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Coal Seam Gas: Issues for Consideration in the Illawarra Region, NSW, Australia

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Coal Seam Gas: Issues for Consideration in the Illawarra Region, NSW, Australia

Abstract

Coal seam gas (CSG) is a naturally occurring gas, predominantly methane (CH4) that can be used as a fuel to generate electricity. It is found within the pores and fractures of all sub-surface coal seams, typically at a depth of 300 to 1000 metres. Advances in drilling technology have made CSG extraction more economical, leading to a significant expansion in development, particularly in the eastern coal basins of Australia and parts of the US. This rapid expansion in development has created significant concern as to possible impacts on the environment, particularly issues relating to agriculture, groundwater, and water catchments. The main environmental issues relating to CSG extraction are outlined in this thesis by analysing a range of literature relating to CSG development in the Illawarra region, south of Sydney, a region that has been extensively mined over the past 150 years and is an important water catchment for the Sydney metropolitan area. In addition to discussing exploration and production techniques such as hydraulic fracturing, an analysis of the geology and hydrogeology of the Southern Coalfield is undertaken, with particular reference to the potential impacts on groundwater and water catchments. The study also reviews the legislative framework, and looks at the global and domestic economic conditions currently driving CSG development in this country. This thesis forms an important basis for understanding the current issues relating to CSG in Australia, as well as proving local context for assessing potential impacts in the Illawarra region.

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COAL SEAM GAS:
ISSUES FOR CONSIDERATION IN
THE ILLAWARRA REGION, NSW, AUSTRALIA

by

JOE STAMMERS

A research report submitted in partial fulfilment of the
requirements for the award of the degree of

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ABSTRACT

Coal seam gas (CSG) is a naturally occurring gas, predominantly methane (CH_4) that can be used as a fuel to generate electricity. It is found within the pores and fractures of all sub-surface coal seams, typically at a depth of 300 to 1000 metres. Advances in drilling technology have made CSG extraction more economical, leading to a significant expansion in development, particularly in the eastern coal basins of Australia and parts of the US. This rapid expansion in development has created significant concern as to possible impacts on the environment, particularly issues relating to agriculture, groundwater, and water catchments.

The main environmental issues relating to CSG extraction are outlined in this thesis by analysing a range of literature relating to CSG development in the Illawarra region, south of Sydney, a region that has been extensively mined over the past 150 years and is an important water catchment for the Sydney metropolitan area.

In addition to discussing exploration and production techniques such as hydraulic fracturing, an analysis of the geology and hydrogeology of the Southern Coalfield is undertaken, with particular reference to the potential impacts on groundwater and water catchments. The study also reviews the legislative framework, and looks at the global and domestic economic conditions currently driving CSG development in this country.

This thesis forms an important basis for understanding the current issues relating to CSG in Australia, as well as proving local context for assessing potential impacts in the Illawarra region.

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1. INTRODUCTION

Coal seam gas (CSG) is a naturally occurring gas, predominantly methane (CH_4), found within the pores and fractures of all sub-surface coal seams typically at a depth of 300 to 1000 metres (CSIRO, 2012). Once extracted, it can be used as a fuel in turbines to generate electricity, or compressed and transported in a natural gas pipeline for export or domestic use (Rutovicz et al., 2011).

In the past number of years in Australia, the development of CSG has emerged as one of the country's most highly contentious environmental issues. The issue has led to the formation of numerous community groups such as Stop CSG Illawarra and Lock the Gate Alliance who have secured strong community support in opposing potential CSG development. The issue has also created unlikely alliances between community groups, farmers and Greens; groups that may have been ideologically opposed to each other in the past.

Figure 1 Human sign at Austinmer Beach, Wollongong, NSW, May 30 2011. (O'Brien, 2011)

Although there are genuine concerns about the potential *social* impacts of this rapidly evolving industry, the main concerns raised by the community groups tend to concentrate on the possible *environmental* impacts of CSG development, particularly local and regional impacts on groundwater, water catchments and agricultural land. Independent researchers and numerous government agencies have also expressed concern, particularly at the apparent lack of independent scientific research and baseline data with which to make informed decisions, and the difficulty in regulating such a rapidly developing industry (NSW Inquiry into CSG, 2012, IIESC, 2012).

Although the concerns raised about the potential environmental impacts of CSG are typically of local or regional significance, it needs to be recognised that the demand for natural gas, both domestically and globally, is expected to grow significantly over the next couple of decades. The major reason for the growth in demand is a global shift away from coal-fired power, and towards a less carbon-intensive global economy relying increasingly on solar, wind and natural gas. This growth in global demand for natural gas, particularly from Asia, is largely responsible for the rapid development of liquefied natural gas (LNG) infrastructure in Queensland. Estimates suggest that by 2035 almost 70% of the CSG extracted in Queensland will be processed and shipped as LNG to Asia. Domestic demand for natural gas is to some extent expected to reflect the increase in global demand, particularly if state and federal governments continue to seek reductions in carbon emissions. Also of concern are dwindling conventional gas reservoirs in the Cooper Basin and Bass Strait, which are causing a degree of apprehension about gas supply, particularly in NSW (Geoscience Australia and BREE, 2012).

The rapid development of CSG in Australia and globally has been driven by significant advances in drilling methods and technology, partly a consequence of the shale gas boom in the United States. Advances in hydraulic fracturing, horizontal and multi-lateral drilling methods are now allowing access to a significantly greater surface area of the coal seam than would have been possible with traditional vertical wells. Consequently, the same quantities of gas are able to be extracted with proportionally less surface disturbance (Ayers, 2002, ALL Consulting, 2012, Freij-Ayoub, 2012).

