different source and muds comprising of bentonite stabilisers. However, drilling a CSG well has no increased risk in contaminating a Water Resource Aquifer than drilling any other type of bore. Methods for drilling bores have been well established over many years and are discussed in ASTM D6286 and DTIRIS (2012b).

Chemicals used in fraccing are released intentionally into the CSG aquifer and unless there is distinct flow out of the capture zone of the CSG well, there is negligible risk of contamination to neighbouring water resource aquifers. Fraccing chemicals are expected to be largely recovered from the CSG aquifer because the pressure gradient is towards the CSG well. The potential for flow out of the CSG aquifer transporting fraccing (and other) chemicals is discussed in Section 4.4 as it depends on a leakage pathways, pressure gradients and diffusion.

Produced waters from CSG operations may be of high salinity (brackish) and of poor quality. If released directly into a upper alluvial aquifers there is a high potential for it to contaminate the aquifer. If it is treated by processes such as desalination, the resultant water can be of lower salinity than the Water Resource Aquifer which may be suitable for surface water discharge, but not aquifer injection. Following desalination, in some cases produced waters need post treatment, whereby the ions are replaced into the cleaned waters. This is done to avoid low ionic strength and high corrosion potential that can cause reactions with minerals and clays in the aquifer matrix (Dillon *et al.*, 2009). In practice, post-treatment of desalinated water involves conditioning and stabilisation to increase the alkalinity and the pH of the product water. It is important that any releases to the surface aquifer be carefully planned for both volumes and water quality.

Operational spills or leaks offer a risk of contamination to a Water Resource Aquifer. As these are entirely operationally based, risks are minimised through adequate training, mentoring, supervision, minimum codes of competency for personnel, risk assessment procedures, safe work procedures and emergency response plans.

Operations must consider the economic costs to monitor and maintain decommissioned boreholes and coal seam gas wells indefinitely. Without such monitoring and maintenance any of the adverse consequences may be realised.

4.4 Groundwater Processes Occurring Leading to Contamination

Once a CSG aquifer has been depressurised, there is little risk that any poor quality water from the CSG aquifer will mix with neighbouring Water Resource Aquifers. This is because the pressure gradients will result in flow into the CSG aquifer and not out of it.

After operations are complete, the CSG aquifer may be artificially repressurised by pumping water into the aquifer or it may repressurise naturally over an extended period of time. Once repressurised, the pressure gradients may allow for flow out of the CSG and into neighbouring water resource aquifers. In this instance, any fraccing chemicals remaining in the CSG aquifer may also be transported. The potential flow rates would be greater than pre-CSG extraction only if the aquitard integrity had been compromised or decommissioned wells were not adequately sealed.

The purpose of reducing the pressure in the CSG aquifer (by extracting some water) is to release methane gas from the coal matrix (as discussed in Section 3). The methane is expected to follow the pressure gradient (also created by pumping) towards the extraction well. However the risk exists that some methane may flow through preferential paths into overlying water resources aquifers or to the ground surface. Methane as a gas will be able to flow through a geological matrix faster than water. The fact that low permeability geological strata is more permeable to gases than to water is attributed in part to “slip-flow” (two phased flow) of gases (Ziarani and Aguilera, 2012).

4.5 Case Studies

There have been few realised groundwater consequences in Australia resulting from CSG extraction. The reader should be aware that the following are not expected to be the only case studies where there have been groundwater consequences. These are provided as examples of actual risks and consequences. For a synopsis of additional cases see Gore (2013).

4.5.1 Bubbling of the Condamine River

This case study provides potential evidence of the contamination risk of methane gas (and/or other constituents) being released from a depressurised coal seam matrix and mixing into a Water Resource Aquifer and surface waters.

It was reported on the 30th May 2012 that there is video evidence of coal seam gas leaking into a major southern Queensland River, the Condamine (Rego, 2012). The video clearly shows gas bubbling to the surface of the river. Having learnt about this on the 17th May 2012, the QLD Department of Natural Resources and Mines launched an investigation, although preliminary findings indicated that the bubbling was unlikely to be caused by coal seam gas (CSG) activities in the region (DNRM, 2012). The following paragraph is a summary from DNRM (2012).

As well as onsite testing, desktop reviews were undertaken for an extensive area around the gas seeps, focusing on coal seam gas activities and tenure, groundwater and geology. Anecdotal accounts supported the regional incidence of gas migrating to the surface, although the activity of May 2012 would appear to be more vigorous than had been previously observed. "*Gas was sampled for compositional and isotopic analysis at selected key river gas seeps and local groundwater bores, in order to enhance understanding of the seep gas and to explore potential sources*" DNRM (2012). Results indicated the gas is predominantly composed of biogenic methane, likely formed through a CO_2 reduction pathway of organic matter, consistent with gas originating from the Surat Basin geological formations. However, these results do not provide definitive evidence of the source or cause of the Condamine River gas seeps. Evidence may become apparent through ongoing monitoring.

4.5.2 Leakage between the Walloon Coal Measures and the Springbok Aquifer

The NSW Parliamentary Inquiry (NSWLC, 2012) into Coal Seam Gas reported on damage to the Walloon Coal measures (QLD) through fraccing to extract CSG:

"It is acknowledged that in one case in Australia, fraccing resulted in damage to the Walloon Coal measures, causing leakage between that and the Springbok aquifer. While apparently the damage was eventually made good by sealing the damaged area, submissions to the Committee raised a number of concerns:

- *that there seemed too little accountability. It is claimed that the company involved did not advise the Government for 13 months and the Commonwealth Water Minister may never have been advised;*
- *that the potential for damage to occur was known prior to the fraccing and that this was treated as an acceptable risk;*
- *that part of the boundary between the aquifer and the coal seam was intentionally fracced; and*
- *that it took 21 months to seal the interconnection."* (p.36)

No technical information could be found about this incident, first reported in 2009.

4.5.3 Contamination in the Pilliga State Forest

Contamination of 3.5 hectares of the Pilliga Forest was a reported case involving a contamination event (ABC, 2013). This event is important as community concerns regarding the environmental pollution were dismissed by the authorities (NSWLC, 2012). It has been revealed that a previously dismissed concern, namely the pollution of the Pilliga Forest by Eastern Star Gas, was ultimately proven correct (NSWLC, 2012).

Within the NSW Parliamentary Inquiry; "*witnesses accused Eastern Star Gas (now taken over by Santos) of breaching environmental regulations in its operations in the Pilliga State Forest. Numerous examples were provided in the oral evidence and written submission from local landholder Mr Pickard, who referred to incidences such as unlined and overflowing drill ponds (which could lead to chemicals contaminating the soil and water), spills of produced water (which could contaminate surface and groundwater), inappropriate disposal of solid waste from drill sites, and direct venting of gas into the atmosphere*" (p. 209).

Sampling of CSG released water from Bohena Creek in the Pilliga Forest, NSW, detected methane at the Eastern Star Gas discharge site at 68 micrograms per litre (ug/l), whereas it was not detected in the upstream control sample (NTN, 2013).

The NSW Environmental Protection Authority has since issued Eastern Star Gas with two penalties and fines of $3,000 for discharging polluted water to Bohena Creek in the Pilliga Forest, in North West NSW (OEH, 2012). Santos, a shareholder in Eastern Star Gas, took over the site in November 2011. The ABC (2013) reported that Santos have spent $17 million on clean-up costs. NSW government is now prosecuting Santos and has proposed amendments to legislation to allow prosecution of directors in future cases (SMH, 2013). The Maules Creek Community Council (MCCC, 2013) reported that Santos pleaded "guilty to charges of spilling of large quantities of waste water in the Pilliga, operating a faulty water treatment plant and failing to report the incidents" in September 2013 with hearings to resume on 18 and 19 December 2013.

No detailed technical information could be found about this contamination event.

4.5.4 International Examples

Internationally there have been many reports of contaminated groundwater in regions where drilling and fraccing is being performed to enhance shale gas production. However shale gas is generally much deeper than CSG, further separated from water resource aquifers and subject to more intensive hydraulic fracturing operations.

In the San Juan Basin in New Mexico and Colorado (USA) contaminants in the water resource aquifer and methane gas bubbling to the surface have been discussed (Beckstrom and Boyer, 1993). However, testing for both these risks could not prove, or disprove, the observations were due to CSG activity.

Within the vicinity of Pavillion, Wyoming (USA) it has been confirmed by the USEPA an enhanced migration of gas has occurred within groundwater at depths used for domestic water supply and to domestic wells (DiGiulio *et al.*, 2011). Alternative explanations for groundwater impacts have been explored, however the data indicates likely impact to groundwater can be explained by hydraulic fracturing. Groat and Grimshaw (2012) suggest there is little or no evidence of groundwater contamination from hydraulic fracturing of shales at normal depths, with "no evidence of chemicals from hydraulic fracturing fluid … found in aquifers as a result of fracturing operations" (p.18). However in some cases, such as the Pavilion area, Wyoming, fracturing has been performed at depths shallower than normal for shale gas wells (Groat and Grimshaw, 2012).

A recent study by Osborn *et al.* (2011) examined methane concentrations in 60 private wells of various depths in aquifers overlaying the Marcellus and Utica shale formations in North West Pennsylvania. The results detected methane concentrations in 85% of the wells tested, regardless of gas industry operations, however concentrations in the wells near the mining operations were significantly higher. The study also tried to find evidence to clarify the source of the methane gas. This was done by comparing the methane from wells near the active drilling sites and neighbouring non active sites by looking at the ratio of methane to higher-chain hydrocarbons. The data showed increasing ratios closer to the mining operations (Figure 15). There was no description of the mechanisms which may have led to the heightened values, that is, if the gas detection was a result due to well failure or due to hydraulic fracturing.

With respect to groundwater level impacts in the Powder River Basin in Wyoming, Myers (2009) reported instances of groundwater level drawdown of up to 6 m at distances of up to 29 km from coal bed methane pumping wells. Frost *et al.* (2002) reported that a 3 – 6 m decline in groundwater level in sandstone aquifers above the coal measures were observed after five years of production. Numerical models of these operations predict a 45 year period for recovery of river base flows from the most significant impacts with full recovery in approximately 200 years (Myers, 2009).

Source: Osborn *et al.*, 2011

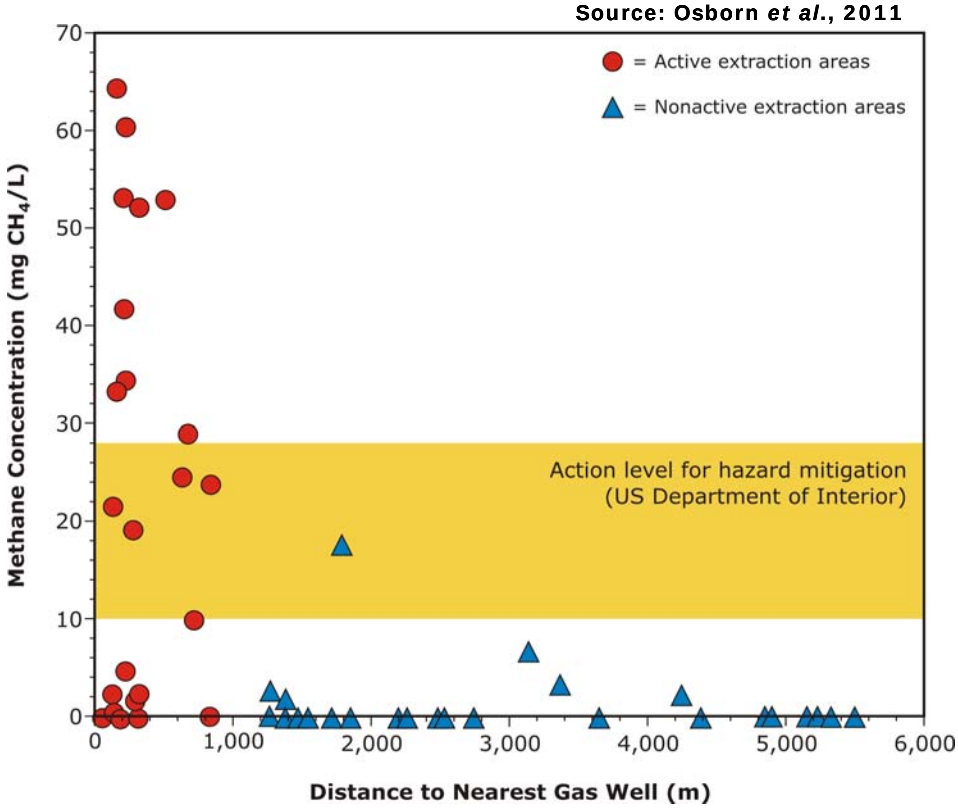


Figure 15: Methane Concentrations near Shale Gas Wells

4.6 Worst Case Scenario

Groundwater naturally migrates across aquitards from one aquifer to another. This flow may occur through the pores of the aquitard material (slow) or through preferential flow pathways such as a fracture (fast). In both cases the rate of groundwater flow is proportional to the natural pressure gradient. When pumping influences the system the pressure gradient and rate of groundwater flow increases.

As described in Section 3.7 the rate of groundwater flow across aquitards depends on the pumping rate, the hydraulic conductivity and storativity of the aquifers and aquitards, and the proximity to nearby sources of surface and subsurface water. The rate of groundwater flow across aquitards (depletion) is independent of whether the pumping occurs during exploration or assessment (pilot testing) or actual production.

A worst case scenario for groundwater resources involving CSG pumping of a volume of groundwater for pilot testing or production would involve all of the following:

- Loss of the same volume of beneficial groundwater from an overlying aquifer as a result of:
    - Enhanced flow along preferential geological pathways (if these exist);
    - Enhanced leakage of water through the pores of aquitards;

- Leakage along or through the CSG well casing, if:
  - The well did not achieve a perfect seal with the aquifers during completion;
  - The well casing materials (i.e. concrete) shrink with time; and
  - The well construction materials break or become permeable with time.

- Changes in groundwater chemistry and beneficial use category due to enhanced mixing of groundwater and gas from different aquifers and aquitards, e.g. salty water from deep aquifers and aquitards mixes with fresh groundwater from shallow aquifers;
- Deterioration of the groundwater quality in the beneficial aquifer to a point at which the quality no longer meets the needs of the groundwater users and/or the beneficial use category for that groundwater as established by government; and
- Subsequent depletion of the groundwater in the beneficial aquifer to a level or pressure which prevents other groundwater users, including the environment, from accessing their groundwater entitlement for its intended purpose. That is to say, all local groundwater flows towards the CSG aquifer and there is no groundwater left for the environment or other licenced users.

These worst case scenarios do not include operational matters such as accidental discharges to surficial aquifers as this is outside the scope of this report.

At the time of writing, the likelihood or risk of a worst case scenario was, to our knowledge, not quantified or addressed in the literature as it has not been observed. WRL recommends that all of the methods discussed in Section 5 are used to address the environmental conditions that may realise these worst case scenarios.

The current view of Geoscience Australia in regard to the potential water quality impact on sandstone aquifers in the Surat Basin as a result of groundwater extraction, is that “there is a low likelihood of cross-contamination, as the majority of inter aquifer transfer will involve the migration of higher quality water from adjacent underlying and overlying sandstone aquifers into the coal measures containing lower water quality” (NSWLC, 2012).

In Queensland CSG producers are required by law to ‘make good’ any impact (Nicola, 2012). That is, if they impact groundwater to the point where it interferes with another person’s licenced use of that groundwater that person must be compensated by the CSG producer. The main issue of concern is that it may take decades for these impacts to be realised. Groundwater management in NSW is discussed further in Section 7. Effective groundwater management requires a quantification of likelihood and risk which requires quality environmental data and best practice data management and modelling (Section 5).

5. Quantifying Risks and Processes

5.1 Overview

This section addresses methodologies and practises for quantifying risks and processes. The emphasis of this section is understanding the uncertainties involved with groundwater processes and the background to methodologies associated with quantifying these uncertainties in relation to CSG extraction.

Section 4 presents that CSG extraction may cause depletion of water resource aquifers by groundwater flowing into the CSG aquifer. Water extracted from the CSG creates the pressure gradients for flow to potentially occur. This potential flow is retarded or inhibited by aquitards of uncertain (and possibly altered) integrity.

In order to quantify processes that may lead to depletion and contamination of the water resource aquifers, it is imperative to determine the inherently uncertain geological and hydrogeological conditions within and around a CSG lease. Uncertainty can only be reduced with quality data and information as discussed throughout this section.

Best practise for quantifying risks and processes cannot be prescribed as any particular combination of methods (as different characteristics of the Groundwater and CSG systems at different sites would require different treatments). As such, “best practice” should be considered as the data collection and data analysis process that adequately reduces uncertainty and/or knowledge gaps. Targeted data collection programs and comprehensive data analysis will decrease these knowledge gaps.

We have been deliberately cautious of defining “typical” data collection programs or instrumentation. It is our experience that the data collection must be designed for specific conditions as discussed in Section 5.2.

5.2 Identification of Hydrogeological Features

The CSG resources of NSW are reasonably well mapped and are discussed in the following section. Regional geology is also reasonably well understood as to where water resource aquifers are located relative to the CSG aquifers.

Region wide hydrogeological assessments may provide guidance on aquifer and aquitard thicknesses and permeability, however local and specific hydrogeological features can only be identified through site specific fieldwork.

Geophysical methods of identifying the subsurface strata have inherent limitations and uncertainties (Section 3.5.1). Surface geophysical methods are best used in conjunction with a drilling program which usually combines core logging of strata, down-hole geophysical logging, pump tests and installation of monitoring equipment such as pressure transducers and water quality samplers. Isotope analysis provides indications of water age, water sources and mixing.

Key hydrogeological features to be identified include permeability and 3D architecture of aquitards, fracturing, pressure gradients and potential recharge pathways. Exploratory boreholes must consider the three dimensional nature of these features. Referring to government databases of existing water extraction bores may provide little information since data quality is variable and many of these boreholes only intersect the upper level strata.

Drilling many exploratory boreholes cannot totally remove uncertainty regarding aquitard permeability or connectivity. For example, 5 bores of 50 mm diameter over 1 hectare represent 0.0000196% of the total area. The thickness of the coal seam and aquitards may have considerable variation. Geophysical methods are essential for reducing uncertainty.

Cored borehole samples may be tested for permeability (hydraulic conductivity) using a range of techniques. Modern methods for determining the point-scale permeability of ultra-low permeability strata include geocentrifuge testing (Timms *et al.*, 2012). Such testing is often the only successful testing method to obtain vertical hydraulic conductivities of ultra-low strata, and has been demonstrated to provide a minimum value of permeability to better constrain numerical models (Bouzalakos *et al.*, 2013).

However uncertainties still exist associated with estimating hydraulic conductivities of different media at larger scales. A combination of laboratory and field scale testing can provide the most realistic range of values. The hydraulic conductivity of glacial and fluvial sediments from two locations in Wisconsin, USA varied by as much as two orders of magnitude depending on the sample volume and measurement method (Bradbury and Muldoon, 1990). It has also been indicated that hydraulic conductivity determinations of aquitards in the Surat basin of Queensland can vary by as much as six orders of magnitude (Evans, 2012).

Effectively, there is no absolute way of identifying all hydrogeological features and some uncertainty will always exist. As a result, further information about the hydrogeology must always be inferred from analysis of groundwater monitoring data collected prior to, during and after pilot testing. This data must then be analysed as a water balance potentially (as best practice) utilising numerical models of groundwater flow.

5.3 Monitoring

The peizometric head, storage and water quality in a Water Resource Aquifer fluctuate due to pumping rates, recharge rate (rainfall), evapotranspiration and lateral flows. It is imperative that the existing conditions are well understood by a statistically rigorous baseline monitoring program before any CSG extraction takes place, in order to be able to assess potentially changed conditions resulting from CSG extraction.

Baseline monitoring must be undertaken for a long enough period to establish seasonal and preferably inter-annual variability. This is generally considered to be more than two years for current best practice (NOW, 2012), but may need to be longer depending on the site and conditions (i.e. drought and flood regime). Significant multi-decadal cycles in groundwater level are recognised in many NSW inland alluvial systems as a result of drought and flood regimes. Baseline monitoring should include automated in situ monitoring of water levels so that regular (daily or sub-daily) fluctuations can be considered. Baseline monitoring should be undertaken before exploration drilling and pilot testing commences.

The number of bores and duration of baseline monitoring should be determined by analysing the statistical certainty required. A baseline monitoring program should be designed to understand and quantify the hydrogeological processes taking place and not to simply measure any potential later response in a presently utilised water resource aquifer.

While existing production bores can be used to monitor water levels (Alberta Government, 2013), best practise would also include specific monitoring bores selected in strategic locations to identify groundwater flow directions. When multilayered aquifers exist, this may include bores screened into multiple aquifers, especially those closer to the CSG aquifer.

Baseline monitoring of water quality and hydro-chemical analysis can be used to identify the existing variability within an aquifer. This can be done by assessing the unique chemical characteristics of different aquifers, which may be used as tracers to provide semi quantitative estimates of the degree of mixing. Tracers can include chlorides, carbonates, pH as well as stable isotopes of water and carbon. Chloride (Cl) is ubiquitous in groundwater and often is the most dominant dissolved conservative anion. Chloride seldom substitutes as a trace element in other minerals, it is highly mobile and is not involved in common geochemical reaction in aquifers. This property makes it a very good tracer for mass balance estimates as it does not participate in reactions induced by the mixing between two water masses. Other assessments can include looking at radioactive isotopes. Isotopes can include Carbon (12-14), Chloride (16), Hydrogen (1-3) and Oxygen (16-18) and can be used to determine water age and the exchange between aquifers.

It is important to realise that the pressure (and peizometric head) will change substantially faster than water is transported, so using water quality to identify post CSG aquifer leakage may only be realised after excessively long periods of time. Conversely, if water pressure declines are gradual and masked by geologic uncertainty, seasonal variability, consumption by other water users or a lack of appropriate baseline monitoring data, isotopic analysis methods (i.e. oxygen, deuterium, strontium) may provide the earliest possible warning.

Where multiple operations are occurring near one another, it is important to identify this in the baseline monitoring and quantify the target aquifers, water taking schedules and pumping rates for each operation.

Ideally, relationships between baseline data, environmental conditions and any other extractions should be able to be described to provide an indication of the cumulative impacts of activities.

Figure 16 is a schematic presenting monitoring bores located in various aquifers and aquitards above and below the CSG bearing aquifer for the purpose of measuring and monitoring vertical hydraulic gradients throughout a hydrogeological system. Measuring and monitoring changes to horizontal hydraulic gradients and groundwater flow directions requires a triangular arrangement of monitoring wells at key locations within each aquifer. Without these monitoring arrangements the hydrogeological properties and impacts of an activity cannot be adequately assessed.

The same monitoring program undertaken as baseline sampling should extend throughout and beyond the period of operation. This will provide information on the responses in pressure (and inferred flow) in other aquifers resulting from the depressurisation of the CSG aquifer. Further aquifer testing may include specific pump or pressure pulse testing to infer the hydraulic properties of the CSG aquifer and any connectivity with surrounding aquifers (QGC, 2012).

Geochemical analysis of samples can be used to undertake environmental audits and can be used as primary evidence to assess the potential changes to water quality and beneficial use. As discussed in Section 6, it is important to realise that while the pressure response of the subsurface strata can be near instantaneous (if the hydraulic diffusivity is high enough), the migration of the elements may happen over much longer periods of time as related to the connectivity (after which point the impacts may be irreversible). As such chemical and isotopic tracers to identify contamination of aquifers may not be realised in the relatively short span during which monitoring takes place.

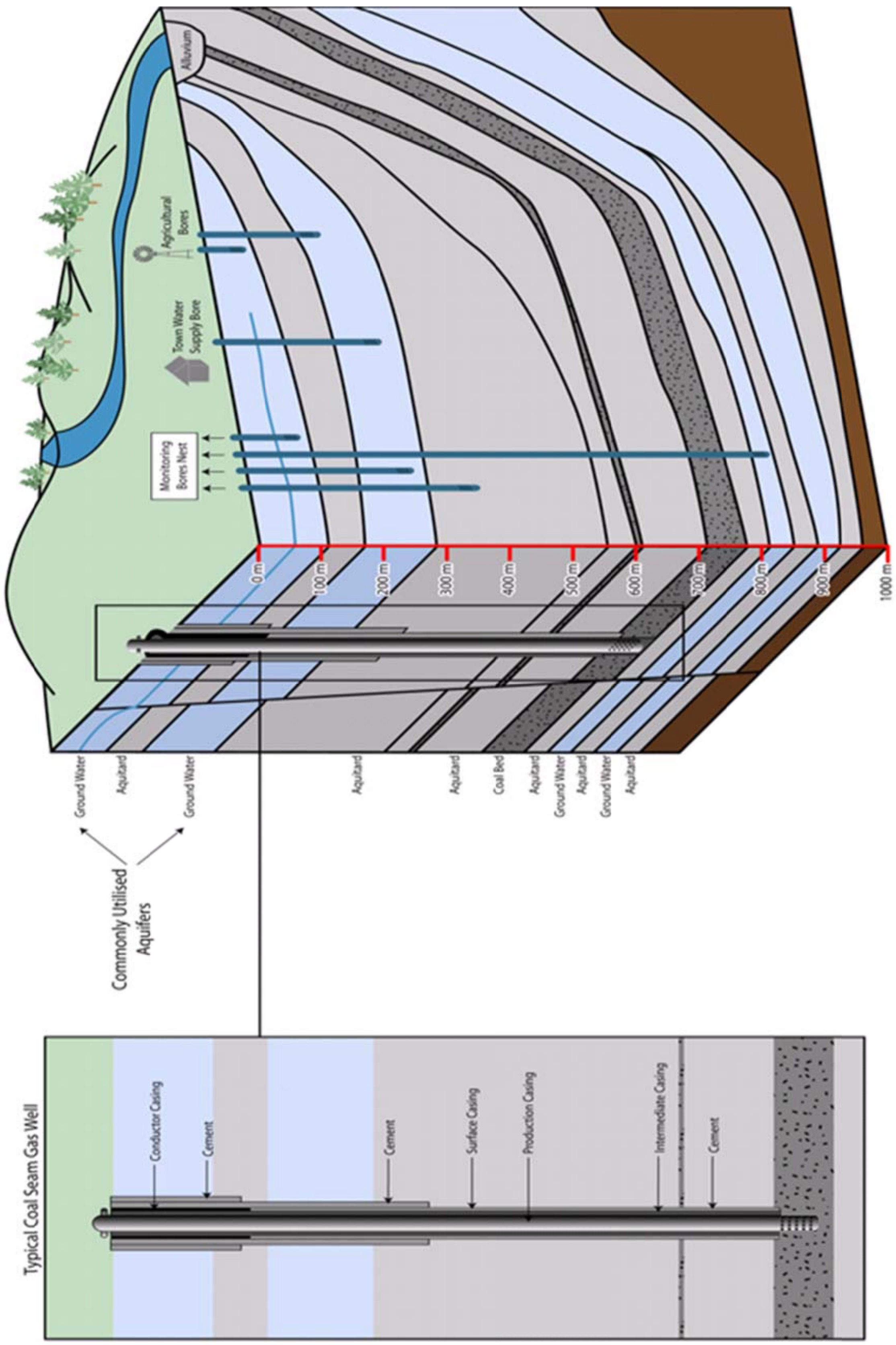


Figure 16: Schematic of Monitoring and Extraction Bores

The risk of methane gas travelling through aquitards and into above water resource aquifers is very difficult to quantify. Gas will flow more easily than the water through an aquifer and is also a compressible fluid. As such, it is recommended that all monitoring bores also be sampled for methane release in a statistically rigorous manner.

5.4 Hydraulic Connectivity

Hydraulic connectivity refers to the relative ease with which groundwater is exchanged between aquifers (across aquitards) and between groundwater and surface water systems, such as lakes, rivers, creeks, streams and wetlands (see Section 2). Hydraulic connectivity is the primary determinant of the depletion risks present in Table 2 (see Section 4.1).

Hydraulic connectivity is not a physical quantity. As described in Sections 3.7 and 4.5.4, hydraulic connectivity is controlled by many factors. These include:

- **Hydrogeological Properties**: Aquifer / aquitard transmissivity and storativity;
- **Condition of Wells:** Condition of wells drilled through aquifers and aquitards;
- **Available Water:** Pressures / levels in aquifers, aquitards and surface water; and
- **Gradients:** Pressure, heat and quality between aquifers, aquitards and surface water.

Hydraulic connectivity between aquifers and coal seams is assessed by applying methods and techniques to directly or indirectly measure the physical quantities relevant to the above factors.

5.4.1 Direct Measurement

Hydrogeological properties are directly measured by extracting a core sample of the geology from a test well and submitting the core sample to a laboratory for a range of geotechnical and hydrogeological tests. These tests determine the physical properties including the hydraulic conductivity, and the porosity and compressibility of the material which can be used to calculate the formation storativity coefficients.

5.4.2 Indirect Estimates

Hydrogeological properties are typically inferred by monitoring changes in groundwater pressure, level, heat, water quality and gradient at monitoring wells (see Section 5.3) in response to some natural or external stimuli and then subjecting this data to mathematical analysis using equations of groundwater and/or heat flow. This process is called aquifer testing and analysis. Geophysical and remote sensing techniques can also provide useful information on the variability of aquifer and aquitard properties between boreholes.

Aquifer tests can include drill stem tests, slug tests, pumping tests and tracer tests. The mathematical analysis of data from aquifer tests involves the:

- Creation of a conceptual or numerical model of the aquifers and aquitards in the system and all their assumed or measured hydrogeological properties; and
- Adjustment of assumed or measured hydrogeological properties until the modelled predictions of the physical quantities match the observations.

5.4.3 Uncertainty

Indirect estimates of hydraulic connectivity are subject to considerable uncertainty. Regardless of how many direct measurements and indirect estimates are obtained over any period or scale, the uncertainty in hydraulic connectivity assessments cannot be fully removed. Many assumed combinations of conditions may be able to describe the limited observations. This is commonly called a non-uniqueness problem.

The consequences of non-uniqueness are reduced by integrating knowledge obtained from direct measurements of aquitard permeability using laboratory instrumentation (i.e. permeameters) and indirect estimates covering as many environmental conditions (natural and perturbed by test pumping) as possible.

5.5 Methods and Techniques

Methods, techniques and instruments for characterising groundwater are constantly evolving. This section describes some, but not all, of the available methods. Determining the appropriate combination of methods and techniques for a water study requires peer review by a multidisciplinary team of experts including professional geologists, hydrogeologists, hydrologists, managers and consultation with community. Best practice is the data collection and analysis process that adequately reduces uncertainty.

Table 3 provides a summary of the general methods and techniques that can be applied during a groundwater assessment to assess groundwater levels, depth, pressure, quantity, quality and extent. Remote sensing and geophysics methods (Section 3.5.1) can supplement but not replace direct observations taken from boreholes.

At the time of drilling, drill returns are analysed in the field to establish the encountered geology and core samples are sent to the laboratory for analysis of mineralogy, geotechnical and hydrogeological properties such as hydraulic conductivity, porosity, unconfined compressive strength, Poisson's ratio, constrained modulus etc. Various combinations of these parameters can be used to calculate aquifer specific storage. The hydraulic conductivity of rock and aquitard material can be measured with triaxial cells and permeameter apparatus (i.e. constant or falling head, gas pulse, liquid pulse, centrifuge).

Once a borehole has been drilled and/or completed (Section 3.3) down hole geophysical logs, drill stem tests and aquifer tests are run to obtained to characterise the formation. Geophysical logs provide a detailed record of the electrical, acoustic, magnetic, electromagnetic and nuclear properties of the formations penetrated by a well and can be combined with other data to infer the subsurface properties such as geologic make-up, formation orientation, density, porosity, permeability and fracture orientation and spacing (Wikipedia, 2013b). Drill stem and aquifer tests provide data on yield (water quantity) and the formation's response to pressure changes. Drill stem and aquifer tests require the deployment of groundwater pressure sensors.

Once a borehole is drilled it is monitored for changes in groundwater level, pressure, depth, temperature, and quality. Changes in groundwater pressure can be used to infer hydraulic conductivity and specific storage with aquifer test analysis software. Groundwater quality parameters are used to identify and monitor the environmental values (or beneficial use) of an aquifer. The measurement or groundwater levels, pressure, depth, temperature, quality and the assessment of beneficial use is described in more detail in Sections 5.5.1, 5.5.2 and 5.5.3.

Table 3: Methods and Techniques For Groundwater Assessment

Groundwater Metric	**Mapping Data** (previous studies)	**Geophysical Methods** (before / after well installation)	**Remote Sensing Methods** (basin scale characterisation)	**Direct Measurement at Well** (during / after well installation)	**Modelling** (Analytical or Numerical)
Depth Level Pressure	Maps, data and reports are most useful when planning CSG extraction.	Geophysical methods (e.g. gravity, seismic, resistivity, tomography) provide insight into subsurface conditions. Most useful when planning CSG extraction. Can also be used to extrapolate known conditions or measurements between groundwater wells.	Gravity, visible, infrared and other electromagnetic satellite techniques provide insight into conditions and changing conditions at the basin scale. Useful for planning. Potentially useful for monitoring large regional scale effects.	Water level or water pressure sensors are essential for planning and monitoring CSG extraction. Barometric sensors allow pressures / levels to be corrected for earth-tide effects.	Models can be used to predict changes in groundwater depth, pressure, quantity and quality in response to a simulated withdrawal (or injection) of water, heat and/or chemicals. Models are essential for planning and monitoring CSG extraction. Monitoring data that deviates from model predictions demonstrates an uncertainty that needs to be investigated and understood. There are many available analytical and numerical models. Existing models of basin geology and CSG extraction impacts contain uncertainty. Development of better data analysis techniques, modelling approaches and modelling codes is an active area of research and development.
Quantity				Aquifer tests measure depth and pressure changes while introducing (or removing) a known volume of fluid into (or from) the aquifer using a well. These tests are essential for planning CSG extraction and measuring hydraulic connectivity.	
Quality				Water quality field sensors, water sampling and laboratory water quality and isotope analysis are essential tools for planning and monitoring CSG extraction and for assessing changes to beneficial use category.	
Extent	Integrated interpretation of geological data with information obtained from the methods and techniques outlined above				

5.5.1 Level, Pressure and Depth

Depth to groundwater can be measured with a dip meter. A dip meter is a tape measure with a sensor at one end that is lowered down the well to detect the water level in the well.

Groundwater level, pressure and depth can also be measured with pressure transducers. Pressure transducers are instruments that can be placed at a known depth within a groundwater well to record the water pressure or height of water above the sensor. Sensors may measure pressure using vibrating-wire, pneumatic, or strain-gauge principles. Output is converted to an electrical signal that is stored within the device or transmitted to the surface via a cable and subsequently converted to the required system of units. Sensors can be vented or unvented to the atmosphere.

For detailed hydrogeological analysis data from dip meters and pressure transducer may need to be corrected for a variety of effects including density, atmospheric pressure, earth-tide effects, and temperature (Post and von Asmuth, 2013). To facilitate these corrections and to assist with assessments of aquifer connectivity many pressure transducers also contain temperature and electrical conductivity sensors. To correct non-vented sensors for atmospheric pressure effects, barometric pressure sensors can also be deployed. Rau *et al.* (in review) provides a review of temperature methods for assessing surface water and groundwater connectivity, which is a very important aspect of water balance studies.

Most field transducers can be connected to data loggers which can be configured to transmit collected data over mobile or copper phone networks to a centrally connected database server. For the purpose of observing coal seam gas extraction WRL can see no reason why continuous data logging of water pressure, temperature, conductivity (and atmospheric pressure) should not be routinely undertaken.

5.5.2 Quality

Groundwater quality is closely related to aquifer temperature, pressure, oxygenation, mineralogy, carbon content and microbial communities. For these reasons groundwater quality must be measured both in the field and in the laboratory.

Field measurements must identify the redox state of the samples on collection and may require preservation of the samples prior to transport to the laboratory. Field sampling requires specialist equipment including low flow pumps, flow-cells, glove-boxes and electrical sensors. Typical field measurements include electrical conductivity (EC), dissolved oxygen (DO), temperature, pH and reduction-oxidation (redox) potential (Eh or pE).

Laboratory testing of groundwater, effluent, catchment, potable and waste waters can involve comprehensive nutrient analysis (Nitrogen, Phosphorus etc.), physical tests (colour, conductivity, turbidity etc.) and Chemical tests (Anions, Cations, Biochemical Oxygen Demand, Chemical Oxygen Demand, Total Organic Carbon, Cyanides, Isotopes etc.).

Sample preparation techniques for the measurement of water analytes may include: Inductively Coupled Plasma (ICP), Laser Ablation (LA), Combustion Analysis (CA), Microwave Digestion (MD), Flow Injection (FI), Discrete Analysers (DA), and Continuous Flow Analysers (SFA or FIA). Detection methods include Gas Chromatography (GC), Liquid Chromatography (LC), Ion Chromatography (IC), Mass Spectrometry (MS), and Optical Emission Spectroscopy (OES).

A compilation of groundwater quality analytes from recent groundwater quality monitoring reports presented by CSG companies is reproduced in Table 4.

Table 4: Groundwater Quality Parameters Tabulated in Recent CSG Monitoring Reports

Analytes (A-D)	Analytes (E-P)	Analytes (R-Z)
Alkalinity (Carbonate as CaCO3)	Electrical Conductivity	Reactive Phosphorus
Alkalinity (Hydroxide) as CaCO3	Ethyl Benzene	Redox Potential (Eh)
Alkalinity (Total) as CaCO3	Filterable Reactive Phosphorous	Selenium
Aluminium	Fluoride	Silica
Ammonia	Formaldehyde	Silver
Antimony	Hexacholributadiene	Sodium
Arsenic	Hydrogen Sulphide	Strontium
Barium	Iodide	Styrene (vinyl benzene)
Benzo(a)pyrene	Iodine	Sulphate
Beryllium	Iron	Temperature
Bicarbonate	Lead	Tetrachloroethene
Boron	Lithium	Toluene
Bromide	Magnesium	Total Dissolved Solids
BTEX (Benzene, Toluene, Ethylbenzene and Xylenes)	Manganese	Total Kjeldahl Nitrogen
Cadmium	Major Anions	Total Organic Carbon
Calcium	Major Cations	Total Phosphorous
Carbon Dioxide	Mercury	TPH (Total Petroleum Hydrocarbons)
Carbon Monoxide	Methane	Tributylin Oxide
Carbon Tetrachloride	Molybdenum	Trichloroacetaldehyde (Chloral Hydrate)
Carbonate	Napthalene	Trichlorophenol
Chloride	Nickel	Trihalomethanes
Chlorobenzene	Nitrate	TSS (Total Suspended Solids)
Chlorophenol	Nitrilotriacetic Acid	Turbidity
Chromium	Nitrite	Uranium
Chromium (III+VI)	Oxygen	Vanadium
Cobalt	Polycyclic Aromatic Hydrocarbons	Vinyl Chloride
Copper	Peak LEL (Lower Explosive Limit)	Volatile Organic Compounds
Cyanide	pH	Xylene
Cyanogen Chloride	Phenols	Zinc
Di(2-ehytlhexyl) Phthalate	Polycyclic Aromatic	
Dichlorobenzene	Potassium	
Dichloroethane		
Dichlorophenol		

Sources: Santos (2007), GQC (2013b), LEP (2013)

Based on presentations by various CSG companies at the 2013 International Association of Hydrogeologists Congress in Perth and reports (Parsons Brinckerhoff, 2013) WRL understand that these analyses also include isotopes such as ^{2}H, ^{3}H, ^{13}C, ^{14}C, ^{18}O, ^{35}Cl, ^{37}Cl, ^{86}Sr and ^{87}Sr.

These data can be analysed and interpreted with a range of exploratory data analysis techniques that include stiff diagrams, box-plots, piper diagrams, hierarchical cluster analysis, discriminant cluster analysis and principal component analysis.

5.5.3 Environmental Values

The National and State guidelines for groundwater protection rely on a framework in which there is identification and classification of existing environmental values (beneficial uses) of groundwater. The beneficial use categories adopted by the NSW State Groundwater Quality Protection Policy (DLWC, 1998) are:

- Ecosystem protection;
- Recreation and aesthetics;
- Raw water for drinking water supply;
- Agricultural water; and
- Industrial water.

These categories are defined in the National Water Quality Management Strategy Guidelines for Groundwater Protection in Australia (ARMCANZ and ANZECC, 1995). Each category is defined by strict or preferred limits on individual water quality parameters and/or indicators.

Salinity is one such indicator, but there are numerous others that must be considered depending on the beneficial use category and the aquifer interference activity in question. For further information on water quality indicators and limits in Australia refer to:

- Appendix I and Appendix II of ARMCANZ and ANZECC (1995);
- Australian Guidelines for Fresh and Marine Water Quality (ANZECC and ARMCANZ, 2000);
- Australian Drinking Water Guidelines (NHMRC, 2011); and
- http://www.environment.gov.au/water/policy-programs/nwqms.

5.5.4 Further Reading

References containing specific descriptions and details for various groundwater characterisation methods, techniques and tools can be found in Section 12 of SKM (2012) and:

- **Monitoring:** CWI (2013), NOW (2011c), Sundaram *et al.,* (2007), Jousma (2008), Sorensen and Butcher (2010), and ASTM D4448 and related standards (ASTM, 2013);
- **Aquifer Testing:** Ferris *et al.,* (1962), Osborne (1993) and Duffield (2007);
- **Modelling:** Australian Groundwater Modelling Guidelines (Barnett *et al.,* 2012);
- **Remote Sensing:** GA (2013c), Tregoning (2012), Meijerink (2007); and
- **Geophysical Methods:** Wikipedia (2013), USGS (2013), Bates (2006).

5.6 Water Balance and Numerical Modelling

Figure 4 represents the water balance associated with CSG and surrounding aquifers. The maximum volume of water that can be depleted from other aquifers (and surface waters) will be the same as the volume of water extracted from the CSG aquifer. Establishing the uncertainties in the water balance is imperative to good planning.

Water balance modelling with only regional knowledge lacks understanding of potential flow through aquitards and lateral recharge rates. This provides a great deal of uncertainty. The water balance and potential volumes of flow are very difficult to quantify in the absence of detailed knowledge of recharge, discharge and exchange parameters.