Significant environmental challenges remain however, particularly in regions such as the Illawarra in NSW, where CSG is planned for relatively pristine bushland in an important water catchment for the Sydney Basin. However, the economy of the Illawarra region has been closely tied to coal mining that has powered industries such as the Port Kembla steel works and provided important export revenue to the state for the past 150 years. CSG operations attempt to extract methane gas from the same coal seams that are presently being mined but at greater depths (~300-1000 m) using sophisticated directional drilling techniques.

The environmental concerns about CSG development typically relate to potential impacts on groundwater and surface water, but also encompass issues to do with surface disturbance, bushfire risk, and concerns about a loss of amenity in a rural or scenic area (NSW Government, 2011, Moore, 2012, Freij-Ayoub, 2012). Concerns about water are of particular importance in the Illawarra, as the Southern Coalfield forms part of an important water catchment for the Sydney Basin, supplying drinking water to over 4 million people. Indeed, parts of the catchment proposed for CSG development are considered so important, that they carry $11,000 fines for trespassing on foot into the area. At the same time, the region has been extensively mined for coal in the past, and many environmental impacts on natural features in the catchment, particularly subsidence effects, have already occurred (NSW Government, 2008). It must also be recognised that much of the CSG development proposed for the region will likely involve the extraction of methane stored within collapsed mine workings (goaf). This is an important consideration because one of the major criticisms of CSG are the potential environmental effects of hydraulic fracturing, and draining methane from the goaf does not normally require the use of hydraulic fracturing. In fact, draining methane from the goaf and using it to generate electricity has been happening at the nearby Appin and Tower coal mines for over 15 years.

Concerns over CSG development however, are not restricted to apprehension towards hydraulic fracturing. Issues about extracted water disposal and alterations or contamination of existing groundwater and surface water resources are also an important consideration. However, our scientific understanding of the interactions between groundwater and surface water are perhaps not as well understood as might be hoped when dealing with a region containing an important water catchment. While there is extensive research on the geology of the region (Reynolds, 1976, Bembrick et al., 1980, Hutton et al., 1990, Bamberry, 1991, Dehghani, 1994, Stewart and Alder, 1995, Hutton, 1999, Haworth, 2003, Volk et al., 2011), there is much less research relating to the hydrogeology of the region. In fact, it has been recommended by both the 2012 NSW Legislative Council Inquiry into CSG and the 2008 Strategic Review into the Impacts of Underground Coal Mining on Natural Features in the Southern Coalfield, that the integration of private company, academic and government data sets needs considerable improvement, particularly regional data sets relating to aquatic communities, aquifers and groundwater resources (NSW Government, 2008, NSW Inquiry into CSG, 2012).

Other environmental considerations with CSG development include the ecological effects of clearing bushland, transport and storage of water, storage of chemicals, and the building of roads, pipelines and associated infrastructure. These issues are not insignificant, and need careful consideration particularly in water catchments and areas prone to bushfire.

The main environmental issues relating to CSG extraction are outlined in this thesis by providing an analysis of the main environmental issues relating to CSG extraction in the Illawarra region. In addition to this, a review of the exploration and production processes involved in CSG development are analysed, as well as investigating the geology and hydrogeology of the Southern Coalfield, with particular reference to groundwater and water catchments in the Illawarra region. An important aspect of this literature-based thesis is to highlight current gaps in knowledge in order to help focus future scientific studies relating to CSG. Also discussed are the global and domestic economic conditions currently driving coal seam gas development in Australia, in addition to an overview of the legislative framework in NSW as it exists today, with possible avenues for further research provided at the conclusion of this study.

1.1. AIMS AND OBJECTIVES

The overarching aim of this project is to objectively assess the current state of knowledge regarding CSG extraction and its potential environmental impacts so that local government can make informed decisions relating to future CSG developments. A critical review of available scientific, government and private company research will form the central body of evidence from which to point out potential gaps in knowledge relating to CSG developments in the Illawarra.

The project was broken down into a number of more specific and achievable objectives, which include:

- An overview of the global and domestic economic conditions currently driving CSG development in Australia.
- An outline of the geological conditions leading to CSG formation within the Sydney Basin and a review of the hydrogeology of the Southern Coalfield, with particular reference to the potential environmental impacts of CSG development on groundwater and water catchments in the Illawarra region.
- A detailed analysis of the exploration and production techniques used in coal seam gas development.
- A review of the currently evolving CSG legislative framework.
- A critique of current scientific, government, and private company research outlining current gaps in knowledge with a view to providing direction for future research.

2. GLOBAL AND LOCAL GAS MARKET

To understand the various economic and policy pressures underpinning the recent surge in CSG development in Australia, it is imperative to understand the global and domestic markets currently driving the demand for gas development.

2.1. GLOBAL GAS MARKET

Natural gas is the world's third largest energy source and currently accounts for approximately 21% of the world's primary energy consumption, with roughly 40% of the natural gas produced in the world used to generate electricity (Geoscience Australia and BREE, 2012). In terms of gas use, global consumption has been increasing at an average annual rate of around 2.9% since 1971 (IEA, 2011). Some of the major reasons for this growth include an increase in gas-fired power plant development, improvements in gas extraction and processing technology, and the implementation of government policies designed to encourage alternative fuels (such as gas) that are viewed as cleaner alternatives to traditional coal-fired power (Geoscience Australia and BREE, 2012).

The International Energy Agency (IEA) has estimated that at present rates of production, the world has enough recoverable conventional and unconventional gas reserves to last for approximately 250 years (IEA, 2011). In its 2011 World Energy Outlook New Policies Scenario, the IEA has projected world demand for natural gas to increase over 40% to 2035, with a significant proportion of this increase predicted to come from non-OECD countries, particularly in Asia.

Currently, Australia accounts for around 2% of world gas reserves and production, but ranks as the fourth largest exporter of liquified natural gas (LNG) with 9% of world LNG trade in 2010. LNG is produced by cooling natural gas to around -162° at close to atmospheric pressure, where it condenses to a liquid taking up around 1/600th the volume of natural gas in the gaseous state (Geoscience Australia and BREE, 2012). This process makes it economically viable to transport in LNG tankers over long distances where pipelines do not exist.

It has been predicted that the global trade in LNG will increase substantially from 9263 petajoules (PJ) in 2009 to around 18,632 PJ in 2035. Significantly, much of Australia's gas production has been designated for export, with around 48% of gas production in 2009-10 exported as LNG (1,053 PJ valued at $10.4 billion) to countries such as Japan (69.7 %), China (21%) and South Korea (5%). As shown in Figure 2, Australian exports are expected to increase considerably over the next twenty years, with LNG exports expected to account for around 68% of Australian gas production by 2035 (Geoscience Australia and BREE, 2012).

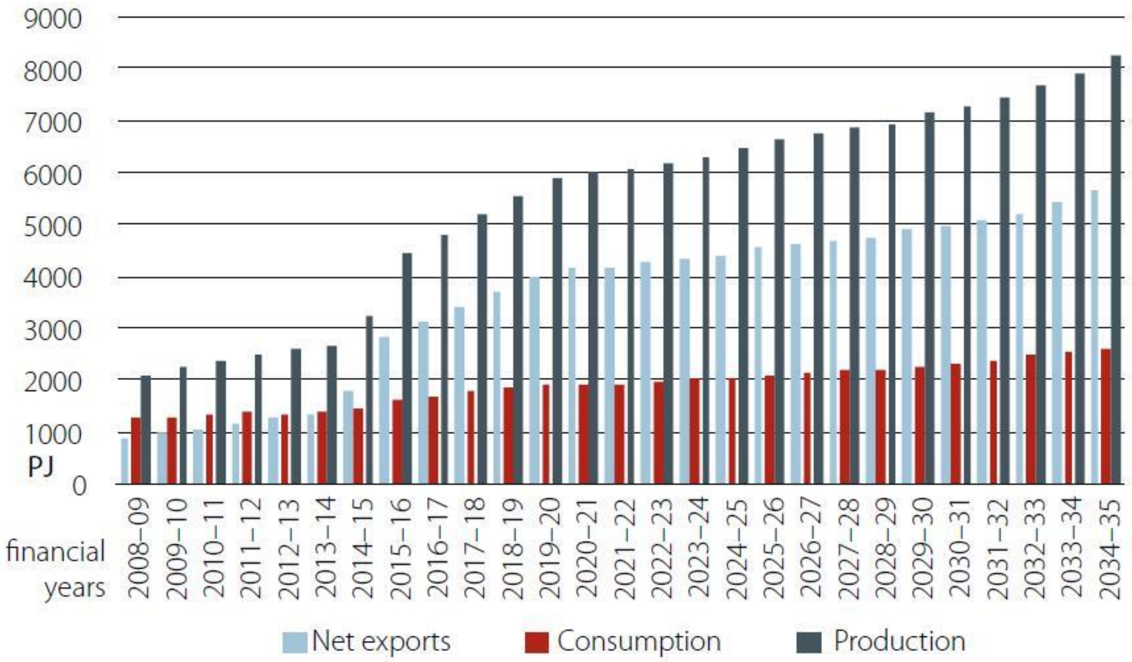


Figure 2 Australia's gas balance to 2034-35 (BREE, 2011)

2.2. AUSTRALIA'S GAS RESOURCES AND MARKET

Gas is Australia's third largest non-renewable energy resource after coal and uranium, with around 92% of the country's conventional gas resources located off the north-west coast of Western Australia in the Carnarvon, Browse and Bonaparte basins (Figure 3). Combined total identified gas resources (including conventional, CSG, shale and tight gas) have been estimated at over 430,000 PJ which is enough to last approximately 184 years at current production rates (Geoscience Australia and BREE, 2012).

Coal seam gas resources are currently estimated to represent around one third of the recoverable reserves from Australia's conventional gas fields, with coal seam gas production currently accounting for around 10% of total gas production (Geoscience Australia and BREE, 2012) and around 20% of domestic gas production (Australian Energy

Regulator, 2011). Most CSG resources are located in the coal basins of Queensland and New South Wales, with additional potential resources in South Australia (Figure 3). Australia also has a significant quantity of potential shale gas, with resources identified throughout Western Australia, Northern Territory, Queensland and South Australia.