Uncertainties within a water balance must be reduced through local information and observations. Data from within the CSG aquifer itself (as gathered during pilot testing and exploration wells which can also be used to test the resource) will yield the useful knowledge of flows and responses only when coupled with data gathered from surrounding aquifers and aquitards.

The most practical use of a water balance is to assess the uncertainties. Any water balance presented without a commensurate discussion of uncertainty should not be accepted.

Complex numerical modelling is often presented as the only method for understanding or assimilating all of the information regarding flows and 3D geology. However, the assumptions in numerical modelling are not understood by all those that practise it, and the visually impressive outputs can inspire unfounded confidence.

Numerical models are tools containing simplified representations of reality. They are used to help inform management decisions. Numerical models are created by modellers who make numerous simplifying assumptions. The primary job of a modeller is to reduce the subjectiveness and bias introduced by their decisions to simplify. If this is done correctly the model will make predictions with minimum error variance. The modeller's next objective is to quantify the amount of uncertainty in their model using special mathematical tools and techniques. Quantification of uncertainty is called uncertainty analysis. Uncertainty is highest when there is no site specific data.

With a numerical tool finally in place the modeller and decision maker can test various scenarios which attempt to disprove their management decision hypotheses. Usual hypotheses include negligible risk of some bad outcome and/or the feasibility of some engineering activity. In our experience it is rare to find a single simplified representation of reality that answers all hypotheses with minimum bias and minimum error variance. In our experience it is also rare to find modelling reports that clearly state and comprehensively attempt to disprove the management decision hypotheses. Comprehensive efforts require consideration and discussion of uncertainty and the subsequent numerical testing of alternate boundary conditions, alternate conceptual models, and alternate geological and stratigraphic models.

Numerical modelling can incorporate complex numerical formulations and time transient conditions. However the accuracy of the resulting model is no better than the accuracy of the input data, the boundary conditions or the appropriateness of the model design. Model results need to be presented with supporting evidence validated from site specific calibration and clear uncertainty analysis. For example, if little information is known about potential fractured flow through an aquitard, model simulations should be undertaken with and without such flow.

Many CSG assessments we have reviewed did not incorporate numerical modelling due to inadequate data and instead relied on water balance assessments alone. The decision not to embark on a complex modelling program when the required information is not available should be applauded. However, the understanding of what data is lacking for establishing a numerical model is inherently the understanding required for designing a suitable monitoring program.

The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development recommends regional water balance models as the most appropriate basis for assessing potential changes in water resources. They recommend developing site specific local water balances for each project complemented by a regional water balance, which covers the larger area of potential impact to assess cumulative impacts possible from the CSG developments (IESC, 2013a). Any regional numerical model also requires commensurate data collection to ensure that confidence could be placed in its predictions.

While documents exist such as the Australian Groundwater Modelling Guidelines (NWC, 2012a), it is imperative to understand that good modelling is undertaken by skilled numerical modellers with many years of experience and not simply by software packages. For additional information on groundwater modelling approaches see Doherty and Simmons (2013).

Exploration, data collection and assessment activities (including sound modelling practice) are ALL required to develop a realistic conceptual understanding of the structure, extents and properties of the coal seams, the integrity of the surrounding aquitards and the potential for any impacts to nearby beneficial aquifers and surface water resources.

5.7 Qualified Staff

Assessment of the risks to groundwater systems requires experienced staff. The International Association of Hydrogeologists (IAH), industry and government could explore options for encouraging the redistribution of experienced and inexperienced resources throughout industry and establishing appropriate training and mentoring programs. Some of NSW's best engineering practitioners were lifelong veterans of the NSW Public Works Department, the Department of Land and Water Resources, Sydney Water and the Electricity Commission. Practitioners in these departments received traineeships, cadetships and extensive mentoring when joining industry between 1960 and 1988. With the subsequent commercialisation and outsourcing of state engineering activity there has been a significant increase in competitive tendering in private engineering practice, often with low probability of success. In this environment many new graduates do not receive the same training opportunities as their forebears and must move from company to company to obtain appropriate experience and industry exposure.

NSW Government must ensure that all applications for CSG are assessed by suitably qualified and resourced personnel.

The risks of well failure allowing flows between aquifers otherwise separated by aquitards is very real. However, it must be addressed by skilled and well-resourced operations. A report published in the Oilfield Review by Schlumberger, presents data that shows that without careful attention to well cement design, up to 50% of wells can leak gases within a 15 year period from construction. Gas leakage through the well annulus can be detected by sustained casing pressure (SCP), with construction methods to avoid these issues being presented (Brufatto *et al.*, 2003). This report discusses sealing and isolation methods, well testing and improvement of cement bonds to improve well integrity over the long term. These methods all require well trained and experienced staff (in addition to further research and development).

6. NSW Resources and Groundwater Use

Groundwater is a single, continuous resource found everywhere in the saturated zone. In Australia, the groundwater resource makes up approximately 17% of accessible water resources and accounts for over 30% of our total water consumption (GA, 2013a).

Like surface-water, groundwater is a resource that obeys no boundary. Given enough time and the right pressure gradients, groundwater is free to move anywhere. It might move to a different geological unit, across a surface water catchment divide or even into another state or territory. It might also discharge to the ground-surface and/or evaporate. The only constraint on the subsurface movement is the permeability of the rocks containing the groundwater, and this can vary significantly in both the horizontal and vertical directions both within and across individual aquifers, aquitards and basins.

The groundwater resource, like surface-water, also exhibits significant spatial and temporal variability with respect to quality and yield. In groundwater this variability is controlled by geology, groundwater residence time, interactions with surface water and any aquifer interference activity. **Aquifer interference** is any activity that changes the quality of the groundwater or the pressure under which it is held. Examples of aquifer interference activity include the digging of a well, the drilling to the water table or a lower aquifer, the removal of water from an aquifer (generally by pumping) or discharge of water into the subsurface.

6.1 Classification of the NSW Groundwater Resource

Since groundwater is continuous and variable everywhere across Australia, it is too large to manage as a single resource and requires classification (delineation) into smaller, more manageable zones. The groundwater resource in NSW is currently classified according to a number of geological, hydrological and water resource management constructs.

These constructs include:

- Geological Basins and Provinces;
- Surface Water Catchments;
- Aquifer Types;
- Groundwater Sources;
- Water Sharing Plan (WSP) Areas;
- Groundwater Management Areas (GMAs);
- Groundwater Management Zones; and
- Groundwater Management Units (GMUs).

Table 5 summarises the number of WSP areas, GMAs and groundwater sources in: all of NSW; the major coal producing basins; and recent petroleum titles and application areas.

Table 5: Groundwater Management Units in NSW (Sources: NOW, 2013; DTIRIS 2013)

Management Unit	NSW	Major Coal Producing Basins	Petroleum Titles and Applications
Water Sharing Plan Areas	60	35	21
Groundwater Management Areas	101	60	31
Groundwater Sources	365	184	37

Maps of coal producing basins, petroleum titles and wells in NSW are provided in Section 6.2. Historical estimates of NSW groundwater quantity are provided in Section 6.3. Groundwater sources, management areas and Water Sharing Plans are discussed in Section 6.4.

6.2 Coal Producing Basins, Petroleum Titles and Wells of NSW

Over 60% of New South Wales is covered by sedimentary basins. In the east, the coal and coal seam methane rich Permian-Triassic Sydney-Gunnedah-Bowen Basin system is overlain by the gas-prospective Jurassic-Cretaceous Great Artesian Basin, comprising the Clarence-Moreton, Surat and Eromanga Basins (NSW Trade & Investment, 2013).

The major coal producing basins of NSW, the Sydney-Gunnedah-Bowen Basins, as well as the Gloucester and Clarence-Morton Basins (Figure 17) are all being actively explored for CSG. No commercial discoveries have been made in the NSW part of the Surat Basin (Sydney Catchment Authority, 2012). The coal seams in the aforementioned basins have good lateral continuity, substantial net coal thickness, appropriate maturity and gas saturation and occur at depths suitable for the extraction of methane. In NSW the coal seams targeted for gas production are generally found between 200 m and 1000 m below the ground (NSW Office of Water, 2013).

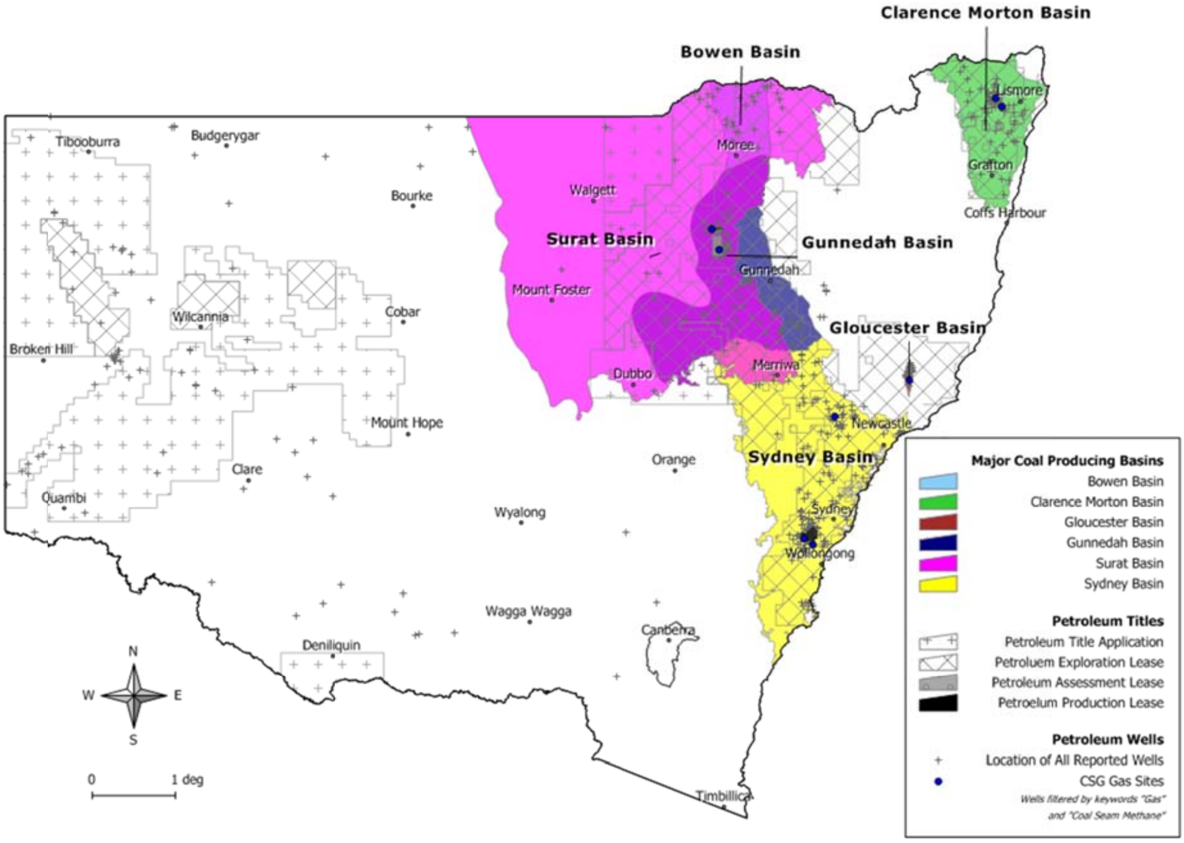


Figure 17: Major Coal Producing Basins and Petroleum Titles in NSW (August 2013)

The geospatial data in Figure 17 has been derived from a number of data sources (GA, 2013d; DTIRIS, 2013b; 2013c; 2013d; 2013e). The base mapping for the figure was sourced from the National Geoscience Dataset. The petroleum titles, title applications and geological basins are from the NSW Government MinView Database. The petroleum wells, also from MinView, are all those wells with a business purpose of "coal seam methane" or a company name containing the word "gas". The plot shows all wells entered into the public database regardless of status or condition and petroleum titles for sixteen of the larger industry groups. The currency of data in the MinView database was not specified in the downloadable metadata.

6.3 Historical Assessments of the NSW Groundwater Resource

In the year 2000 the Federal government spatially defined set of 538 groundwater management units (GMUs) across Australia. As groundwater management units often overlie each other, these GMUs were aggregated for mapping and reporting purposes into 69 broadly defined groundwater provinces (SEWPAC, 2007), seven of which lie within NSW (Figure 18). Table 6 summarises the estimated sustainable yield of these provinces, the total abstraction and the groundwater allocation, as provided in the Australian Water Resources Assessment 2000 (NHT, 2001). These GMUs were revised in 2005 without corresponding updates to the data in Table 6.

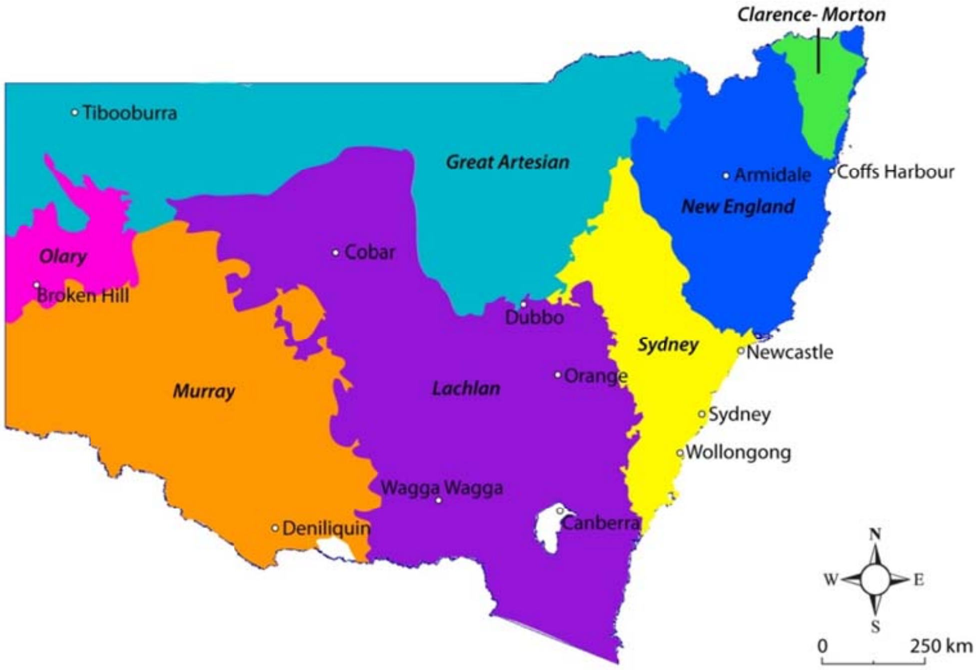


Figure 18: Groundwater Provinces in NSW
(as used for reporting purposes in the Australian Water Resources Assessment 2000)

Table 6: NSW Groundwater Provinces, Sustainable Yield and Groundwater Abstraction and Allocation (Source: NHT, 2001)

Groundwater Province (NSW Components)	Number of GMUs	Sustainable Yield[1] (ML)	Total Abstraction[2] (ML)	Groundwater Allocation[3] (ML)
Clarence-Morton	5	610500	14029	23467
New England	8	1948934	62216	113641
Sydney	13	1485300	203904	510223
Lachlan	15	895300	180032	552430
Murray	5	966300	330137	995050
Olary	1	153000	265	501
Great Artesian	6	238260	217941	470536

(1) Sustainable Yield –The level of extraction measured over a specified planning timeframe that should not be exceeded to protect the higher value social, environmental and economic uses associated with the aquifer.

(2) Total Abstraction – Average annual volume extracted for use.

(3) Groundwater allocated in formal agreements.

6.4 NSW Groundwater Sources

Following publication of the Australian Water Resources Assessment 2000, NSW began transitioning to a new system of groundwater management and reporting under the Water Management Act 2000. Groundwater use in NSW aquifers is now, or will shortly be, managed by Water Sharing Plans (WSPs). Regions without WSPs are managed under the Water Act 1912. The March 2013 map of commenced NSW water sharing plans is reproduced in Figure 19.

Water Sharing Plan Areas in NSW are subdivided by Groundwater Management Areas (GMAs) and Groundwater Sources. The major coal producing basins of NSW contain 35 WSPs, 60 GMAs and 184 groundwater sources and summarising this material would be an exceedingly large exercise beyond the scope of this report.

Due to water sharing plans being in a range of release conditions (draft, final, incomplete), containing varying detail on groundwater sources and being of various qualities of production we considered it possibly misleading to summarise which groundwater systems are at risk from coal seam gas activity.

To facilitate access to data on groundwater sources Appendix A lists February 2013 water sharing plans that intersect the petroleum titles shown on Figure 17. Current maps and descriptions for each Water Sharing Plan, GMA and groundwater source can be obtained from the NSW Office of Water at:
http://www.water.nsw.gov.au/Water-Licensing/About-licences/Which-Act-applies-/

For background information on NSW geology and hydrogeology see Ward and Kelly (2013) and O'Neill and Danis (2013). Environmental Impact Statements, Reviews of Environmental Factors and Groundwater Impact Studies prepared for CSG prospects are another good source of summarised hydrogeological data. For example, see Golder (2011) for a report on the Santos Gunnedah Basin CSG Project.

6.5 Relativity of Water Usage

Detailed information comparing volumes, levels and quality of groundwater associated with CSG extraction to other regional groundwater uses in NSW was not obtainable. This is an issue with current NSW groundwater management practice which is discussed in Section 7.

6.5.1 Quantity

As discussed in Section 3.5.3, the amounts of water associated with CSG production in NSW (coastal) Permian Basins to date are small (Roy, 2012), compared to other Australian CSG productions (Figure 20).

The observations by Roy (2012) are supported by the National Water Commission (RPS, 2011) who estimated future groundwater pumping volumes for NSW CSG operations on the basis of available 2P reserve and water energy ratio data (Table 7).

To put these NSW CSG production estimates in context, Table 8 displays the volumes of groundwater extracted in 2009 from different groundwater areas within the Namoi region (NSW) and Table 9 presents non-petroleum and gas groundwater extraction (ML/year) in the Surat Cumulative Management Area (QLD).

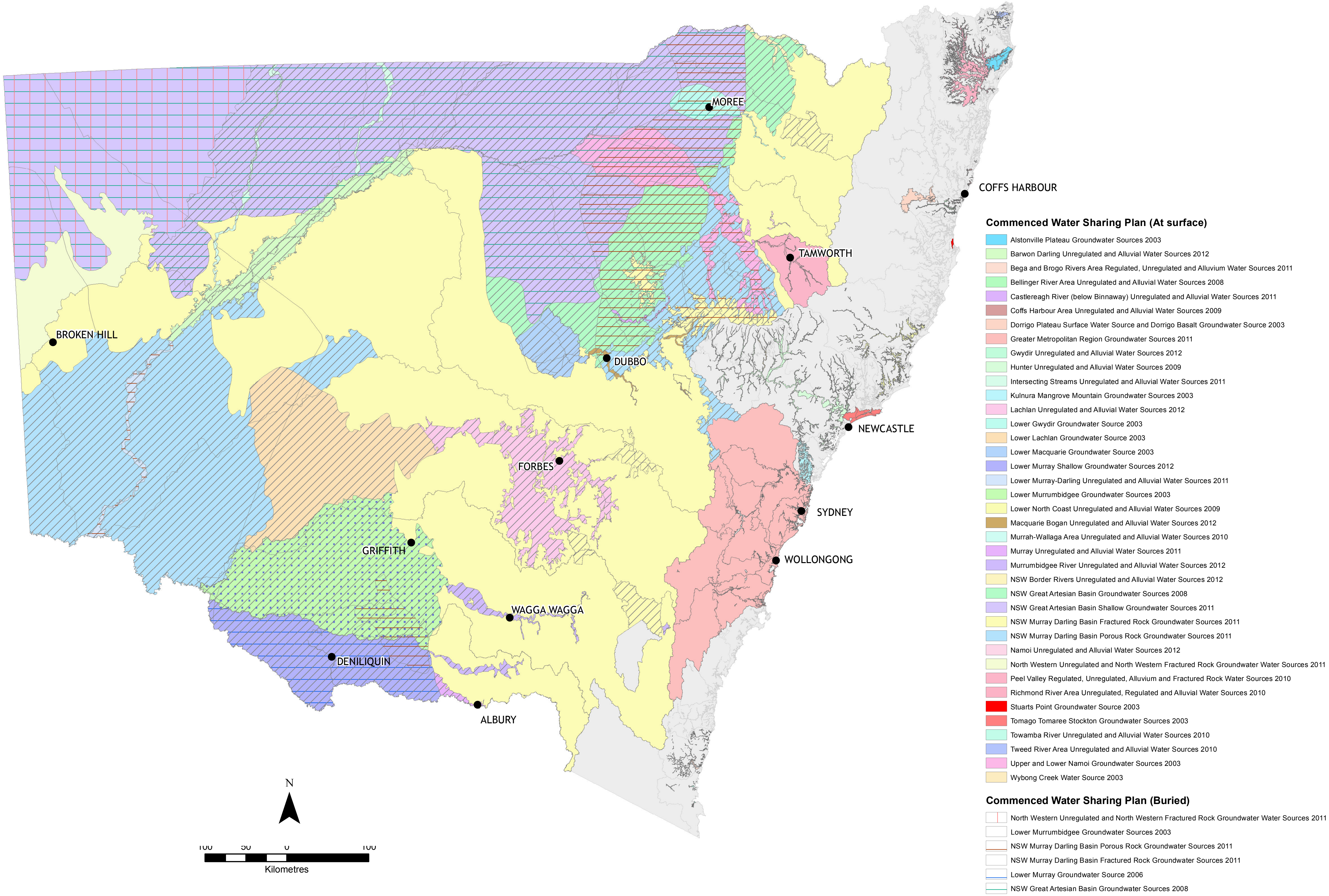


Figure 19: Water Sharing Plans for Groundwater in NSW as of March 2013 (NOW, 2013)

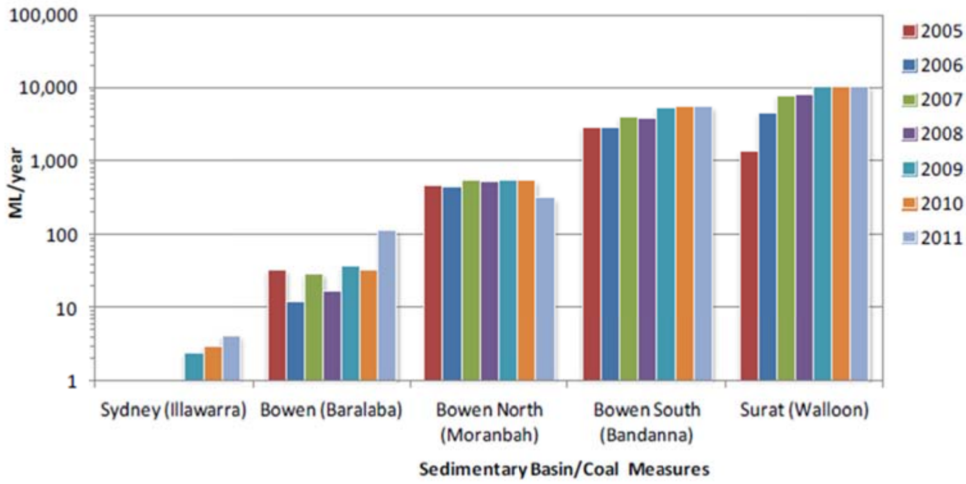


Figure 20: Estimated Volume of Co-Produced Water from QLD and NSW (Source: SCA, 2012)

The data in these tables indicate:

- Agriculture and stock and domestic groundwater consumption accounts for more than 85% of non-petroleum groundwater use in the Great Artesian Basin, while industrial and urban use responsible for the remaining 15%;
- NSW CSG production is likely to consume less groundwater than QLD CSG production;
- Projected water demand for potential CSG operations in the Gunnedah Basin (1.4 GL/yr) is approximately 1% of existing total groundwater production in the Namoi (148 GL/yr).