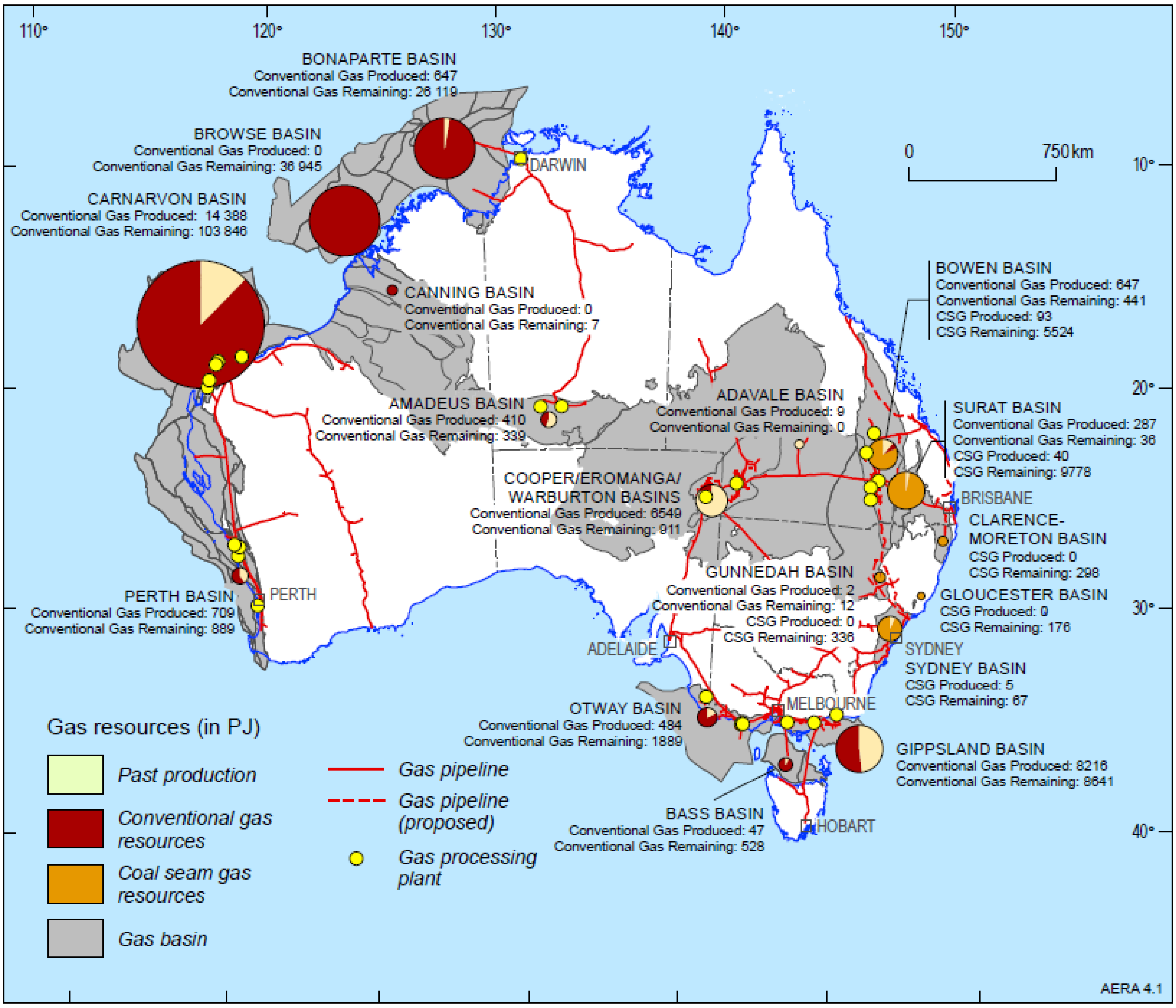


Figure 3 Location of Australia's gas resources and infrastructure (Geoscience Australia, 2012)

Gas currently accounts for around 23% of Australia's total primary energy consumption and approximately 15% of electricity generation, with domestic gas consumption increasing approximately 4% per year since 2000. Gas consumption is divided between manufacturing (32%), electricity generation (29%), mining (23%) and residential (10%) (ABARES, 2011). It has been projected that gas will be the fastest growing fossil fuel consumed over the period to 2035, with domestic growth expected to increase at an average rate of approximately 2.9% per year, with total share of primary energy consumption expected to rise from 22% to around 35% in 2035 (Figure 4). This rise will be largely driven by growth in gas-fired electricity generation and increased use of gas-fired power in the mining sector.

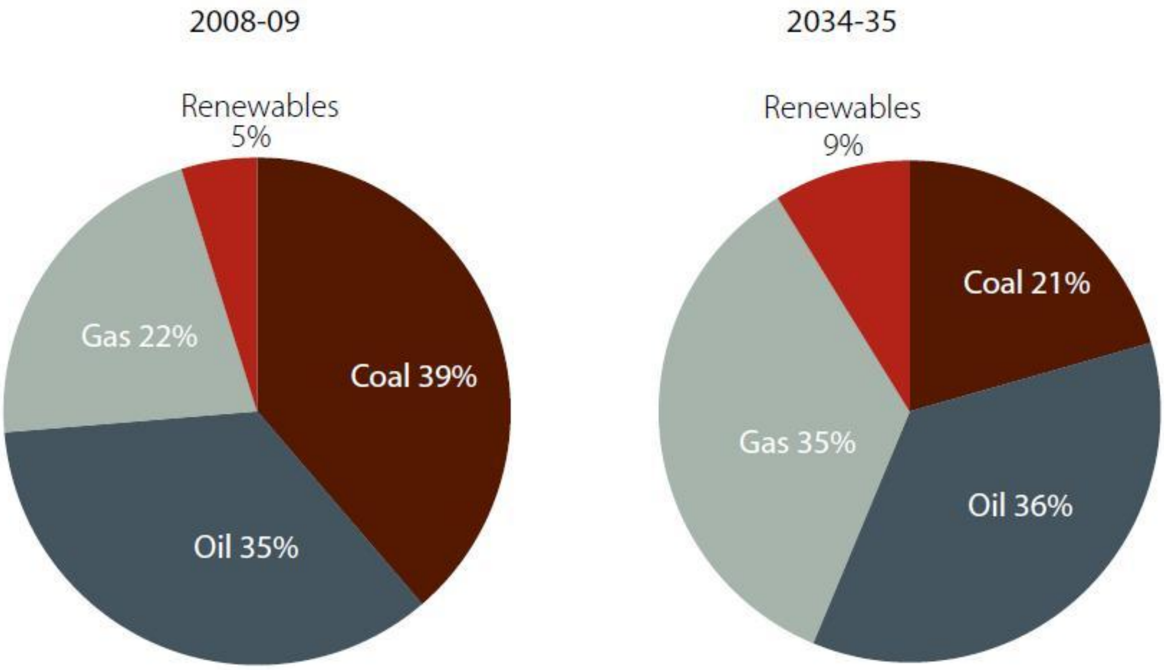


Figure 4 Australia's total primary energy supply: 2008–09 and 2034–35 (BREE 2011)

It is important to understand that many of the projections about the role of natural gas in the energy mix assume that gas will act as the major transition fuel between coal and renewables. Some of the reasons for these assumptions are because gas is currently the next cheapest source of electricity generation after coal, and gas-fired power plants are able to respond quickly to variations in electricity demand (Rutovicz et al., 2011). Also, natural gas is widely considered to be an environmentally cleaner fuel than coal due to the absence of detrimental by-products such as sulphur, mercury, ash and particulates, and also because it provides twice the energy per unit of weight with half the carbon footprint during combustion (Jaramillo et al., 2007, Burnham et al., 2011, Cathles et al., 2012). There does however remain considerable debate as to the greenhouse gas credentials of gas when taking into account life-cycle emissions (see Chapter 7) (Weber and Clavin, 2012, Jaramillo et al., 2007, Burnham et al., 2011, Saddler, 2012).

2.3. THE EASTERN GAS MARKET

Australia has three distinct regional gas markets (Figure 5); the eastern market (Queensland, New South Wales, Victoria, Tasmania, South Australia and Australian Capital Territory), the Western market (Western Australia) and the Northern market (Northern Territory). This market segmentation is attributable to the large distances between the three markets, which makes pipeline construction and distribution currently uneconomic. The consequence of this segmented regional market is that all gas production is either consumed within its own regional market or exported as LNG (Geoscience Australia and BREE, 2012).

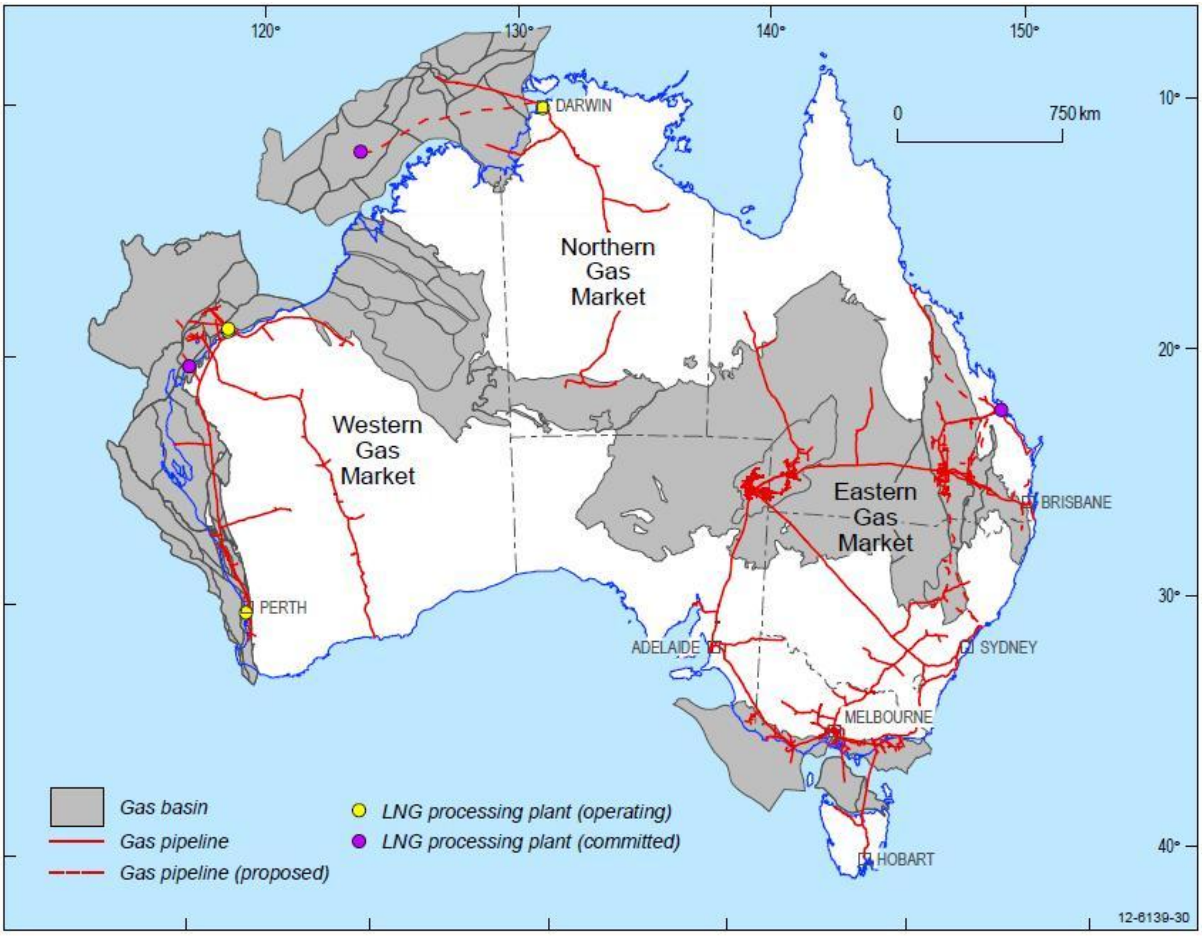


Figure 5 Australia's regional gas markets and facilities

The eastern gas market is the largest consumer of natural gas in Australia, and represents around 35% of Australia's gas production, and 63% of domestic consumption (Rutovicz et al., 2011). It contains around 39% of Australia's total gas reserves, of which the majority are CSG reserves in the Surat – Bowen Basin in Queensland (Figure 6). The CSG reserves in Queensland and New South Wales currently account for 78% of total gas reserves in the region and it is projected that by 2030 these CSG reserves will supply at least 30% of the national domestic gas market and 50% of the Eastern gas market (Australian Energy Regulator, 2011).