Table 7: Estimated Water Production from known NSW CSG Basin Reserves (RPS, 2011)

Basin	Current 2P Reserves (PJ)	Water Energy Ratio (ML/PJ)		Estimated Design Life (Years)	Estimated Water Production (ML/yr)	
		Min	Max		Min	Max
Sydney	129	1.15	1.15	-	6	6
Gloucester	423	7.10	23.64	14	214	714
Gunnedah	1520	1.15	23.64	25*	70	1,437
Surat	24,775[1]	-	-	-	10,000[2]	
Bowen	8,258[1]	-	-	-	6,000[2]	
Clarence-Moreton	397	1.76	1.76	25	28	28

1. GA (2012)
2. SCA (2012)

Table 8: Groundwater Extraction in 2009 (Source: Schlumberger, 2012)

Groundwater Area	ML/year
Upper Namoi Alluvium - Narrabri Formation and Gunnedah Formation	70,149
Lower Namoi Alluvium – Single unit	63,800
Hard Rock - Units below the Pilliga to the east of GAB extent	14,355

Table 9: Non-Petroleum and Gas Groundwater Extraction (ML/year) in the Surat Cumulative Management Area (Source: QLD Water Commission, 2012)

	Agriculture	Industrial	Urban	S&D
Non GAB upper formations	84,293	3,313	10,324	29,212
GAB	22,250	8,700	6,427	48,061
Non GAB lower formations	16	20	0	2,759
Total	106,559	12,033	16,751	80,032

- Agriculture includes irrigation, aquaculture, dairying and intensive stock watering but does not include non-intensive stock or domestic use.
- Industrial includes industrial, commercial and mining.
- Urban is primarily town water supplies but also includes supplies for schools and similar institutions, reticulated domestic supply systems operated by groups of individuals and some commercial and industrial use where the water is delivered through town water reticulation systems.
- S&D refers to stock and domestic supply.
- Details about other shallow alluvial systems may not be complete but these systems are not well connected from the GAB and are not significant in the context of this report.

6.5.2 Groundwater Level and Quality Impacts

An unbiased and scientific assessment of the impacts of petroleum and non-petroleum activity groundwater levels and quality requires a detailed consideration and analysis of data that was both inaccessible and whose compilation was beyond the scope of this commission.

Plots of recent groundwater levels in two beneficial aquifers from two randomly chosen government monitoring bores in the Gwydir River Basin near Moree are reproduced in Figure 21 and Figure 22. Groundwater use in the Gwydir River Basin is dominated by agricultural production with some town water supply. These monitoring bores show seasonal groundwater level variations from pumping in the range of three m to 18 m. A plot of long term groundwater level fluctuations in a shallow aquifer less than one km from one of Moree's town water supply bores is shown in Figure 23. The data in these plots was obtained from a NSW Government data CD (NOW, 2010b) and an online database (NOW, 2013i).

Data and modelling work from QLD, where coal seam gas water production is high, suggests that the majority of groundwater level impacts on shallow aquifers will be less than five m for consolidated aquifers and less than two m in unconsolidated aquifers, and that 85 of 21,000 bores will experience more severe drawdown (QWC, 2012). This is not too dissimilar to the CBM experience in the USA (Section 4.5.5). Predictions for Arrow Energy's Surat Gas Project (Arrow Energy, 2011) are reproduced in Table 10.

These estimates are difficult to transfer to the NSW context due to differing geology and water production estimates. For example, AGL's CSG operation in Camden produces very little water with monitoring wells installed only in 2011 and 2013. Cumulative impact "rules" for new aquifer interference activities in NSW are discussed in Section 7.

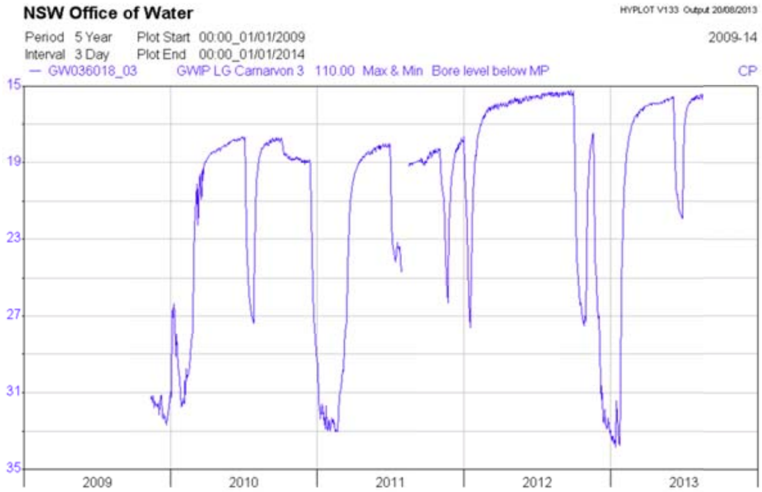


Figure 21: Recent Groundwater Levels at Monitoring Well GW036018_03 (© NOW, 2013i)

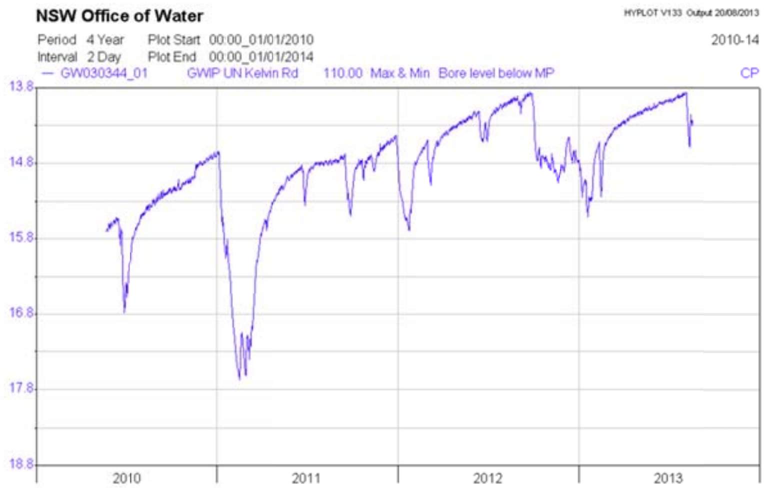


Figure 22: Recent Groundwater Levels at Monitoring Well GW030344_01 (© NOW, 2013i)

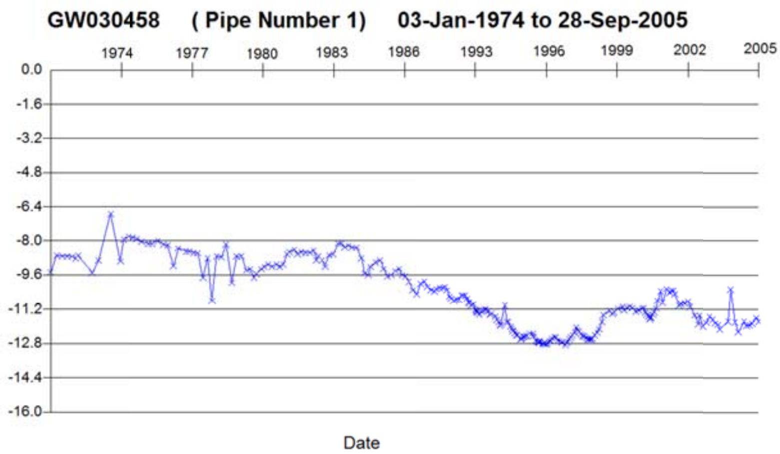


Figure 23: Historical Groundwater Levels at Monitoring Well GW030458_01 (© NOW, 2010b)

Table 10: Summary of Cumulative Drawdown Impacts for Surat Gas Project (Arrow Energy, 2011)

Groundwater System and Aquifer	Predicted Maximum Groundwater Drawdown – Surat Gas Project Only	Predicted Maximum Groundwater Drawdown - Cumulative
Shallow groundwater system	> 0.1 m to < 1 m	2.5 m
Intermediate groundwater system	30 m	60 m
Coal seam groundwater system (Walloon Coal Measures)	> 75 m	150 m
Deep groundwater system	10 m to 30 m	75 m

6.5.3 Uncertainty

In making the above comparisons the uncertainty in the estimates of water usage must be acknowledged. Roy (2011) reports that limited basin or project scale data is available for NSW:

- The Gunnedah Basin contains more than 60% of current 2P CSG reserves in NSW but no estimates or reliable data were available to predict future co-produced water quantities from this basin; and
- "*…It's impossible to say with certainty how much water is present in the coal seams within the Gloucester Basin*".

The ABC coal seam gas by the numbers website (ABC, 2013) flags significant differences in projected estimates of groundwater consumption. Their info graphic (Figure 24) compares water consumption estimates from the National Water Commission (RPS, 2011) of 300 GL/yr to industry predictions of 61 GL/yr (for four CSG companies). More recent estimates from the Queensland Water Commission (QWC, 2012) predict 95 GL/yr of water production from QLD petroleum wells compared to a usage of 215 GL/yr from other groundwater users.

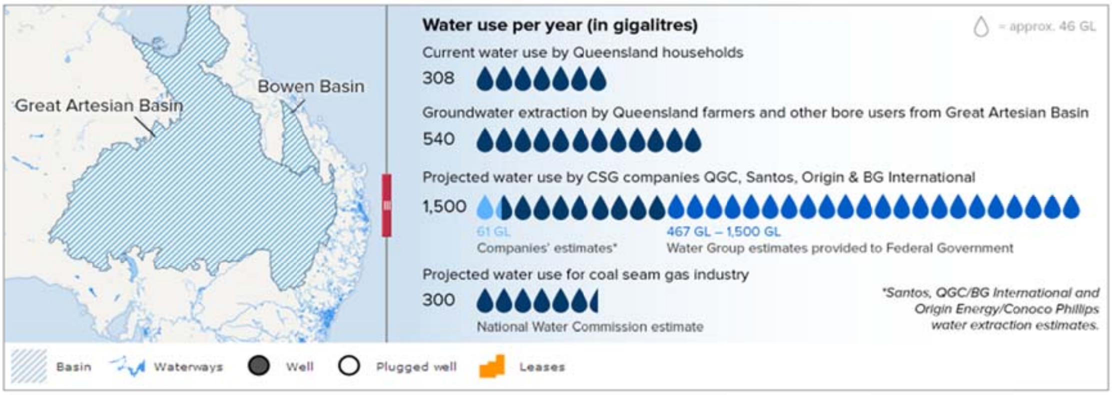


Figure 24: Estimated Volume of Co-Produced Water from QLD and NSW (© ABC, 2013)

7. Water Management Practice

7.1 Legislative Framework for NSW Water Management Practice

NSW's legislative framework for water management practice is highly complex. The NSW Office of Water website (NOW, 2013b) states that "*Managing New South Wales water resources is a huge task, involving a range of legislation, initiatives and cooperative arrangements with the Commonwealth and other state government departments*".

This section provides an overview of the NSW legislative framework to manage CSG activities and water resources through Acts, Plans, Regulations, Policies, Guidelines and Codes of Practice. This section does not attempt to provide a definitive guide of all legal instruments or how they refer and trigger each other. Rather, the water management practices are presented with regards to how, in May 2013, they addressed the potential groundwater consequences and methods for assessing risks raised in Sections 4 and 5.

Presently, NSW water management practice is transitioning and the NSW legislative framework for water resources and energy is being reformed at a considerable pace. For the most up to date information we recommend that readers contact NSW government directly.

7.1.1 Acts Pertaining to Coal Seam Gas and Petroleum in NSW

In May 2013, the use of unconventional gas resources in NSW was governed by:

- The *Petroleum (Onshore) Act 1991*;
- The *Mining Act 1992; and*
- Recent amendments to these acts, and associated regulations.

These legal instruments are governed by the Department of Trade and Investment, Regional Infrastructure and Services (DTIRIS). Within DTIRIS exists the Office of Coal Seam Gas (OCSG) within the Division of Resources and Energy (DRE).

Section 74 of the *Petroleum (Onshore) Act 1991* places no obligation on the Minister to consider water resources in environmental studies - only the flora, fauna, fish, fisheries and scenic attractions, and features of Aboriginal, architectural, archaeological, historical or geological interest. Consideration of water resources is triggered by qualitative discretionary conditions of development consent established for each and every petroleum licence or lease.

On 28th May 2013, the NSW Legislative Assembly passed the *Petroleum (Onshore) Amendment Bill 2013* containing provisions for compliance, audits, royalties and codes of practice to the NSW Legislative Council for concurrence (NSWLC, 2013). When passed, new and renewed petroleum leases may require adherence to codes of practice such as:

- Draft Code of Practice for CSG Explorations (DTIRIS, 2012c);
- Code of Practice for Coal Seam Gas Well integrity (DTIRIS, 2012b); and
- Code of Practice for Coal Seam Gas Fracture Stimulation Activities (DTIRIS, 2012a).

Section 47[1] of the Act establishes post 1991 state environmental planning policies (i.e. State Significant Development) as the only environmental planning instruments capable of preventing or modifying a petroleum leaseholder's exploration or assessment operations.

7.1.2 Acts Pertaining to Water Resources in NSW

Water resources in NSW are governed by:

- The *Water Act 1912*;
- The *Water Management Act 2000*;
- The *Protection of the Environment Operations Act 1997* (Part 5.3);
- The *Catchment Management Authorities Act 2003* (see e.g. s20);
- The *Environment Protection and Biodiversity Act 1999 (Cth);*
- Over seventy water sharing plans (NOW, 2013a); and
- Regulations (NSW PCO, 2013).

The Water Acts, sharing plans and regulations are administered by the NSW Department of Primary Industries, specifically the NSW Office of Water. The administration of these instruments is facilitated by numerous policies, strategies and guidelines.

Some of the more relevant water management documents include the:

- *Aquifer Interference Policy – September 2012* (NOW, 2012)*;*
- *Australian Groundwater Modelling Guidelines* (NWC, 2012a);
- *NSW State Groundwater Quality Protection Policy – December 1998* (DLWC, 1998)*; and*
- *National Groundwater Quality Management Strategy* (ARMCANZ and ANZECC, 1995).

7.1.3 Governance of Petroleum and Water Management Practice

The approvals process for combined petroleum and water management practice in NSW is governed by the relevant Acts listed in Sections 7.1.1 and 7.1.2 in conjunction with further Acts, Regulations, Policies and Instruments some of which are administered by the NSW Department of Planning and Infrastructure (DP&I). These include:

- The 'EP&A Act 1979': the *Environmental Planning and Assessment Act 1979*;
- The *Environmental Planning and Assessment Regulation 2000*;
- The 'Mining SEPP': *State Environmental Planning Policy (Mining, Petroleum Production and Extractive Industries) 2007* (and 2012 amendment);
- The 'State Development SEPP': *State Environmental Planning Policy (State and Regional Development) 2011;*
- The *Strategic Regional Land Use Policy;*
- The 'Gateway': *Environmental Planning and Assessment (Gateway Process for Strategic Agricultural Land) Regulation 2012;*
- *Guidelines for Agricultural Impact Statements; and*
- *ESG2 – Environmental Impact Assessment Guidelines.*

The compliance aspects of water management practice in NSW are governed by the above Acts with reference to the *Protection of the Environment Administration Act 1991, Protection of the Environment Operations Act 1997* and its instruments. The *Protection of the Environment Operations Act 1997* is administered by the NSW Environmental Protection Authority (EPA) with the assistance of the Government agencies listed above. Any contamination of land or water is governed by the Contaminated Lands Management Act 1997.

7.1.4 Triggers for Water Resources Assessment and Licencing

In May 2013, the formal consideration of water resources in CSG activity commenced following a proponent's seeking of an Access Arrangement (AA) for on-site activity. Water resources matters to be considered by a proponent were described in the conditions and in the schedule of the proponent's petroleum licence or lease. For the licence WRL inspected, PEL470, a Review of Environmental Factors (REF) was required for all petroleum well drilling, fraccing, pumping, pilot testing, etc. (category 3 activity) but not for borehole drilling and borehole use (category 2 activity). In other cases an EIS may be required.

The ESG2 Environmental Impact Assessment Guidelines (DTIRIS, 2012d) detail the requirements for an REF or EIS and the steps for review by Government. After review the activity can be approved with conditions, and this may include a requirement for an Aquifer Access Licence (AAL) and/or an Aquifer Interference Approval (AIA). The association of AALs and AIA requirements with conditions of development consent implies a discretionary process.

Our review found ambiguities as to whether Aquifer Access Licences (AALs) and Aquifer Interference Approvals (AIAs) were required or would be considered for all category 3 and category 2 activity. From the relevant legislation it was apparent that:

- Under the present planning system, which is to be revised (DP&I, 2013), the *EP&A Act 1979* s89J exempts all State Significant Development (CSG production activity and all exploration activity with more than five wells – see below) from the need to seek a water use or water management works approval. Such projects are not AIA exempt.
- Under the *Water Management (General) Regulation 2011*, if the amount of water pumped from a coal seam is predicted to be greater than three megalitres per year and the activity will not otherwise be exempt from holding an AAL, the CSG producer must apply for licences to take water (see Section 7.2.1).
- Under a revised planning system (DP&I, 2013) it has been suggested that approved State Significant Development would be exempt from obtaining AIAs on the basis that appropriate consideration of aquifer interference would form part of the revised planning process (White, 2012; personal communication).

The *State Environmental Planning Policy (Mining, Petroleum Production and Extractive Industries) 2007* states that "*development for any of the following purposes may be carried out only with development consent:*

(a) petroleum production on land on which development for the purposes of agriculture or industry may be carried out (with or without development consent),…
(c) petroleum production in any part of a waterway, an estuary in the coastal zone or coastal waters of the State that is not in an environmental conservation zone,…
(e) petroleum production on land that is reserved as a state conservation area under the National Parks and Wildlife Act 1974,
(f) drilling or operating petroleum exploration wells, not including:
(i) stratigraphic boreholes, or
(ii) monitoring wells, or
(iii) a set of 5 or fewer wells that is more than 3 kilometres from any other petroleum well (other than an abandoned petroleum well) in the same petroleum title,
(g) drilling or operating petroleum exploration wells (not including stratigraphic boreholes or monitoring wells) that is carried out in an environmentally sensitive area of State significance"

7.2 Aquifer Interference Policy

The *NSW Aquifer Interference Policy – September 2012* is administered by the NSW Office of Water (NOW), an office of the NSW Department of Primary Industries (DPI). It is considered to be the most relevant single policy addressing the groundwater risks and consequences raised in Section 4.