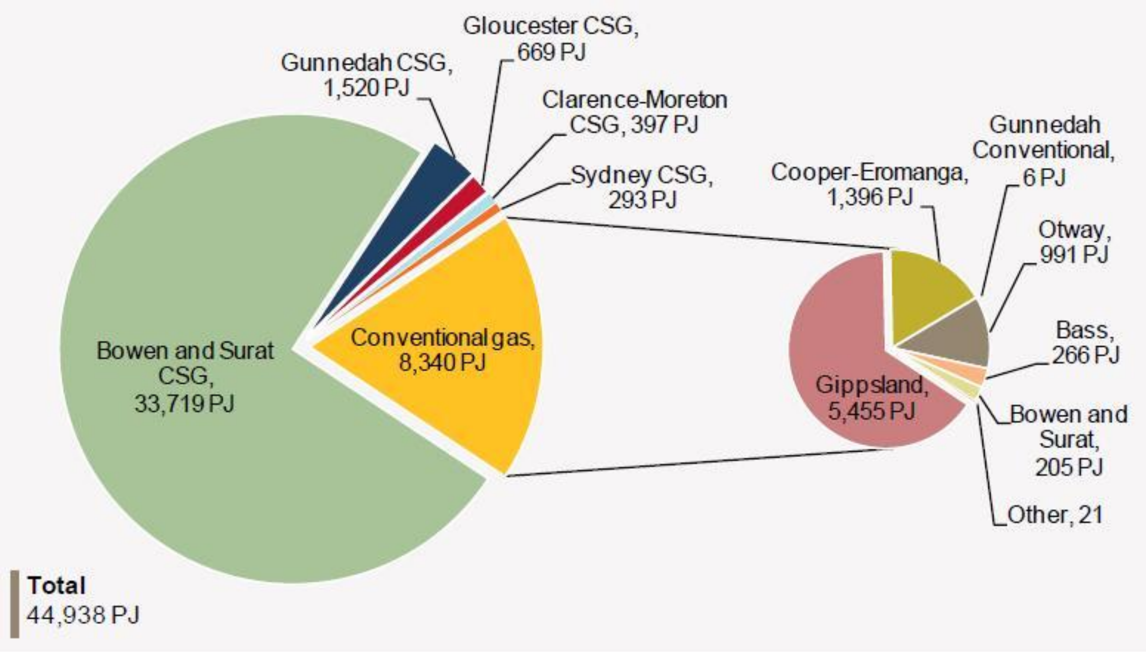


Figure 6 Remaining proved and probable (2P) gas reserves in the Eastern gas market (AEMO, 2011)

The eastern gas market has been subject to a number of major changes over the past few years, which together have contributed to a certain degree of uncertainty in the market. These changes include the scheduled export of LNG from Queensland, the depletion of conventional gas resources in the Cooper and Gippsland basins, and an increase in demand from gas-fired electricity.

1. ***The scheduled export of LNG from Queensland***

   Until now, all gas produced in the Eastern market has been consumed within its own market, however new LNG facilities currently under construction at Gladstone in Queensland (due to be completed around 2014-15) will see the Eastern market export LNG for the first time. This is predicted to lead to a tightening in the domestic market as a significant proportion of CSG in Queensland has been designated for export (Figure 7).

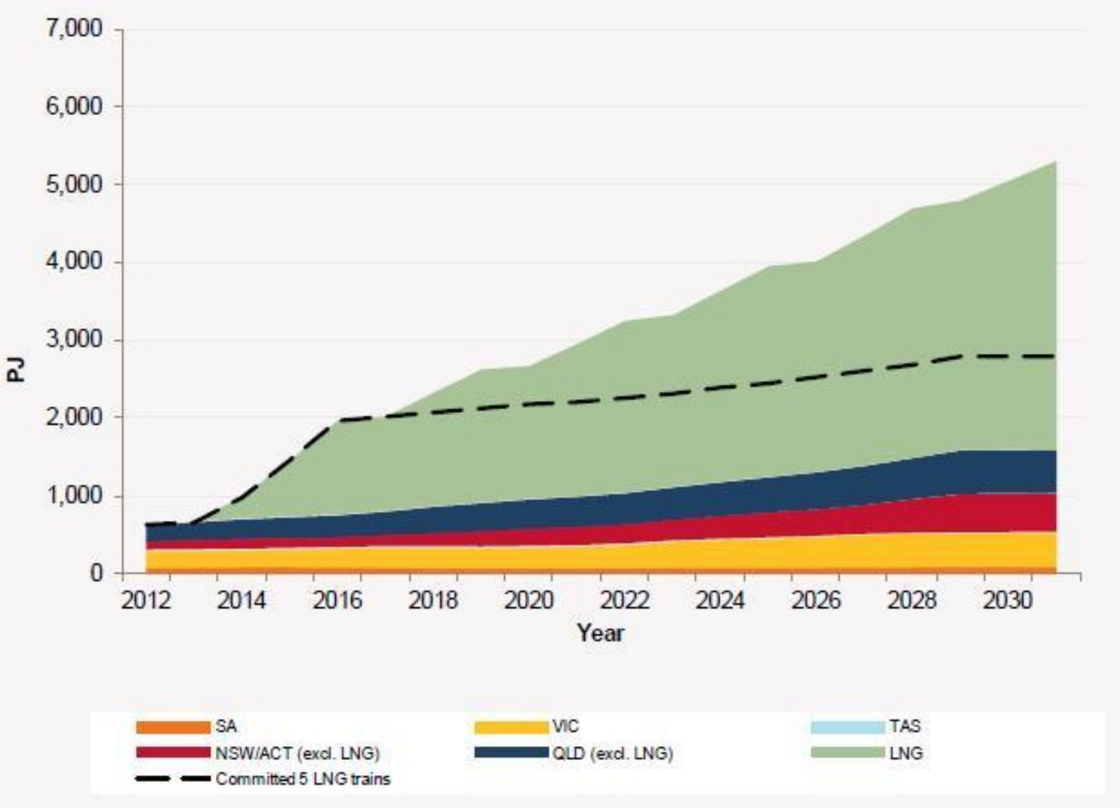


Figure 7 Eastern gas market annual demand projections including LNG export (AEMO, 2011)

2. ***The depletion of conventional gas resources in the Cooper and Gippsland basins.***

   The gradual depletion of conventional gas supplies from the Gippsland and Cooper basins has been of particular concern for NSW, which produces only a small percentage (around 6%) of its gas demands. Previously, NSW has relied on importing gas from the conventional gas fields of Victoria and South Australia (Figure 8) however depletion of these conventional gas reservoirs has forced the NSW Government to reassess its options. The details of this re-assessment by the NSW Government are discussed in more detail below.