Aquifer Interference is any activity that interferes with the subsurface. NSW's Aquifer Interference Policy has two components:

1. **Water Access Licences:** being approval provided to a proponent to take water under the provisions of one of the following Acts:
   - *The Water Act 1912; and*
   - *The Water Management Act 2000.*

2. **Aquifer Interference Approvals:** being approval provided to a proponent to interfere with the subsurface and/or a process to provide recommendations for conditions of development consent to a consent authority (DTIRIS-DRE-OCSG, DP&I, PAC, Gateway, or other) under one or more of:
   - The EP&A Act 1979; and
   - The *Water Management Act 2000.*

The Policy states that "Aquifer interference approvals are not to be granted unless the Minister is satisfied that adequate arrangements are in force to ensure that no more than minimal harm will be done to any water source, or its dependent ecosystems..."

The 31-page policy can be summarised to the following six guiding principles:

1. Classify groundwater resources;
2. Predict all water extractions and impacts of the activity with modelling tools;
3. Monitor all activities prior to and throughout the course of the activity;
4. Measure all significant water takings;
5. Compare predictions and outcomes to Minimal Harm Criteria – An objective (quantitative) criteria developed to protect resources; and
6. Enforce activities that result in more than minimal harm.

The risk assessment methods discussed in Section 5 of this report cover all of these six principles.

Under the Water Management Act 2000 and the Water Management (General) Regulation 2011, the NSW Office of Water (NOW) is provided with the ability to:

- Request estimates of total groundwater pumping for a planned activity;
- Request estimates of incidental withdrawal of groundwater from connected water sources such as adjacent aquifers;
- Issue licences for the direct and incidental withdrawal of groundwater from all aquifers;
- Consider whether an activity will cause more than minimal harm to a water resource, a cultural site or a connected ecosystem; and
- Provide recommendations for conditions of development consent.

7.2.1 Data Requirements for Licencing and Assessment

Figure 25 shows a simplified concept diagram of a coal seam gas operation that illustrates the types of water volumes (A through F) that must be predicted by a proponent with a desktop assessment or mathematical model when planning a CSG exploration, assessment or production activity as required by the Water Management Act 2000.

The CSG proponent must predict how much:

- Water they will pump from the coal seam (A);
- Extra water will leak into the coal seam (B);
- Extra water will travel laterally into the study area from further afield (C);
- Extra water will leak to or from streams and other connected surface waters (D);
- Treated water will be treated and subsequently re-injected into an aquifer (E);and
- Treated water will be re-used in some fashion (F).

Furthermore the CSG proponent must provide a quantitative uncertainty analysis of their predictions. They must also predict water level and pressure changes at key points throughout the aquifer (see Section 7.2.3).

7.2.2 Assessment Procedures

The Aquifer Interference Policy requires water users to employ specific prediction methodologies to generate the data that will support the approval of their planned activity. The specific requirements are detailed in Aquifer Interference Policy. In summary:

- Production activity requires the application of complex modelling platforms;
- Gateway projects require application of simple modelling tools; and
- Other activities require application of simple modelling tools or desktop assessments.

WRL firmly recommends models with increased complexity must have commensurately complex data collection. The NSW Office of Water procedures for assessment are described in the Aquifer Interference Policy. Draft guidance for the assessment of aquifer interference activity were circulated to the NSW Chapter of the International Association of Hydrogeologists (NSW IAH) on 30th May 2013.

The NSW Office of Water, and the NSW Department of Planning and Infrastructure and the NSW Coal Seam Gas websites are the best source of current information on assessment procedures:

- http://www.water.nsw.gov.au/Water-management/Law-and-policy/Key-policies
- http://www.planning.nsw.gov.au/srlup
- http://www.csg.nsw.gov.au

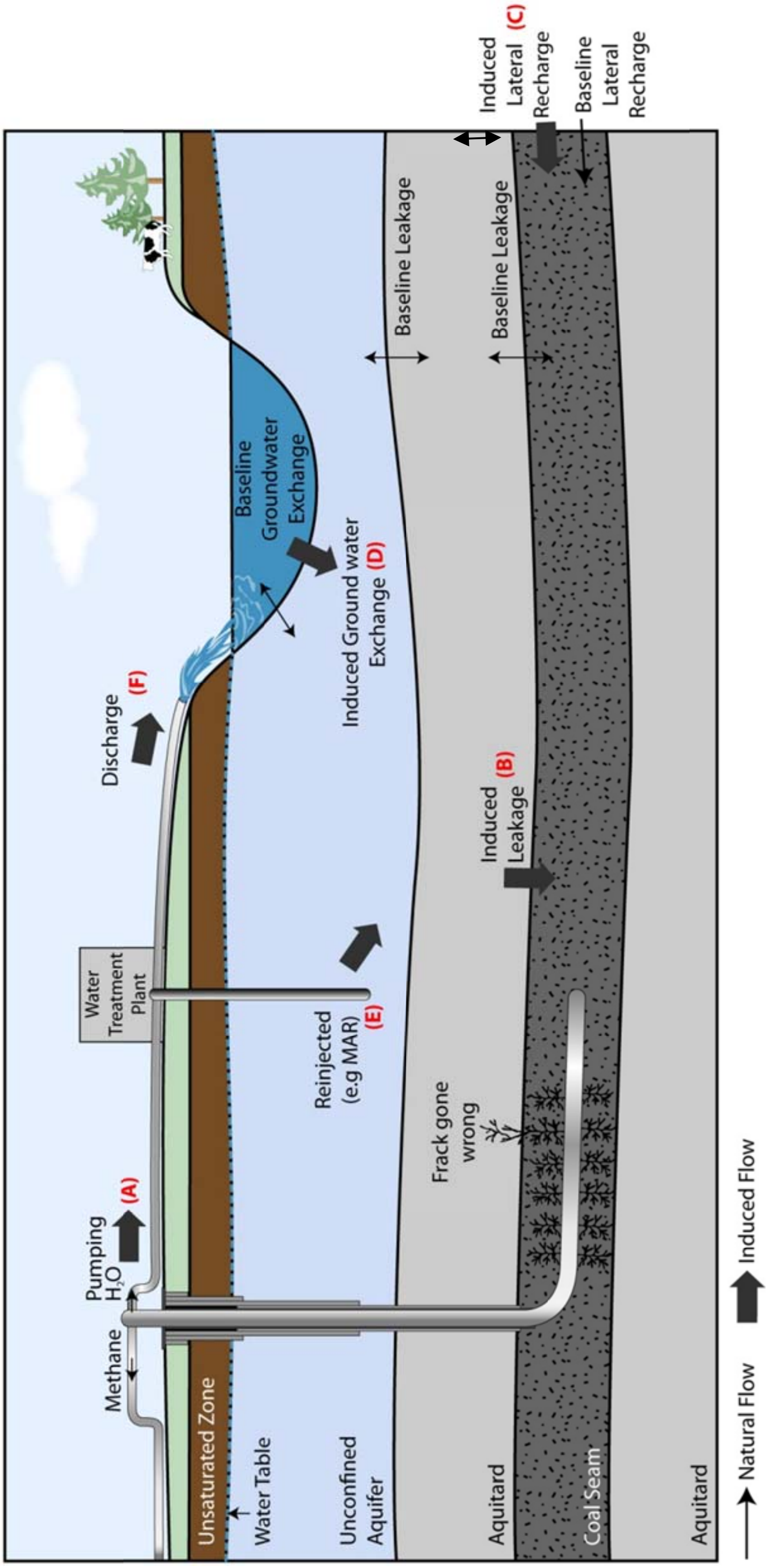


Figure 25: Aquifer Interference Policy - Flows that must be Modelled, and Possibly Licenced, under the Water Management Act 2000

7.2.3 Minimal Harm Criteria

The minimal harm criteria of the Aquifer Interference Policy (NOW, 2012; NOW, 2013f) can be loosely generalised as follows:

- Less than 40% cumulative pressure head decline (up to two m decline in the water table) at any water supply work;
- No more than 10% cumulative change in the water table about Groundwater Dependent Ecosystems (GDEs) and Culturally Significant Sites (CSSs);
- No more than a cumulative 30 m decline in the Surat, Warrego and Central Groundwater Sources and 15 m in the Eastern Groundwater Sources;
- No change to River Condition Index or less than 1% increase in average salinity; and
- No change to the beneficial use category at a distance of 40 m from the activity (unless this change will not prevent the long-term viability of a GDE, CSS or water supply work).

The minimal harm criteria for alluvial and coastal sand groundwater sources are presented in Figure 26 and Figure 27. For other sources see NOW (2013f).

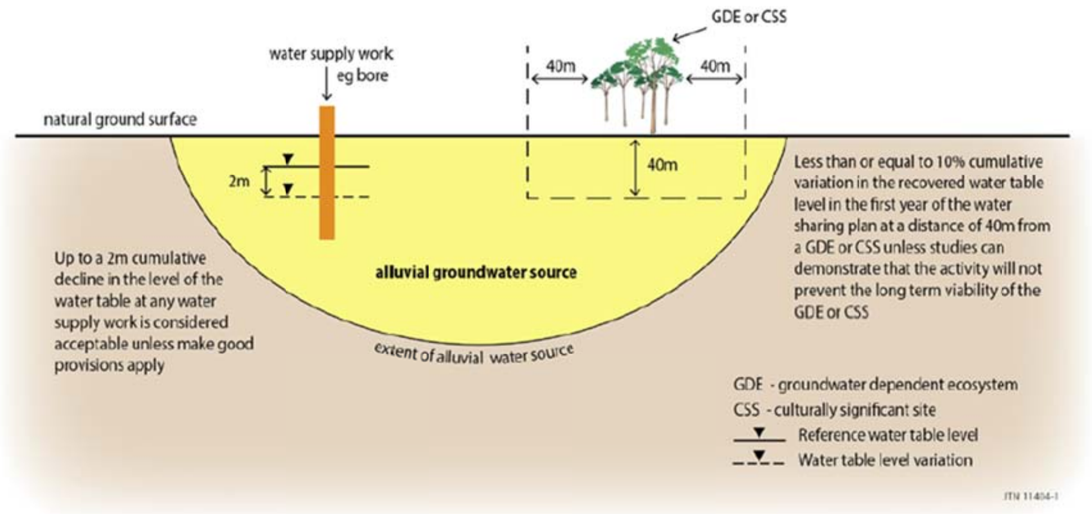


Figure 26: Minimal Harm Groundwater Level Criteria for Alluvial Aquifers (© NOW, 2013f)

These minimal harm criteria constitute guiding principles for the assessment of aquifer interference proposals, not enforceable limits for licenced aquifer interference activity under the minimal harm test of the Water Management Act 2000, which has not been activated for the assessment of impacts (NOW, 2012). This would imply that the success of the aquifer interference policy is dependent on:

- Pre-exploration and pre-production volumetric estimates of CSG produce water;
- Pre-exploration and pre-production model predictions of groundwater impacts; and
- Compliance activities enabled by the *Petroleum (Onshore) Amendment Bill 2013.*

Our review was unable to establish if or when, and under what conditions, the minimal harm test of the Water Management Act 2000 would be activated to support compliance groundwater monitoring activities that may be authorised following concurrence of the *Petroleum (Onshore) Amendment Bill 2013*. This is of concern for many stakeholders (e.g. NSWIC, 2013).

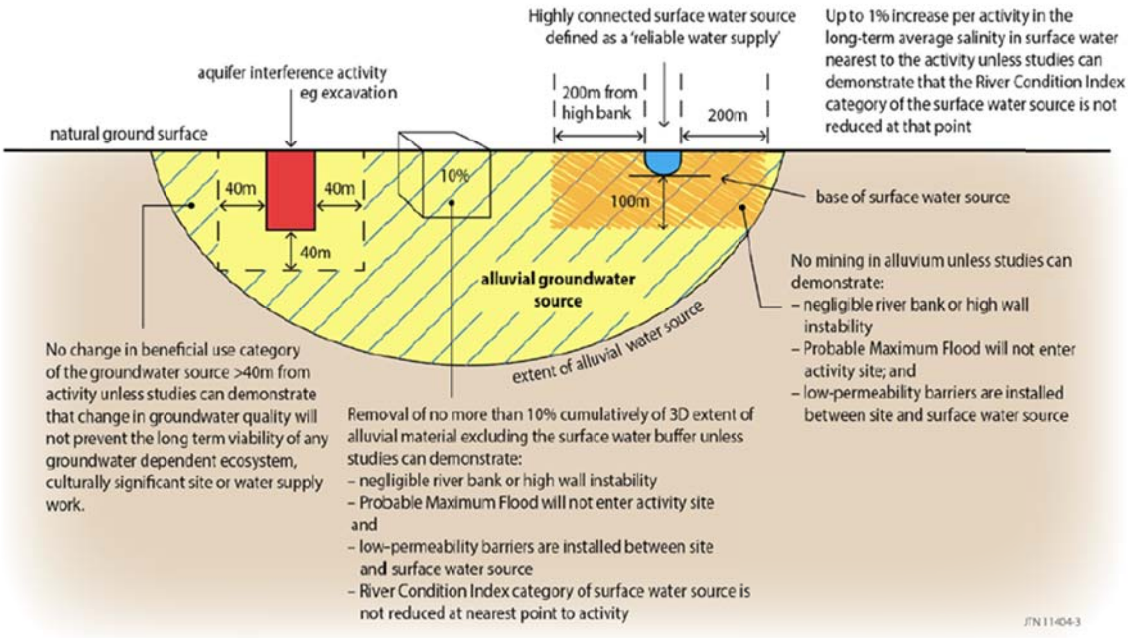


Figure 27: Minimal Harm Groundwater Quality Criteria for Alluvial Aquifers (© NOW, 2013f)

7.2.4 Comments on the Policy

Following the publication of the Aquifer Interference Policy in September 2012 there have been a number of changes in the assessment procedures for coal seam gas projects and additional research and development by industry and government. The policy may need to be updated to reflect these developments.

For example:

1. The policy describes that the groundwater impacts of exploration activity are assessed under Part 5 of the Environmental Planning and Assessment Act 1979 and that DTIRIS may require an applicant to prepare a Review of Environmental Factors (REF). The policy does not place these requirements in the context of new and pre-existing approvals, State Significant Development and exploration activities with more than five wells which may be subjected to an alternate approvals process.
2. The policy does not provide an objective or measurable criteria concerning the assessment of potential changes to hydraulic connectivity stating only: "*The Ministers advice will consider whether bore construction is likely to cause or enhance hydraulic connection between aquifers based on a consideration of whether the 'Code of Practice for Coal Seam Gas Well Integrity' [or 'Code of Practice for Coal Seam Gas Fracture Stimulation'] will be complied with*".
3. Conditions of development consent for petroleum exploration licences (PELs) contain specific definitions for petroleum wells and bores. The Aquifer Interference Policy does not define the word "bore" and does not mention petroleum wells.
4. The Petroleum (Onshore) Act 1991 provides clear definitions of exploration licences, assessment leases and production leases. The policy does not define these activities and does not mention protocols for petroleum assessment activity.

7.3 Co-Produced Water Solutions

Whilst coal seam gas activity has a potential to negatively impact groundwater quantity and quality (Section 4), net increases in water resources are also achievable. Positive outcomes can be achieved by sacrificing some recovered coal seam gas energy to treat the (typically) salty CSG produce water as it is produced and supply it to consumers that would otherwise use groundwater, surface water or town water. See Gore (2013) for a background review concerning CSG produce water.

Potential applications for treated CSG produce water include one or more of:

- Irrigation: to supplement or replace a groundwater or surface water taking;
- Reinjection: into beneficial aquifers for storage until needed (Figure 26E);
- Town Supply: to supplement drinking water supply;
- Controlled discharge: to restore river health (Figure 26F); and
- Dust suppression: to reduce air quality pollution at open cut mines.

With such water management strategies in place and with appropriate protections to prevent or reduce aquifer connectivity with coal seams there is a real potential for coal seam gas activity to halt declines and foster improvements in air quality and groundwater levels and quality, at least for the early stages of a CSG project (Figure 11). Thus, if NSW as a community decides to mine coal seam gas, the principles of sustainable development would dictate that mined water is put to good use, not transported large distances via pipelines or evaporated (without good reason).

The NSW Government recognises these needs as evidenced by:

- A ban on the use of evaporation ponds (NOW, 2013h) which not only wastes the (untreated) water but also creates a risk of contamination to shallow aquifers in the case of pond liner failure; and
- NSW Aquifer Interference Approvals, Groundwater Quality Policies and Environmental Protection Licences which require CSG companies to devise methods and systems to treat CSG produce water to a suitable standard for beneficial reuse.

RPS (2011) summarises the state of co-produced water management practice in Australia during 2010. Recent industry research and development programs by companies such as Santos (2013), Origin (2013) and QGC (2013) demonstrate increased synergies between coal seam gas extraction and co-produced water management practice with a large number of co-produced water reuse trials underway. Some of these trials include the:

- Fairview Irrigation Project - 240 hectares of drip-irrigation of legume forage crops and over 2,000 hectares of Chinchilla white gum to produce forage for 1,500 head of cattle and up to 400 cubic metres of saw logs for milling (Santos, 2013);
- Roma Managed Aquifer Recharge Feasibility Study – Feasibility study by Santos, CSIRO and URS Great to inject up to 3–10 ML/d of treated water into the Great Artesian Basin to reduce draw on Roma's municipal water supplies (Santos, 2013; IAH, 2013);
- Spring Gully (Roma) Irrigation Project – Pongamia plantation to produce farm fodder and bio-diesel (Origin, 2013);
- Tallinga (Chinchilla) Irrigation Project – 530 hectares of irrigated crops such as sorghum, chickpea and lucerne to be mainly used as animal feed (Origin, 2013);
- Condamine River Environmental Flows – Origin Energy are releasing some of the water from the Talinga water treatment facility into the Condamine river to help secure water.

7.4 Cumulative Impacts

In the last two years there has been, and there continues to be, an evolution in the way water practitioners address and manage cumulative impact issues. The single biggest impediment to accurate assessment of cumulative impact is the timely and complete sharing of data. See Intersect (2013) for a discussion of data aspects of CSG. Franks *et al.* (2010) provides a 68 page introduction to cumulative impact concepts and discusses the identification, assessment, management, monitoring and reporting of cumulative impacts. See Rawling and Sandiford (2013) for a background paper on cumulative impacts.

7.4.1 Definition of Cumulative Impact

In a groundwater context cumulative impact can be defined as the net decline or increase in water pressure or quality as a result of all activities. Other definitions include:

- NSW Department of Urban Affairs and Planning: the result of "*a number of activities with similar impacts interacting with the environment in a region…they may also be caused by the synergistic and antagonistic effects of different individual impacts …[and] due to the temporal or spatial characteristics of the activities and impacts*" (NSW DUAP, 2000).
- The University of Queensland: "*the successive, incremental and combined impacts of one, or more, activities on society, the economy and the environment*" (Franks *et al*., 2010).
- Cumulative Impacts Project: "*the total harm to human health and the environment that results from combinations of assaults and stressors over time*" (Cumulative Impacts Project, 2013).
- The Canadian Minister for Public Works and Government Services: "*changes to the biophysical, social, economic, and cultural environments caused by the combination of past, present and 'reasonably foreseeable' future actions*" (Government of Canada, 2013).

7.4.2 National and International Standards

The consideration of cumulative impact issues in mining has been recognised in industry standards and guiding principles for many years (Franks *et al*., 2010):

- International Council on Mining and Metals: *"Assess the positive and negative, the direct and indirect, and the cumulative environmental impacts of new projects – from exploration through closure*";
- International Finance Corporation: Impact assessments should consider "*areas potentially impacted by cumulative impacts from further planned development of the project, any existing project or condition, and other project-related developments that are realistically defined at the time the Social and Environmental Assessment is undertaken; and (iv) areas potentially affected by impacts from unplanned but predictable developments caused by the project that may occur later or at a different location*"; and
- Minerals Council of Australia:
    - "*Predict, assess and monitor emissions to air, land and water, including noise, odour and vibration; ensure design emissions are within standards and guidelines; make project changes as necessary to ensure commissioned site can meet emission standards; provide a basis for future improvements",*
    - "*Undertake social and economic research and assessment in partnership with communities and appropriate organisations to support planning and development of operations with subsequent management review of social and economic effects through the whole cycle",*
    - '*Recognise existing community planning processes and utilise these where feasible*

to achieve mutually beneficial social outcomes. Develop community partnerships and work to secure community ownership of the processes and outcomes.'

7.4.3 National Water Commission Position Statement

In December 2010 the National Water Commission (NWC, 2013) released a position paper stating that the "*potential impacts of CSG developments, particularly the cumulative effects of multiple projects, are not well understood*."

"*The Commission is concerned that CSG development represents a substantial risk to sustainable water management given the combination of material uncertainty about water impacts, the significance of potential impacts, and the long time period over which they may emerge and continue to have effect. Therefore, an adaptive and precautionary management approach will be essential to allow for progressive improvement in the understanding of impacts, including cumulative effects, and to support timely implementation of 'make good' arrangements*."

"*The Commission proposes the following principles be applied by state and territory jurisdictions to managing the cumulative impacts of CSG water:*

- *Adequate monitoring, including baseline assessment of surface and groundwater systems, should be undertaken to provide a benchmark for assessing cumulative impacts on other water users and water-dependent ecosystems.*
- *Jurisdictions should work to achieve consistent approaches to managing the cumulative impacts of CSG extraction. Such arrangements should consider and account for the water impacts of CSG activities in water budgets and manage those impacts under regulatory arrangements that are part of, or consistent with, statutory water plans and the National Water Initiative.*
- *Potential options to minimise the cumulative impacts of extraction on the water balance should be pursued as a first priority. These options include aquifer reinjection, where water quality impacts are acceptable, and groundwater trading or direct substitution for other water use.*
- *Clear accountabilities should be identified for any short- or long-term cumulative impacts from CSG processes, clarifying which organisations are responsible for managing and rectifying or compensating for any impacts.*"

7.4.4 Research and Development Activity

Since the publication of the NWC position statement in December 2010, there has been significant expenditure by a large number of state, federal and non-governmental agencies to develop new frameworks for cumulative impact identification, assessment and management, and to better characterise and model hydrogeological environments.

Contributions to improvements in the management of cumulative impacts have been provided by various university groups (i.e. Franks *et al.,* 2010), the NWC (i.e. Howe, 2011), various committees (i.e. IESC, 2013c), Catchment Management Authorities (i.e. NCMA, 2013), CSG companies, the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Bureau of Meteorology (BOM), the Department of Sustainability, Environment, Water, Population (SEWPaC) Office of Water Science (OWS) and Geoscience Australia (GA).

Presentations and abstracts from the September 2013 International Association of Hydrogeologists (IAH) congress in Perth provide a good perspective of the current state of practice. Research directions in Queensland are summarised in Appendix I of the Surat Underground Water Impact Report (Queensland Water Commission, 2012).

7.4.5 National Partnership Agreement

A major outcome of recent research and development activity has been the establishment of the National Partnership Agreement on Coal Seam Gas and Large Coal Mining Development (NPA).

The Government of South Australia (2013) states:

"*The Agreement strengthens the regulation of coal seam gas (CSG) and large coal mining by informing decisions with best-available science and advice from the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Developments (IESC).*

Under the NPA all coal seam gas or large coal mining proposals must be referred to the IESC for advice if the proposal is likely to have a significant impact on water resources, either in its own right or cumulatively with other actions. As with other stakeholder consultation, IESC advice informs decision-making on licences and conditions.

The IESC aims to improve the collective scientific understanding of the water-related impacts of coal seam gas and large coal mining developments through targeted research and a transparent assessment process. The IESC provides advice on the direct and cumulative impacts of proposed coal seam gas and large coal mining developments across the NPA participating states, allowing a more comprehensive review of potential impacts to water resources, particularly those that cross state boundaries."

7.4.6 Bioregional Assessment Program

The bioregional assessment program is a federal scientific collaboration between SEWPaC, BOM, CSIRO and GA that commenced on 1 July 2013 (GA, 2013e) to "*produce bioregional assessments for six priority* (Figure 28) *regions by 30 June 2016, to underpin advice from the IESC and decision making by regulators on development proposals*" (OWS, 2013).

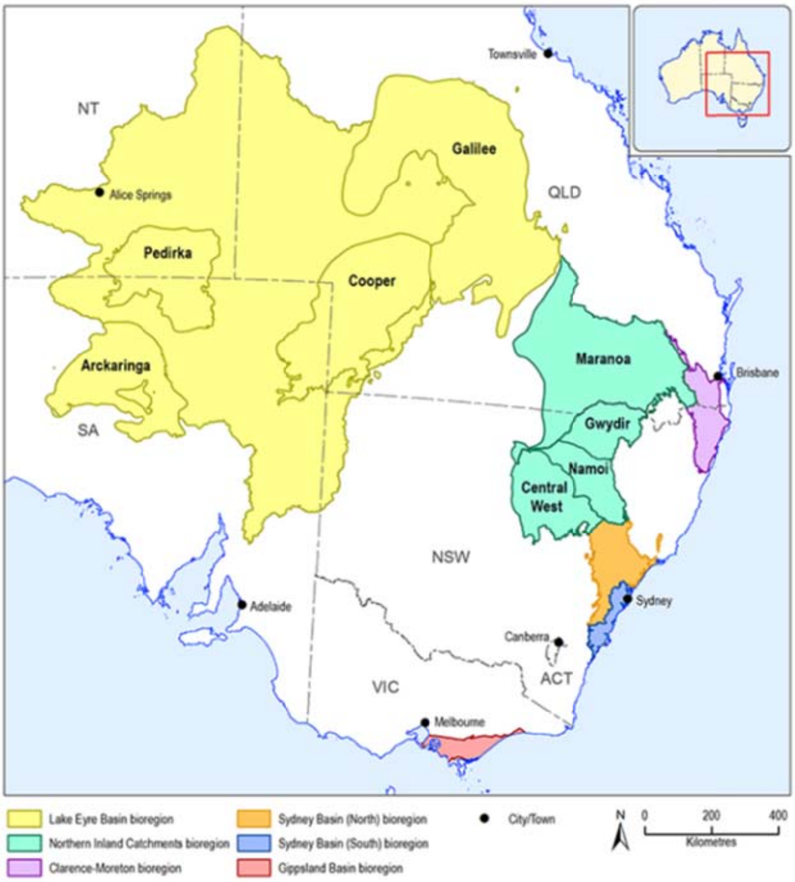


Figure 28: Priority Regions for Bioregional Assessment (© Geoscience Australia, 2013)

The priority regions were established based upon (IESC, 2013d):

- "*the extent of the current level of exploration activity for coal seam gas and the number of current and potential coal seam gas and coal mining developments in these regions,*
- *areas where there is a high level of uncertainty and lack of information and data to assess and understand the potential impacts and cumulative impacts of coal seam gas and coal mining developments; and the presence of water assets of concern to the Australian Government*"

OWS (2013) have indicated that a bioregional assessment is a data gathering exercise to provide a "*scientific analysis of ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of potential direct, indirect and cumulative impacts of coal seam gas and coal mining development on water resources*".

The draft assessment methodology for bioregional assessments is summarised by OWS (2013) in Figure 29.

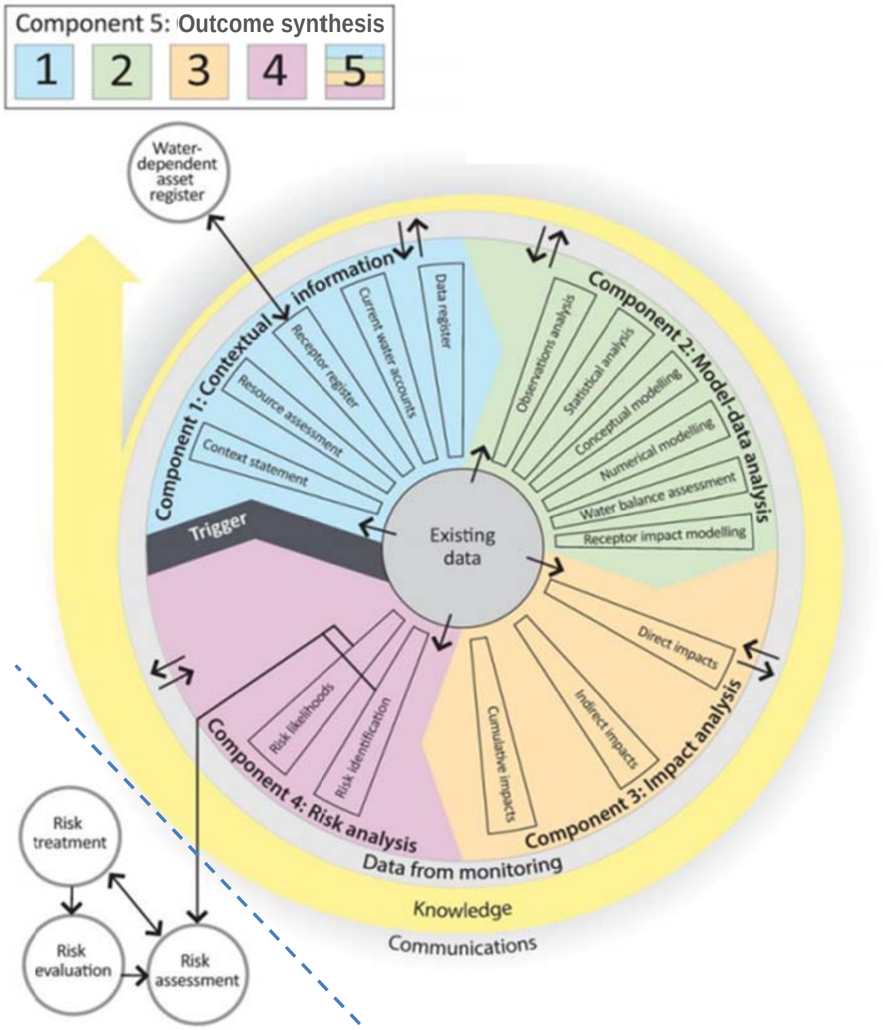


Figure 29: Bioregional Assessment Methodology (© OWS, 2013)

7.4.7 Case Study – Alberta, Canada

In Canada, the Albertan Government have established a guide to groundwater authorisation for aquifer interference activities and a Cumulative Effects Management System (CEMS) (Alberta Environment and Water, 2011, 2013). Groundwater modelling practitioners in Alberta who develop groundwater models for oil sands proposals now routinely supply predictions of groundwater level or pressure impacts at all existing and proposed well locations to Alberta Environment and Water. These predictions are supplied for two scenarios:

1. A relative scenario - prediction of the impacts relative to a baseline scenario that does not explicitly simulate the impacts of other groundwater users; and
2. A cumulative impacts scenario - prediction of absolute impacts including the explicit simulation of all third party groundwater use and activity within the model domain.

Key advantages of this Canadian approach are:

- Groundwater users are encouraged to communicate and exchange data with one another; and
- Alberta Environment and Water build up a database of predicted groundwater impacts at existing and proposed bores from model results supplied by a range of mining companies and consultants utilising various software and model codes. This facilitates better environment management by enabling Alberta Environment to examine the consistency and uncertainty of impacts predicted by individual stakeholders at specific locations.

Other advancements in cumulative impacts management in Alberta have been due to contributions from the Cumulative Environmental Management Association (CEMA), a non-government, multi-stakeholder organisation, established to assist the Government of Alberta to manage the environmental and socio-environmental impacts of oil sands development.

"*CEMA is comprised of more than 50 members who sit on one of four caucuses: Aboriginal, Government, Non Government Organizations and Industry. The membership includes First Nations and Métis Groups, municipal, provincial and federal governments, environmental advocacy groups, educational institutions and the largest group of pit mining and in-situ oil sands operators in the world*" (CEMA, 2013).

Franks *et. al.* (2010) reports that the group receives annual funding from the oil sands industry in the order of CA$8 million and notes some criticism of the organisation's function:

- *"The organisation has been challenged by the difficulty of developing consensus amongst diverse parties on difficult issues and effective administrative and governance systems to help facilitate such agreement."*
- *"The technical nature of the work has also been identified as a barrier to participation*" by some stakeholders."
- The Alberta Government's announcement during 2011 that some of the functions of CEMA would be advanced from within government in an effort to hasten progress.

7.4.8 Case Study – Queensland, Australia

In Queensland the Department of Environment and Heritage Protection (DEHP) have used their *Water Act 2000* (Qld) to allow the chief executive of DEHP to declare Cumulative Management Areas (CMAs) where water extraction by two or more petroleum tenures in a region have a potential to result in cumulative impacts on groundwater (DEHP, 2013b).

"The management of groundwater in Queensland CMAs is overseen and coordinated by the independent Office of Groundwater Impact Assessment (OGIA)… Declaring a CMA enables assessment of future impacts using a regional modelling approach and the development of management responses - such as monitoring programs - that are relevant to the potential cumulative impacts. It also enables responsibilities to be assigned, through the department approved underground water impact report, to each tenure holder in the area for monitoring, bore and baseline assessments, and negotiating make good arrangements… The rights of bore owners within a CMA are not affected by the declaration. If a private water bore has an impaired capacity within or outside the CMA as a result of water extraction by petroleum tenure holders, the petroleum tenure holders must make good the impairment" (DEHP, 2013b).

Key advantages of the Queensland approach are:

- A single regional model for groundwater management;
- Improved communication between stakeholders;
- Less duplication of effort across projects;
- Consistency in management approach;
- Better technical outcomes; and
- Greater transparency.

7.4.9 Case Study – NSW, Australia

For the last thirteen years the NSW Department of Urban Affairs and Planning Coal Mines and Associated Infrastructure EIS Guideline has recommended that mining proponents (NSW DUAP, 2000):

a) "*identify other existing or proposed activities in the area with similar environmental impacts or which are likely to impact on the same elements of the environment (e.g. clearance of the same type of habitat);*
b) *assess the extent to which the environment affected by the proposal is already stressed;*
c) *identify any likely long-term and short-term cumulative impacts, such as air quality, noise or traffic disturbance, visual impacts, surface water and groundwater issues, public health; or loss of heritage items, vegetation or fauna habitat;*
d) *consider the receiving environment's ability to achieve and maintain environmental objectives; and*
e) *consider options for integrating operations with adjoining mines to obtain operational synergies, reduce costs, prevent environmental impacts or lessen land degradation.*"

Following the release of the NSW Aquifer Interference Policy in September 2012 all CSG proponents are now explicitly requested to assess and model the cumulative impact of their planned activity on groundwater levels, groundwater pressure and water quality (NOW, 2012). The NSW Office of Water also state that "*the cumulative impacts of developments on groundwater quality should be recognised by all those who manage, use, or impact on the resource*" and that this statement is a key management principle considered in the administration of the NSW State Groundwater Protection Policy (NOW, 2013g).

In addition to these changes, NSW government regulators may now choose to refer coal seam gas proposals to the IESC for advice which may consider cumulative impact issues. Whilst there are no specific examples of NSW regulators requesting advice from IESC at this time (IESC, 2013), SEWPaC has requested advice from IESC concerning a number of NSW based coal and coal seam gas projects (i.e. Gloucester Coal Seam Gas Project, IESC, 2012).

Most recently the NSW strategic regional land use policy has established a practice of additional consideration and assessment (or exclusion) of coal seam gas projects (and wells) with proximity to particular sensitive pre-existing land uses that may be reliant on groundwater (DP&I, 2013b). This ensures that the contribution of coal seam gas proposals to cumulative groundwater impacts receive more strategic attention in particular regional areas. In other regions, cumulative impacts continue to be considered according to standard practices by CSG proponents and regulators for each and every coal seam gas proposal.

Based on recent discussions with community and industry groups we understand that many NSW stakeholders are currently in a holding pattern awaiting the outcomes of the federal bioregional assessment program which promises to build "*confidence, transparency and community understanding…*" and "*an enduring capacity to produce assessments into the future*" (OWS, 2013).

In the interim, NSW coal seam gas companies need to develop water and impact studies with the aid of a diverse range of specialists. An example of a pilot study water impact report for the Santos Gunnedah Basin CSG Project is Golder (2011). WRL does not endorse any particular report structure or content, however, such reports should at a minimum consider the processes, risks and consequences, and data collection and modelling matters raised in this report.

7.4.10 Comments on NSW Practice

The NSW Environmental Planning and Assessment Act 1979 which is to be replaced (DP&I, 2013) and the *Petroleum (Onshore) Act 1991* make no distinction between cumulative or other impacts (Franks *et. al.,* 2010).

WRL did not identify any specific guidance documents for NSW mining and groundwater modelling practice that concerned cumulative impacts and:

- Management of many wells over a region;
- Assessment of the coincidence of CSG wells and other extractive industries;
- Consideration of drought and flood regime over a coal measure;
- Appropriate modelling and reporting of cumulative impacts;
- Model output requirements for water studies; and
- Minimum data delivery standards to support regulators in their collation, storage and querying of data to manage cumulative impacts.

The lack of guidance may result in some inconsistency and inefficiency in practice across industry, government and consulting practice with possible flow on consequences for the effectiveness of groundwater management.

7.4.11 Comments on Modelling Practice

Groundwater modelling principles are discussed in Section 5.6. In the coal seam gas modelling reports we examined, we did not see much consideration of drought and flood regime and cumulative impact. Most studies adopted a single steady state recharge distribution, sometimes with sensitivity analysis of the recharge parameter. Other studies suggested that climate impact was inconsequential to the relative impacts of a mining operation.

Figure 30 shows 180 years of climate driven water level variations in Lake George, a groundwater dependent lake near Canberra. Water levels in Lake George can be seen to vary by up to seven metres over durations of less than 30 years, the typical duration of a CSG project.

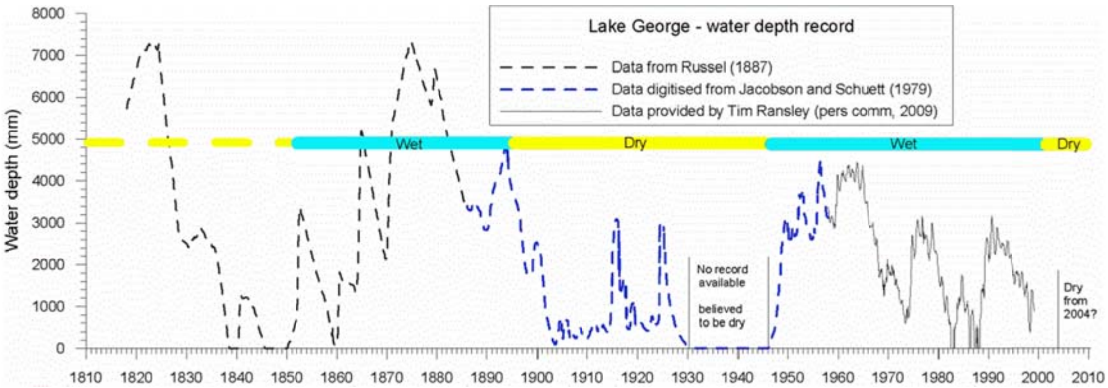


Figure 30: Lake George Water Levels 1820 – 2000 (courtesy of R.I. Acworth)

With minimal harm criteria of no more than two metres of cumulative water level change and potentially large seasonal water level variations due to agricultural activity (Section 6.5.2) it is apparent that, in some environments, there may be some difficulty separating natural climatic variability from the cumulative impacts of human activity. This may have consequences for the subsequent monitoring and enforcement of minimal harm. Numerical models that predict the variability or uncertainty in groundwater levels from climatic oscillations may assist this process.

Additional gaps in Australian hydrogeological modelling practice include:

- The availability (and affordability) of regional groundwater flow and reservoir model codes for the timely simulation of aquifer impacts; and
- The availability of data and up-scaling codes to accurately simulate local-scale aquifer and aquitard heterogeneity in regional groundwater flow models.

These gaps were discussed at the International Association of Hydrogeologists 2013 Congress in Perth and are the focus of active research by the Queensland Office of Groundwater Impact Assessment, Flinders University and CSIRO.

For example, existing modelling codes such as MODFLOW whilst being affordable and fast do not simulate the two phase gas flow that occurs within the vicinity of CSG wells. As a result current MODFLOW models are stated to over-predict the impacts of CSG extraction (if the up-scaling processes are appropriate). In contrast, the more accurate two phase models tend to have licencing costs in the range of $100,000 per year (e.g. ECLIPSE). Two-phase models are also very computationally intensive and require high performance computing solutions. This limits the application of these codes to very well-funded industry, government and consulting groups.

7.5 Mitigation of Impacts

Management strategies and technical solutions to mitigate and/or remediate potential impacts of coal seam gas activity can be grouped into three broad categories:

1. Reducing aquifer connectivity;
2. Mitigating groundwater depletion; and
3. Remediating of groundwater quality impacts.

The literature review did not identify groundwater remediation plans to manage contamination incidents or well degradation, though this does not mean that such plans do not exist. Mechanisms and solutions that can be used to minimise, address or remediate impacts and problems arising from potential water and energy conflicts include:

- Strategic Land Use Planning - solutions to minimise potential groundwater depletion by:
  - Preventing CSG exploration and development in environments with potential for significant connectivity between coal seams and adjacent aquifers, surface water bodies, groundwater dependent ecosystems or culturally sensitive sites;
  - Limiting CSG exploration and development to geological environments that exhibit low water to energy ratios until such time as efficient co-produced water management strategies are developed; and
  - Greater scrutiny for CSG applications about various land uses (i.e. DP&I, 2013b).
- Codes of Practice – Guidance on existing technologies, practices, standards and codes of conduct to minimise accidental aquifer connectivity (i.e. OCSG, 2013a, 2013b).
- Managed Aquifer Recharge - solutions to minimise potential groundwater depletion by treating co-produced water (i.e. reverse osmosis) and:
  - Re-injecting water into beneficial aquifers that are used by, or can be used by, agriculture, industry and water utilities (i.e. Santos, 2013; Origin, 2013);
  - Irrigating crops and pastures to reduce groundwater and surface water reliance (i.e. Santos, 2013; Origin, 2013); and
  - Transporting co-produced water away from an active CSG well and re-injecting that water into a depleted coal seam at some adjacent site.
- 'Make good' arrangements – offers made by CSG companies to water users (i.e. farmers, industries, towns) to maintain or replace a water supply that might be unintentionally impacted by CSG activity (DPI, 2012; Queensland Government, 2012, 2013).
- Security Bonds – payments by CSG companies to governments to encourage good performance or to assist with clean-up of environmental problems (i.e. OCSG, 2013c).
- Improved technologies and methods – to reduce potential aquifer connectivity issues
  - Geological and hydrogeological characterisation and reporting;
  - Modelling aquitard behaviour in regional scale groundwater models;
  - Modelling dual phase flow in regional scale groundwater models;
  - Reporting local and regional hydrogeology;
  - Long-term well integrity, management and maintenance; and
  - Grouting to manage low-frequency, high-consequence events; and
- Groundwater Remediation – contaminated site solutions to improve groundwater quality in case of chemical spills, contamination by flow back water or fraccing fluids or well degradation:
  - Biological and chemical reactive transport barriers; and
  - Pump and treat technology.