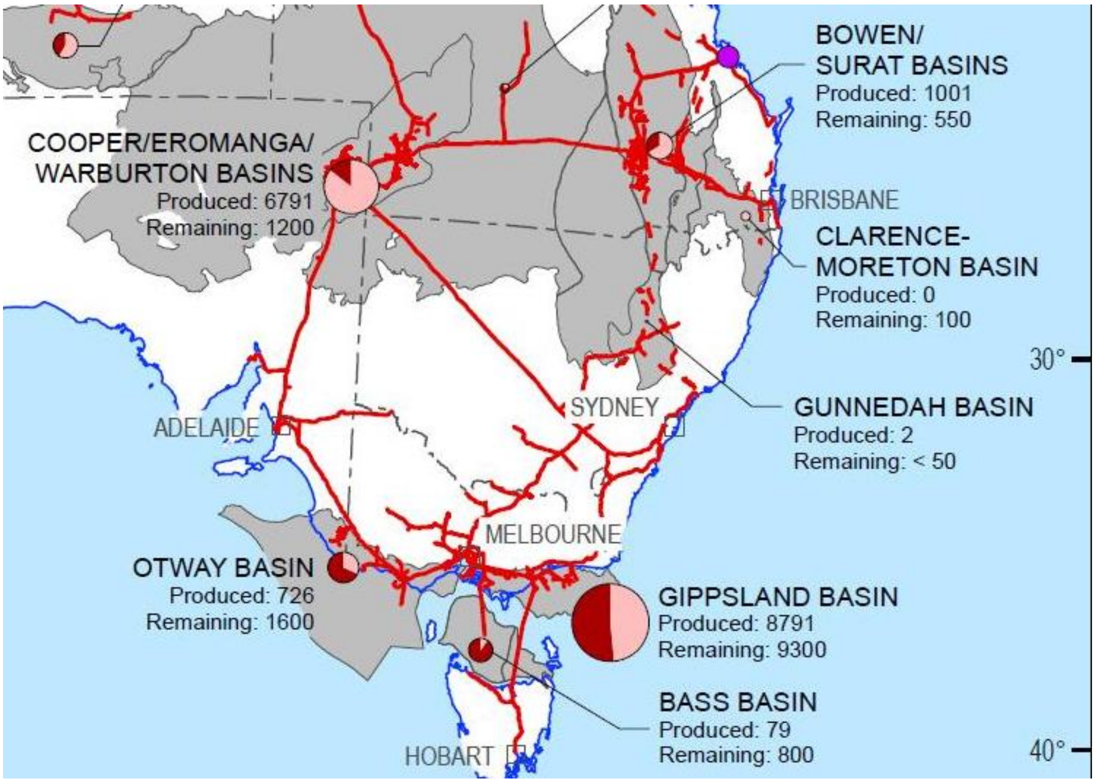


Figure 8 Remaining conventional gas reserves in the Eastern gas market (Geoscience Australia and BREE, 2012)

3. ***An increase in domestic demand from gas-fired electricity***

During 2005 the Queensland Government initiated the Queensland Gas Scheme requiring electricity retailers to obtain a percentage (currently 15%) of their electricity from gas-fired generation. The scheme was set up to help diversify the state's energy mix, encourage the development of new infrastructure (such as the Gladstone LNG facility), expand the gas industry, and assist in reducing greenhouse gas emissions from the electricity sector (Queensland Government, 2011c). It has been anticipated that the introduction of the Commonwealth carbon price in July 2012 will lead to further growth in the gas industry, including Victoria and NSW, with projections indicating that gas-powered electricity generation will be the largest source of growth in domestic demand over the next twenty years (AEMO, 2011).

2.4. NSW GAS MARKET

Gas currently accounts for around ten% of total primary energy use in New South Wales, with coal contributing 48% and oil 38%. Gas consumption within the state has more than doubled since the 1980s, and under a medium-growth scenario is predicted to more than triple over the next 20 years to over 550 PJ a year at an average growth rate of 6.9% per annum (NSW Government, 2011).

Currently, NSW daily gas consumption averages 436 TJ per day, with seasonal variations between 250 TJ and 620 TJ per day (NSW Government, 2011). Approximately 50% of this gas is used by small residential, commercial and industrial users; 32% by large industrial users, and 18% by gas-fired power generators (ACIL Tasman, 2012). As shown in Figure 9, approximately 95% of the gas used in NSW is imported from the conventional gas fields of the Cooper Basin in South Australia (via the Moomba-Sydney Pipeline) and the Gippsland Basin in Victoria (via the Eastern Gas Pipeline) (ACIL Tasman, 2012).