7.6 Bore Maintenance

One certain consequence of coal seam gas activity is the issue of ongoing well maintenance. This issue is summarised in NSWLC (2012) as follows: "*Steel rusts, cement deteriorates and the integrity of these wells is compromised by the natural movement of the earth. Long after the gas companies have gone, New South Wales will be left with the maintenance of these wells at considerable ongoing expense*".

An appreciation for the issues and costs surrounding the maintenance and rehabilitation of coal seam gas wells might be gained by considering the analogue for existing groundwater monitoring well networks across NSW and Australia. These issues and costs are described in the National Water Commission Waterline Reports No. 32 (GHD, 2010) and 90 (SKM, 2012).

Modelling work undertaken by SKM (2012) to forecast the attrition of the aging NSW groundwater monitoring network and to predict the costs of maintenance and rehabilitation are reproduced in Figure 31 and Figure 32. The modelling results predict that monitoring, maintenance and replacement costs for NSW's network of 4,556 wells are approximately $10 million dollars per year. These predictions do not include projections for any additional monitoring required for new coal seam gas wells.

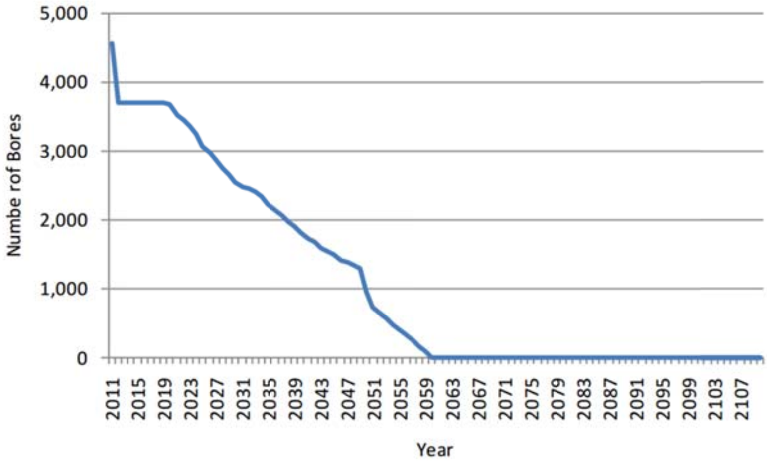


Figure 31: Forecast Attrition of NSW Groundwater Monitoring Assets (© NWC, 2012c)

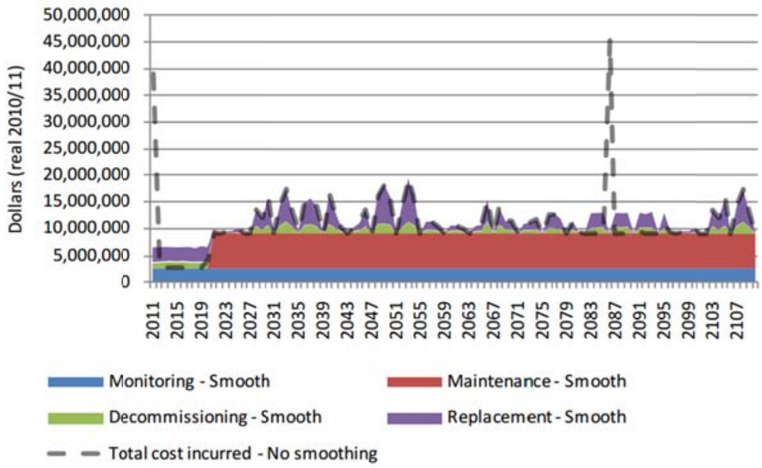


Figure 32: Predicted Monitoring Well Replacement Costs for NSW (© NWC, 2012c)

When considering these groundwater monitoring well analogues the APPEA advised the NSW Government Inquiry into coal seam gas that relative to groundwater bores, best practice "CSG wells are constructed and completed to a significantly higher standard to ensure well isolation and control" (NSWLC, 2012).

In AGL's submission to the inquiry AGL supported the view that CSG wells are constructed and completed to a higher standard by citing the minimal degradation of the cement and casing in their 'sweet gas' wells which date back many decades (NSWLC, 2012).

Mr O'Brien of Metagasco advised the inquiry that the steel casing of a decommissioned CSG well should not corrode for an 'extensive' time period because of the limited potential for oxygen to enter the well. He also noted that any corrosion of the steel due to contact with oxygenated groundwater would result in expansion of the well and that this could actually assist the rehabilitation (NSWLC, 2012).

7.7 International Lessons

Following groundwater studies of the Powder River Basin in Wyoming (USA), Frost *et. al.* (2002) stated that "the effects of the withdrawal of large quantities of groundwater from coal-rich aquifers and the degree of communication between coal and sand aquifers are not well known". Frost *et. al.* (2002) attributed this uncertainty to the very complex stratigraphic nature of coal seam beds that "merge, split and pinch out within several kilometres".

It is now widely acknowledged that the discontinuous nature of coal seams hampers the development of detailed groundwater flow models (Frost *et. al.,* 2002) and reduces the certainty of groundwater impact predictions. Related comments on geological uncertainty have also been made regarding the presence of factures and faults and connectivity between aquifers and coal seams in NSW (i.e. Pells, 2013).

On the coal bed methane (CBM) experience in the USA Moore (2012) reported that "*often the time to understand the geological framework of a CBM reservoir is undervalued and thus neglected. Characterisation of geological influences on a CBM reservoir may be subtle, but are no less important or worthwhile than understanding the vagaries of the market the gas may be sold into*".

Weeks (2004) describes the difficulties associated with interpreting unconventional gas aquifer tests in the Powder River Basin of Montana and provides recommendations for locating observation wells near pumping wells.

In Australia these lessons, and those of Queensland, have resulted in the establishment of research and development programs (Section 7.3.4) to better understand these discontinuities and to appropriately upscale and parameterise the new knowledge in updated and revised groundwater flow models. An example of these research programs include the Walloon Coal Measures and Condamine Alluvium Connectivity studies being run by the Queensland Office of Groundwater Impact Assessment (OGIA, 2013).

7.8 Best Practice

In the context of groundwater resources, WRL technical experts consider the key elements of international best practice in water management to be the functional coexistence of research programs, training programs, codes of practice, policies, plans, regulations and Acts. By functional existence we mean an effective system that communicates and integrates the best aspects of practice that can be devised by government, industry, professional bodies, training groups, research institutions, water users and the general public.

It is our view that international best practice encourages the development of unconventional gas resources whilst protecting and sustainably developing water resources. Best practice protection of the water resource would ensure and enforce no more than minimal harm. Best practice sustainable development of the water resource would involve the treatment and local recycling of produce-water for beneficial use to reduce demands on existing surface or groundwater resources that may, or may not be, over allocated.

The following list summarises how current NSW and Federal water management and legislative frameworks, encourage and enforce various elements of international best practice in NSW:

- **Public Input to, and Scrutiny of, the Approvals Process:** The establishment of the NSW Land and Water Commissioner and the announcement that NOW recommendations for Aquifer Interference Approvals must be published in the public domain, are positive reforms for NSW Water Management Practice. There is also the ability for people to comment on Environmental Impact Statements for State significant development under S89F of EP&A Act 1979.

- **Baseline Monitoring and Reporting Practice:** A legal requirement for the collection and analysis of baseline monitoring of groundwater, surface water and air data (including isotopes and dissolved gases) to inform the progression of energy resource development activities is international best practice. The reforms that allow NOW to request and consider monitoring data in the approvals process are a positive contribution to NSW water management practice. The level of discretion and lack of enforceability of these provisions (Section 7.6) is not best practice.

- **Timely Access to Monitoring Data:** We consider international best practice to be the provision of monitoring data online in near 'real-time' in a readily accessible database format. We understand that NSW CSG companies are only required to report monitoring and compliance data in annual reports. This is not international best practice.

- **Objective (Fact Based) Approvals:** We consider the objective (fact-based) minimal harm criteria and risk-assessments requested for CSG activities by the NSW Office of Water in the Aquifer Interference Policy to be leading practice. The lack of enforceability of these provisions (Section 7.4) is not leading practice.

- **Research and Development:** This aspect of best practice appears to be managed by the National Water Commission (NWC) and the $150 million in funding that was provided to the Independent Expert Scientific Committee (IESC, 2013a). NSW Government has received $17.5 million in funding from the National Partnership Agreement (NPE, 2012) to implement outcomes of the research and development programs. The NSW Office of the Chief Scientist and Engineer are also contributing to this process (OCSE, 2013). The National Centre for Groundwater Research and Training (NGCRT) has been pursuing fundamental and applied research applicable to CSG extraction including: numerical modelling of CSG basins including semi-saturated and dual phase flow; 3D geological modelling that includes genetic processes and scaling up of hydraulic conductivity from point to regional scale; and flow and reactive transport processes in low permeability overburden strata, including dissolved gas permeability.

- **Training for Practitioners:** We understand this topic is receiving the attention of the NWC, IESC and NSW Government. Training is further discussed in Section 5.7. NSW Office of Water circulated a draft assessment framework for the new Aquifer Interference Policy to NSW members of the International Association of Hydrogeologists (IAH) on 30th May 2013. WRL staff are not aware of formal training policies in relation to CSG.

- **Knowledge of Regional Hydrogeology**: Best practice water management requires a good understanding of regional hydrogeology and direct assessment of aquitard integrity. Timms *et al.* (2012) reports that current assessment of aquitard integrity is not best practice. NSW can learn from research being conducted by the QLD Office of Groundwater Impact Assessment. The Federal bioregional assessment program (IESC, 2013b) and Office of Water Science is working to address regional understanding through a collaboration project managed by CSIRO, BOM and GA. This project is due for completion in 2016.

- **Risk Assessment and Management:** Exploration, assessment and production activity is conducted in the face of uncertainty. The current approvals process and aquifer interference policy recognises this uncertainty and implements risk assessment and risk management procedures (PAC for State Significant Development, Gateway Panel for strategic agricultural land and critical industry cluster land, and minimal harm risk assessments for Aquifer Interference Approvals). While this might be best practice for the current legal framework, we consider that the current systems and process that encapsulate this framework are not leading practice (see below). The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) is working to address this matter through the Federal bioregional assessment program.

- **Regulation of Exploration and Assessment Activity:** It is our professional opinion that 'unchecked' petroleum well installation and fraccing activity has the highest risk of creating a permanent increase in the hydraulic connectivity between coal seams and beneficial aquifers. We also consider there to be no clear difference in the risk of water resource aquifer depletion between pilot testing and production activity. The risk of depletion depends solely on the hydraulic connectivity and the volumes of water removed (Section 4.2) and we have heard anecdotal reports of pilot testing operations that have run for many years. The current legal and approvals framework, which focuses effort on assessment of production activity, does not appear to recognise this balance of risk. It is our view that best practice water management provides a commensurate assessment of risk across all activity.

- **Consideration of Cumulative Impacts:** The NSW Aquifer Interference Policy requests that proponents assess the groundwater level and salinity impact of their planned activity in the context of all activities affecting their PEL. This is leading practice. The inability of NOW to enforce this request (see Section 7.6) and the lack of NSW policy, guidance, training and codes of practice for the assessment of cumulative groundwater impacts is not leading practice. We understand that this matter is currently being addressed through interactions between State and Federal Government (Howe, 2011) and the activities of various NSW Catchment Management Authorities (NCMA, 2013).

- **Codes of Practice:** NSW now has draft codes of practice for CSG exploration and codes of practice for well integrity and fraccing. A separate code of practice is being developed in relation to training and certification for the CSG industry (DTIRIS 2012b). We could not find NSW guidelines and codes of practice for monitoring and assessment of cumulative impacts. Compared to the UK, NSW may be missing aspects of guidance in relation to: suspension and abandonment of wells; well operators on well examination; well operators on competencies of well examiners; and competency for wells personnel (UKOOG, 2013). These UK guidelines strictly apply to shale gas activities but they may have relevance for CSG activity.

- **Regulation of Codes of Practice:** The announcement of legislative reform to make NSW codes of practice legally binding conditions for CSG Explorations is positive. This appears to have some similarities with current UK practice (see UKOOG, 2013 for summary). The lack of regulation of codes of practice for existing licences (see Section 7.6) is not leading practice.

- **Compliance:** Best practice is to implement effective monitoring and compliance systems with regulatory capacity for compliance. It also implements appropriate legislated responses for offenders. We have not had an opportunity to explore this matter in detail nor compare regulatory capacity in NSW to other jurisdictions. We note that DTIRIS require substantial bonds from CSG Exploration (DTIRIS, 2012c) and that reforms are in progress for improving auditing and compliance (see Section 7.1.1). This is in accordance with leading practice.

- **Transparent Legislation and Approvals Process:** We consider NSW's current framework for CSG activity approvals and water resources protection to be complex, (see Section 7.6). We count numerous Acts, plans, regulations, policies, guidelines and codes of practice governing CSG activity. This appears to be a fragmented framework which may result in inconsistent water management practice in geological basins that cross state borders. Experience in the Murray Darling Basin has demonstrated that this is not best practice.

- **Review and Reform of Legislative Framework:** The NSW Code of Practice for Coal Seam Gas Well Integrity contains provisions for the review and reassessment of the code in September 2013 and then again every two years. This is leading practice and it will allow NSW Government to review the codes in the context of the new United Kingdom Codes of Practice (UKOOG, 2013) published this year. We consider that the legislative review process and the adaptive policies in place in NSW, in response to the QLD experience and public concern, to be indicative of a functional legislative framework. In light of the cross-border nature of groundwater basins, we consider the pursuit of a national harmonised regulatory framework for CSG by the Standing Committee on Energy Resources (SCER, 2013) to be an example of leading practice.

- **Communication of Water Management Practice:** While we are not aware of online Government resources that succinctly and clearly communicate the timeline and objective of NSW water management reform, we consider the new Office of Coal Seam Gas and their new CSG website (csg.nsw.gov.au) to be an excellent public resource with great potential. It has similarities with leading practice in QLD, specifically their establishment of a 'one-stop CSG shop' (the LNG unit in QLD) in government (NSWLC, 2012).

- **Protection of Water Resources in Petroleum and Mining Legislation:** We consider the protection and sustainable development of water resources in CSG activity to be international best practice and that this objective should be enshrined in Petroleum and Mining Legislation. The lack of consideration of water resources and codes of practice in the *Petroleum (Onshore) Act 1991* (see section 7.1.1) and the absence of quantifiable licencing conditions for groundwater matters in PELs, PPLs etc. is not leading practice. NSW should look to the *Petroleum (Onshore) Act (UK)* for potential improvements.

- **Law and Policy to Encourage Treatment and Local Re-use of Process-water:** Earlier QLD policy and law classified CSG process water as a waste and this may have contributed to the proliferation of a practice of discharging and storing CSG process water in evaporation ponds. The NSW ban on evaporation ponds is encouraging. Leading practice in QLD is a policy that specifically encourages the treatment and beneficial re-use of CSG process water rather than disposal (DEHP, 2013).

7.9 General Comments

General comments on NSW Water Management Practice are provided below:

1. The process for granting water approvals for mining and unconventional gas activity in NSW can be different to those used for other water users.
2. Petroleum legislation and regulation encourages exploration, assessment and production activity. Current NSW environmental legislation, regulation and policies encourages CSG companies to demonstrate sound water management practice. Whilst these requirements are significantly greater during the production stages than the exploration and assessment stages, some stakeholders argue that the relative risks of exploration and assessment may not be significantly less than the production (i.e. Potts, 2012).
3. From our review ambiguities exist as to whether baseline monitoring and well completion (monitoring, pilot, stratigraphic, core) data collected during exploration was independently reviewed or certified by government or the NSW Office of Water prior to the approval of hydraulic fracturing or pilot testing activity and/or the granting of Aquifer Interference Approvals (AIAs). It was also apparent that AIAs might not be required for all activities. Independent peer review is an important component of the scientific process.
4. WRL considers hydraulic fracturing and pilot testing to be inherently more risky than other forms of exploration activity (i.e. geophysics) and no less risky than production activity. This assessment is based on our interpretations of groundwater responses to CSG activity (Section 3.7) and potential worst case scenarios (Section 4.6).

   On this basis, it is understandable why some stakeholders (i.e. Potts, 2012) might suggest that hydraulic fracturing and pilot testing activity require checks and balances similar to those used for production activity. Potts (2012) has suggested that pilot testing activity be undertaken under the assessment lease construct, rather than the exploration licence construct of the Petroleum (Onshore) Act 1991, presumably to provide some additional distinction between activities with different risks.
5. Current professional practice for groundwater assessment in NSW typically involves the identification, sourcing, compiling, quality control and analysis of groundwater data from data CDs and numerous paper reports by many government and industry groups

published over many years. This is an inefficient and time consuming process. This process is often repeated in isolation for different projects by independent professionals.

Groundwater management practice in NSW would be improved by updated infrastructure (boreholes, data-loggers, data transmission networks etc.) collecting real-time information on groundwater use, pressure, level and quality and technology platforms that deliver groundwater data to the general and professional community in an online geo-spatial format on demand. These data collection and reporting platforms are essential for best practice and for improved management practice.

For more detailed discussions of CSG and data management see Intersect (2013).

6. Uncertainties concerning the impacts of coal seam gas operations arise from the non-uniqueness problems described throughout this report and can be minimised through data collection. Best practice should include large data collection and modelling programs. The potentially large expense in collecting such data and modelling hydrogeological systems should not be used as a reason to not minimise uncertainties in potential groundwater responses.

7.10 Further Reading

NSW Government Sites:

Office of the NSW Chief Scientist and Engineer:
http://www.chiefscientist.nsw.gov.au/coal-seam-gas-review/

Office of Coal Seam Gas: http://csg.nsw.gov.au

Legislation: http://www.legislation.nsw.gov.au/

Planning: http://www.planning.nsw.gov.au/legislation-and-planning-instruments

Planning Reform: http://www.planning.nsw.gov.au/exposurebills

Environment: http://www.environment.nsw.gov.au/legislation/poelegisamend2011.htm

Aquifer Interference Policy: http://www.water.nsw.gov.au/Water-management/Law-and-policy/Key-policies/Aquifer-interference/Aquifer-interference

Strategic Regional Land Use Policy: http://www.planning.nsw.gov.au/srlup

Gateway Process: http://www.planning.nsw.gov.au/gateway-process

Research, State and Federal Collaboration and National and International Practice:

Independent Expert Scientific Committee on Coal Seam Gas:
http://www.environment.gov.au/coal-seam-gas-mining/

NSW Standing Committee on Energy Resources:
http://www.scer.gov.au/workstreams/land-access/coal-seam-gas/

Management of Cumulative Impacts by Namoi CMA:
http://www.namoi.cma.nsw.gov.au/41885.html?5

National Water Commission: http://nwc.gov.au/, http://archive.nwc.gov.au/library/

QLD Coal Seam Gas Water Management:
http://www.ehp.qld.gov.au/management/non-mining/csg-water.html

Queensland Office of Groundwater Impact Assessment: http://www.dnrm.qld.gov.au/ogia

SEWPaC: http://www.environment.gov.au/water/index.html

UK Practice: http://www.ukoog.org.uk/elements/pdfs/ShaleGasWellGuidelines.pdf

Recent Commentary on CSG and NSW Water Management Reform:

New South Wales Irrigators Council:
http://gallery.mailchimp.com/c6e5c2d75b14461767c095feb/files/130926_Coal_Seam_Gas_Requirements.pdf

Sydney Morning Herald:
http://www.smh.com.au/business/to-frack-or-not-to-frack-20131013-2vgo3.html

Australia Institute:
http://www.edo.org.au/edonsw/edonsw/site/pdf/pubs/130826CoalandgasmininginAustralia.pdf

Clayton Utz Insights:
http://www.claytonutz.com/publications/edition/23_may_2013/20130523/nsw_planning_reforms_streamlining_approvals_code_assessment_development.page

http://www.claytonutz.com/publications/edition/14_march_2013/20130314/major_new_controls_on_water_impacts_from_mining_and_csg_projects.page

Environmental Defenders Office Policy Submissions:
http://www.edo.org.au/edonsw/site/policy_submissions.php#3

Institute for Sustainable Futures:
http://www.isf.uts.edu.au/publications/rutovitzetal2011sydneycoalseamgasbkgd.pdf

NSW Parliament Coal Seam Gas Inquiry:
http://www.parliament.nsw.gov.au/Prod/parlment/committee.nsf/0/29AE48525CFAEA7CCA2578E3001ABD1C

MaryLou Potts Commentary:
http://www.mlppl.com.au/publications.html

Office of the Chief Scientist of NSW Background Papers:
http://www.chiefscientist.nsw.gov.au/coal-seam-gas-review/csg-background-papers

Office of the Chief Scientist of NSW Public Submissions:
http://www.chiefscientist.nsw.gov.au/coal-seam-gas-review/public-submissions

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APPENDIX A – Lookup Table for Petroleum Titles and Water Sharing Plans

A.1 NSW Petroleum Titles and Petroleum Title Applications

Figure B1 plots petroleum titles and petroleum title applications registered in the DTIRIS MinView Database on 18 August 2013 (DTIRIS, 2013c; 2013d). Applications by the Aboriginal Land Council of NSW which cover a significant portion of the state are excluded.

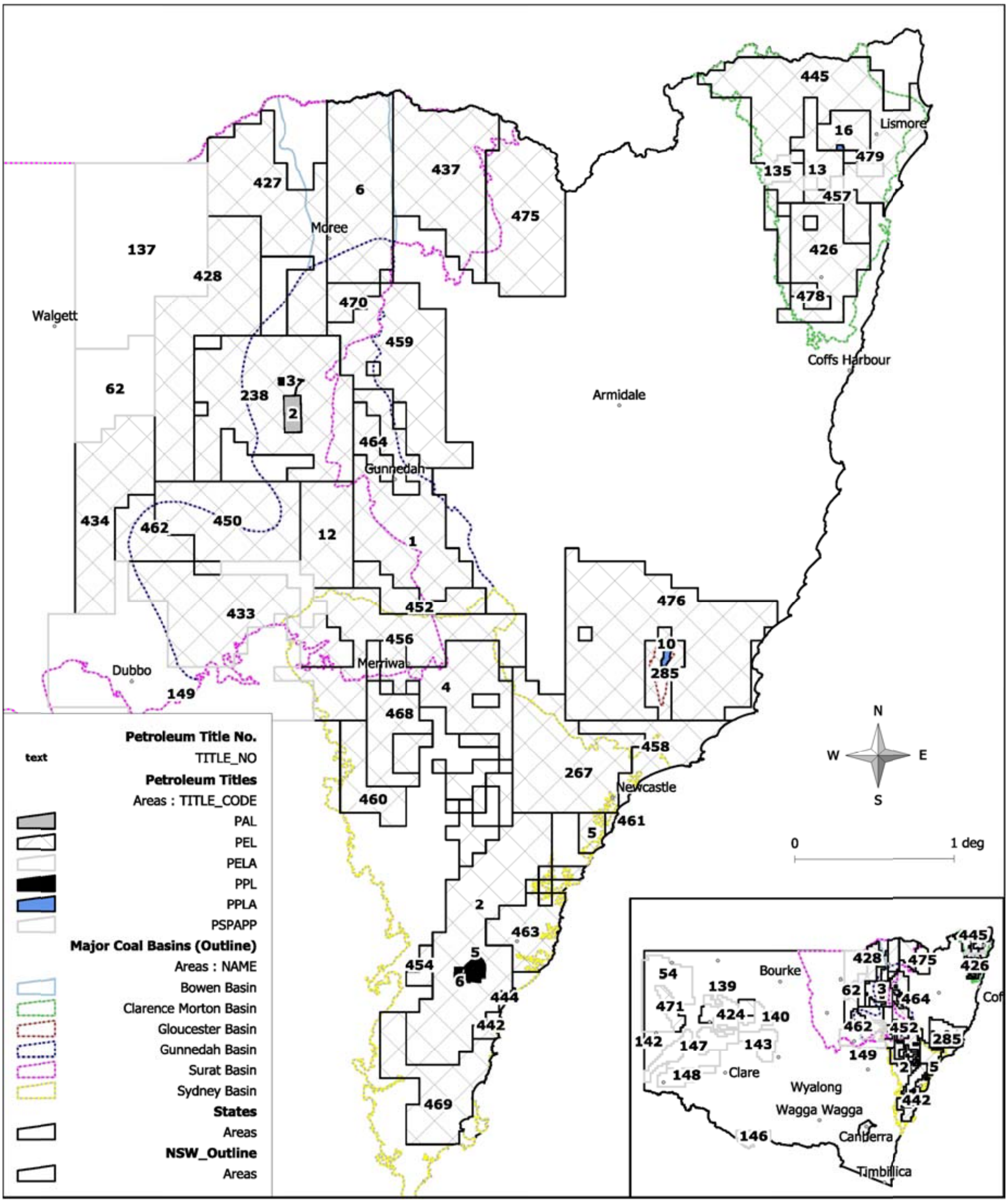

Figure B1: NSW Petroleum Titles and Petroleum Title Applications (August 2013)

A.2 Lookup Tables for Water Sharing Plans

These lookup tables identify water sharing plan areas and groundwater sources that fall within NSW petroleum titles and petroleum title applications, based on a March 2013 GIS dataset provided to WRL by the NSW Office of Water. With these tables the NSW Office of Water website can be consulted to retrieve water sharing plan information relevant to Petroleum Title or Petroleum Title Applications publicised in the DTIRIS MinView database on 18 August 2013.

To use the lookup tables:

1. Identify the petroleum title of interest on Figure B1 (noting the title code label).
2. Lookup the corresponding water sharing plan name from the relevant table below:
    a. Table B1 for PPL, PPLA and PALs
    b. Table B2 for PELs
    c. Table B3 for PELAs.
3. Proceed to the NSW Office of Water website:

   http://www.water.nsw.gov.au/Water-management/Water-sharing/default.aspx
4. Follow the links to commenced or draft water sharing plans and download the relevant PDF files (normally the Background Document and/or the Guide to the Plan).

The downloaded documents may provide descriptions of the groundwater sources and Groundwater Management Areas within each Water Sharing Plan, details of groundwater availability and references to further reading material.

Some polygons in the water sharing plan GIS dataset provided by NOW were attributed with the phrase “water” rather than the name of a water sharing plan. If these “water” features intersected a PPL, PPLA, PAL, PEL or PELA it is listed in Table B1, B2 and B3.

Table B1: Water Sharing Plans Applicable to Petroleum Production and Assessment Activity

Title Code	Company	Petroleum Title	Applicable Water Sharing Plans (March 2013)[1]
Production (PPL)	AGL UPSTREAM INVESTMENTS PTY LIMITED	PPL0001	Greater Metropolitan Region Groundwater Sources 2011
		PPL0002	Greater Metropolitan Region Groundwater Sources 2011
		PPL0004	Greater Metropolitan Region Groundwater Sources 2011
		PPL0005	Greater Metropolitan Region Groundwater Sources 2011
		PPL0006	Greater Metropolitan Region Groundwater Sources 2011
	SANTOS NSW (HILLGROVE) PTY LTD	PPL0003	NSW Great Artesian Basin Groundwater Sources 2008
			Upper and Lower Namoi Groundwater Sources 2003
Application for Production (PPLA)	METGASCO LTD	PPLA0009	Draft North Coast Fractured and Porous Rock Groundwater Sources
			Richmond River Area Unregulated, Regulated and Alluvial Water Sources 2010
	AGL UPSTREAM INVESTMENTS PTY LIMITED	PPLA0010	Draft North Coast Fractured and Porous Rock Groundwater Sources
			Karuah River Water Source 2003
			Lower North Coast Unregulated and Alluvial Water Sources 2009
Assessment (PAL)	SANTOS NSW PTY LTD	PAL0002	NSW Great Artesian Basin Groundwater Sources 2008

1. Table prepared from a topological overlay of geospatial data provided by DTIRIS (2013c; 2013d) and NOW (2013f). For up to date data contact DTIRIS and NOW.

Table B2: Water Sharing Plans Applicable to Petroleum Exploration (includes Pilot Testing)

Company	Petroleum Title	Applicable Water Sharing Plans (March 2013) [1]
ACER ENERGY LIMITED	PEL0422	Barwon Darling Unregulated and Alluvial Water Sources 2012
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
	PEL0424	Barwon Darling Unregulated and Alluvial Water Sources 2012
		Intersecting Streams Unregulated and Alluvial Water Sources 2011
		NSW Great Artesian Basin Shallow Groundwater Sources 2011
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
	PEL0471	North Western Unregulated and North Western Fractured Rock Groundwater Water Sources 2011
		NSW Great Artesian Basin Shallow Groundwater Sources 2011
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
AGL UPSTREAM INVESTMENTS PTY LIMITED	PEL0002	Central Coast Unregulated Water Sources 2009
		Draft North Coast Fractured and Porous Rock Groundwater Sources
		Greater Metropolitan Region Groundwater Sources 2011
		Hunter Unregulated and Alluvial Water Sources 2009
		Kulnura Mangrove Mountain Groundwater Sources 2003
		Water
	PEL0004	Draft North Coast Fractured and Porous Rock Groundwater Sources
		Greater Metropolitan Region Groundwater Sources 2011
		Hunter Unregulated and Alluvial Water Sources 2009
		Wybong Creek Water Source 2003
	PEL0005	Central Coast Unregulated Water Sources 2009
		Draft North Coast Coastal Sands Groundwater Sources
		Draft North Coast Fractured and Porous Rock Groundwater Sources
		Hunter Unregulated and Alluvial Water Sources 2009
	PEL0267	Draft North Coast Coastal Sands Groundwater Sources
		Draft North Coast Fractured and Porous Rock Groundwater Sources
		Greater Metropolitan Region Groundwater Sources 2011
		Hunter Unregulated and Alluvial Water Sources 2009
		Kulnura Mangrove Mountain Groundwater Sources 2003
		Tomago Tomaree Stockton Groundwater Sources 2003
		Water
	PEL0285	Draft North Coast Fractured and Porous Rock Groundwater Sources
		Karuah River Water Source 2003
		Lower North Coast Unregulated and Alluvial Water Sources 2009
APEX ENERGY NL	PEL0442	Greater Metropolitan Region Groundwater Sources 2011
		Water
	PEL0444	Greater Metropolitan Region Groundwater Sources 2011
	PEL0454	Greater Metropolitan Region Groundwater Sources 2011
		Water
AUSTRALIAN COALBED METHANE PTY LIMITED	PEL0001	Namoi Unregulated and Alluvial Water Sources 2012
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
		Peel Valley Regulated, Unregulated, Alluvium and Fractured Rock Water Sources 2010
		Upper and Lower Namoi Groundwater Sources 2003
	PEL0012	NSW Great Artesian Basin Groundwater Sources 2008

Company	Petroleum Title	Applicable Water Sharing Plans (March 2013) [1]
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
		Upper and Lower Namoi Groundwater Sources 2003
B.N.G. PTY. LTD.	PEL0445	Alstonville Plateau Groundwater Sources 2003
		Draft Brunswick Unregulated and Alluvial Water Sources
		Draft Clarence Unregulated and Alluvial Water Sources
		Draft North Coast Coastal Sands Groundwater Sources
		Draft North Coast Fractured and Porous Rock Groundwater Sources
		Richmond River Area Unregulated, Regulated and Alluvial Water Sources 2010
		Tweed River Area Unregulated and Alluvial Water Sources 2010
		Water
		Water Sharing Plan for the Coopers Creek Water Source 2003
CLARENCE MORETON RESOURCES PTY LIMITED	PEL0457	Draft Clarence Unregulated and Alluvial Water Sources
		Draft North Coast Coastal Sands Groundwater Sources
		Draft North Coast Fractured and Porous Rock Groundwater Sources
		Richmond River Area Unregulated, Regulated and Alluvial Water Sources 2010
		Water
	PEL0478	Draft Clarence Unregulated and Alluvial Water Sources
		Draft North Coast Fractured and Porous Rock Groundwater Sources
		Water
	PEL0479	Draft North Coast Fractured and Porous Rock Groundwater Sources
		Richmond River Area Unregulated, Regulated and Alluvial Water Sources 2010
		Water
COMET RIDGE GUNNEDAH PTY LTD	PEL0006	Gwydir Unregulated and Alluvial Water Sources 2012
		Lower Gwydir Groundwater Source 2003
		NSW Great Artesian Basin Groundwater Sources 2008
		NSW Great Artesian Basin Shallow Groundwater Sources 2011
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
COMET RIDGE LTD	PEL0427	Lower Gwydir Groundwater Source 2003
		NSW Great Artesian Basin Shallow Groundwater Sources 2011
		Upper and Lower Namoi Groundwater Sources 2003
	PEL0428	Lower Gwydir Groundwater Source 2003
		NSW Great Artesian Basin Groundwater Sources 2008
		NSW Great Artesian Basin Shallow Groundwater Sources 2011
		Upper and Lower Namoi Groundwater Sources 2003
DREQUILIN PTY LIMITED	PEL0475	NSW Border Rivers Unregulated and Alluvial Water Sources 2012
		NSW Great Artesian Basin Groundwater Sources 2008
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
		Draft North Coast Coastal Sands Groundwater Sources
LEICHHARDT RESOURCES PTY LTD	PEL0468	Draft North Coast Fractured and Porous Rock Groundwater Sources
		Greater Metropolitan Region Groundwater Sources 2011
		Hunter Unregulated and Alluvial Water Sources 2009
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
	PEL0469	ACT
		Draft Clyde River Unregulated and Alluvial Water Sources 2013
		Draft South Coast Groundwater Sources
		Greater Metropolitan Region Groundwater Sources 2011

Company	Petroleum Title	Applicable Water Sharing Plans (March 2013) [1]
		Water
	PEL0470	NSW Great Artesian Basin Groundwater Sources 2008
		NSW Great Artesian Basin Shallow Groundwater Sources 2011
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
MACQUARIE ENERGY PTY LTD	PEL0456	Draft North Coast Fractured and Porous Rock Groundwater Sources
		Hunter Unregulated and Alluvial Water Sources 2009
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
		Wybong Creek Water Source 2003
	PEL0458	Draft North Coast Coastal Sands Groundwater Sources
		Draft North Coast Fractured and Porous Rock Groundwater Sources
		Hunter Unregulated and Alluvial Water Sources 2009
		Karuah River Water Source 2003
		Lower North Coast Unregulated and Alluvial Water Sources 2009
		Tomago Tomaree Stockton Groundwater Sources 2003
		Water
	PEL0459	Gwydir Unregulated and Alluvial Water Sources 2012
		Namoi Unregulated and Alluvial Water Sources 2012
		NSW Great Artesian Basin Groundwater Sources 2008
		NSW Great Artesian Basin Shallow Groundwater Sources 2011
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
		Peel Valley Regulated, Unregulated, Alluvium and Fractured Rock Water Sources 2010
		Upper and Lower Namoi Groundwater Sources 2003
	PEL0460	Draft North Coast Fractured and Porous Rock Groundwater Sources
		Greater Metropolitan Region Groundwater Sources 2011
		Hunter Unregulated and Alluvial Water Sources 2009
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
		Water
	PEL0461	Draft North Coast Coastal Sands Groundwater Sources
		Draft North Coast Fractured and Porous Rock Groundwater Sources
		Hunter Unregulated and Alluvial Water Sources 2009
	PEL0463	Central Coast Unregulated Water Sources 2009
		Draft North Coast Coastal Sands Groundwater Sources
		Draft North Coast Fractured and Porous Rock Groundwater Sources
		Greater Metropolitan Region Groundwater Sources 2011
		Kulnura Mangrove Mountain Groundwater Sources 2003
		Water
	PEL0464	NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
		Upper and Lower Namoi Groundwater Sources 2003
METGASCO LTD	PEL0013	Draft North Coast Fractured and Porous Rock Groundwater Sources
		Richmond River Area Unregulated, Regulated and Alluvial Water Sources 2010
	PEL0016	Draft North Coast Fractured and Porous Rock Groundwater Sources
		Richmond River Area Unregulated, Regulated and Alluvial Water Sources 2010
		Water
	PEL0426	Draft Clarence Unregulated and Alluvial Water Sources

Company	Petroleum Title	Applicable Water Sharing Plans (March 2013) [1]
		Draft North Coast Coastal Sands Groundwater Sources
		Draft North Coast Fractured and Porous Rock Groundwater Sources
		Richmond River Area Unregulated, Regulated and Alluvial Water Sources 2010
		Water
PANGAEA PEL 437 PTY LIMITED	PEL0437	NSW Border Rivers Unregulated and Alluvial Water Sources 2012
		NSW Great Artesian Basin Groundwater Sources 2008
		NSW Great Artesian Basin Shallow Groundwater Sources 2011
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
PANGAEA OIL & GAS PTY LIMITED	PEL0476	Draft North Coast Fractured and Porous Rock Groundwater Sources
		Hunter Unregulated and Alluvial Water Sources 2009
		Karuah River Water Source 2003
		Lower North Coast Unregulated and Alluvial Water Sources 2009
		Peel Valley Regulated, Unregulated, Alluvium and Fractured Rock Water Sources 2010
SANTOS QNT PTY.LTD.	PEL0450	NSW Great Artesian Basin Groundwater Sources 2008
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
	PEL0452	Draft North Coast Fractured and Porous Rock Groundwater Sources
		Hunter Unregulated and Alluvial Water Sources 2009
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
		Upper and Lower Namoi Groundwater Sources 2003
	PEL0462	NSW Great Artesian Basin Groundwater Sources 2008
		NSW Great Artesian Basin Shallow Groundwater Sources 2011
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
SANTOS NSW PTY LTD	PEL0238	NSW Great Artesian Basin Groundwater Sources 2008
		NSW Great Artesian Basin Shallow Groundwater Sources 2011
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
		Upper and Lower Namoi Groundwater Sources 2003
	PEL0433	Castlereagh River (below Binnaway) Unregulated and Alluvial Water Sources 2011
		Draft North Coast Fractured and Porous Rock Groundwater Sources
		Hunter Unregulated and Alluvial Water Sources 2009
		Macquarie Bogan Unregulated and Alluvial Water Sources 2012
		NSW Great Artesian Basin Groundwater Sources 2008
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
	PEL0434	NSW Great Artesian Basin Groundwater Sources 2008
		NSW Great Artesian Basin Shallow Groundwater Sources 2011

1. Table prepared from a topological overlay of geospatial data provided by DTIRIS (2013c; 2013d) and NOW (2013f). For up to date data contact DTIRIS and NOW

Table B3: Water Sharing Plans Applicable to Petroleum Exploration Applications

Company	Petroleum Title	Applicable Water Sharing Plans (March 2013) [1]
TRAPUZZANO, Tito	PELA0127	Draft North Coast Coastal Sands Groundwater Sources
		Draft North Coast Fractured and Porous Rock Groundwater Sources
		Richmond River Area Unregulated, Regulated and Alluvial Water Sources 2010
		Water
	PELA0128	Draft North Coast Fractured and Porous Rock Groundwater Sources
		Richmond River Area Unregulated, Regulated and Alluvial Water Sources 2010
METGASCO LTD	PELA0130	Draft North Coast Fractured and Porous Rock Groundwater Sources
		Richmond River Area Unregulated, Regulated and Alluvial Water Sources 2010
SUMMERLAND WAY ENERGY PTY LTD	PELA0135	Draft Clarence Unregulated and Alluvial Water Sources
		Draft North Coast Fractured and Porous Rock Groundwater Sources
		Richmond River Area Unregulated, Regulated and Alluvial Water Sources 2010
COMET RIDGE LTD	PELA0137	NSW Great Artesian Basin Shallow Groundwater Sources 2011
		Upper and Lower Namoi Groundwater Sources 2003
ACER ENERGY LIMITED	PELA0139	Barwon Darling Unregulated and Alluvial Water Sources 2012
		Intersecting Streams Unregulated and Alluvial Water Sources 2011
		NSW Great Artesian Basin Shallow Groundwater Sources 2011
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
	PELA0140	NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
	PELA0141	Barwon Darling Unregulated and Alluvial Water Sources 2012
		Lower Lachlan Groundwater Source 2003
		Lower Murray-Darling Unregulated and Alluvial Water Sources 2011
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
	PELA0142	Lower Murray-Darling Unregulated and Alluvial Water Sources 2011
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
	PELA0143	Lower Lachlan Groundwater Source 2003
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
PETRO TECH PTY. LTD.	PELA0146	Lower Murray Shallow Groundwater Sources 2012
	PELA0147	Lower Murray-Darling Unregulated and Alluvial Water Sources 2011
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
	PELA0148	Lower Murray-Darling Unregulated and Alluvial Water Sources 2011
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
CEEMAC PTY LTD	PELA0149	Castlereagh River (below Binnaway) Unregulated and Alluvial Water Sources 2011
		Draft North Coast Fractured and Porous Rock Groundwater Sources
		Lower Macquarie Groundwater Source 2003
		Macquarie Bogan Unregulated and Alluvial Water Sources 2012
		NSW Great Artesian Basin Groundwater Sources 2008
		NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011
		NSW Murray Darling Basin Porous Rock Groundwater Sources 2011

1. Table prepared from a topological overlay of geospatial data provided by DTIRIS (2013c; 2013d) and NOW (2013f). For up to date data contact DTIRIS and NOW