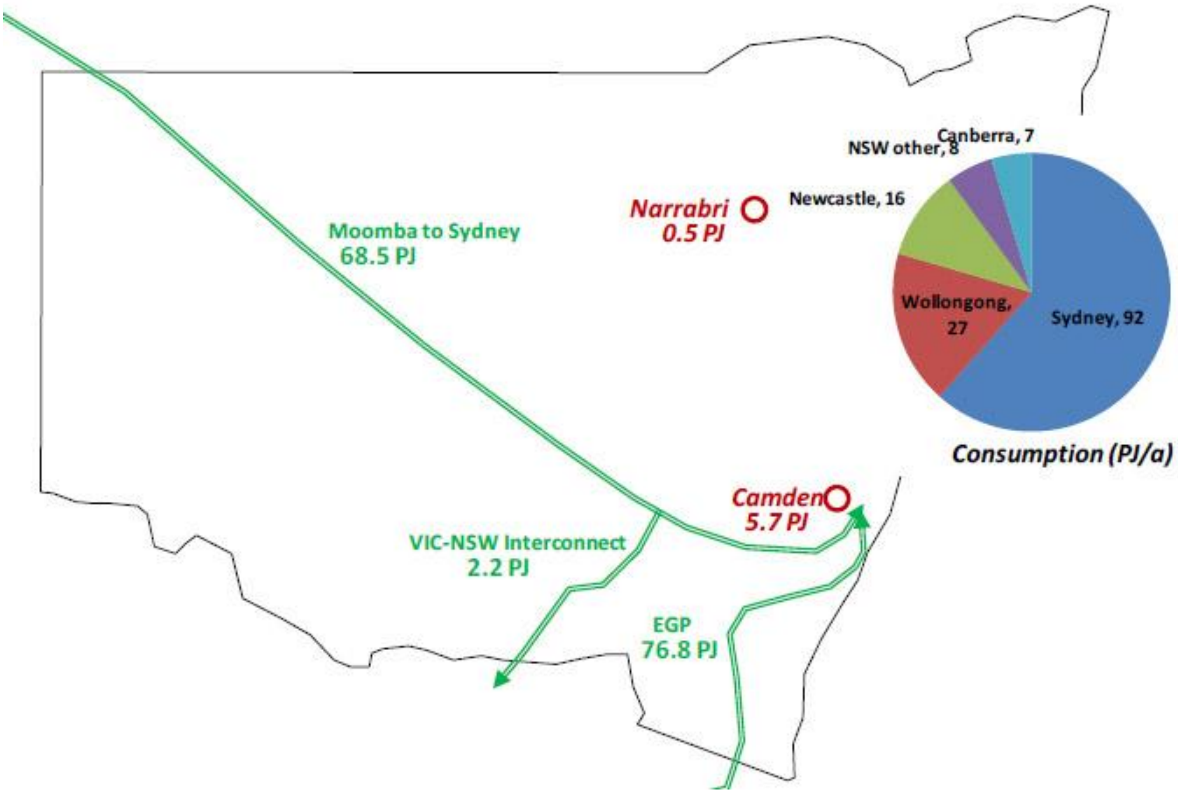


Figure 9 New South Wales gas production and consumption (ACIL Tasman, 2012)

NSW domestic gas production is currently limited principally to AGL Energy's Camden coal seam gas project, which is responsible for supplying around 5% of gas for the Sydney market. The Camden Gas Project is located approximately 60 kilometres south-west of Sydney and has been producing CSG since 2001. It currently has 89 producing wells connected to their Rosalind Park Gas Plant producing approximately 17TJ of gas per day (AGL Energy Limited, 2012a). Other CSG projects approved for development in NSW include Metgasco's Casino Gas Project, and AGL Energy's Narrabri and Gloucester Gas Projects. As of September 2012, only the Camden and Narrabri projects were producing gas commercially.

The NSW Government indicated in its submission to the NSW Legislative Council inquiry into coal seam gas development that securing future gas supply, reducing greenhouse gas emissions, reducing the state's dependence on coal, and developing the domestic gas industry were of considerable importance to the state. The government's submission also indicated that domestic CSG reserves in NSW could supply the state for around 250 years at the predicted consumption of 550 PJ per annum (NSW Government, 2011).

Adding to the pressure of CSG development in NSW are certain issues including:

- the scheduled export of LNG from Queensland.
- the depletion of conventional gas resources in the Cooper and Gippsland Basins.
- the transition to a lower carbon economy creating an increase in demand for gas-fired electricity.
- the expiry of many gas supply contracts over the period 2012-2017.

The scheduled large-scale LNG export developments in Queensland are likely to place heavy demands on Queensland CSG production which in turn may restrict the future availability of Queensland CSG for export to NSW. Furthermore, in the absence of fixed upper price limits or domestic reservation, producers may decide to access higher prices for LNG in the export market, increasing competition for gas and possibly placing upward pressure on gas prices (ACIL Tasman, 2012).

In addition, Australia's transition to a lower carbon economy is predicted to lead to continued growth in gas-fired electricity particularly in the eastern states. This may limit the availability of gas to NSW, particularly from the important Gippsland conventional gas basin in Victoria (ACIL Tasman, 2012).

Further complicating the issue for NSW gas consumers is the continued depletion of the conventional gas resources of the Cooper and Gippsland basins and the expiry of gas supply contracts over the period 2012 to 2017. All reserves in the Cooper Basin are currently fully contracted with no reserves available to replace the contracts with NSW when they expire. In the Gippsland Basin, there are reserves for approximately 15 years at current production rates although growth in demand in Victoria may lead to additional pressure on the discovery and development of new reserves (ACIL Tasman, 2012). The combined effect of dwindling supplies and expiring contracts may lead to higher prices and further difficulties in securing supply for NSW consumers when contracts expire.

The recent inquiry into CSG development in NSW addressed some of the issues affecting the gas market in NSW, however the committee provided only a few economic recommendations. The major economic recommendation by the Committee (Recommendation 29) was to suggest that a domestic gas reservation policy be implemented if the CSG industry was to proceed further. This policy would be similar to the policy in Western Australia where a portion of gas is reserved for the use of the state to help contain prices and enhance energy security (NSW Parliament, 2012).

3. GEOLOGY OF THE SYDNEY BASIN

The Sydney Basin is a large sedimentary basin on the east coast of Australia covering almost 50,000 km^2 with approximately 44,000 km^2 located onshore and another 5,000 km^2 located offshore extending to the edge of the continental shelf (Figure 10). The basin forms part of the larger Sydney-Gunnedah-Bowen Basin system which extends some 1700 km from coastal southern NSW to Townsville in the north.

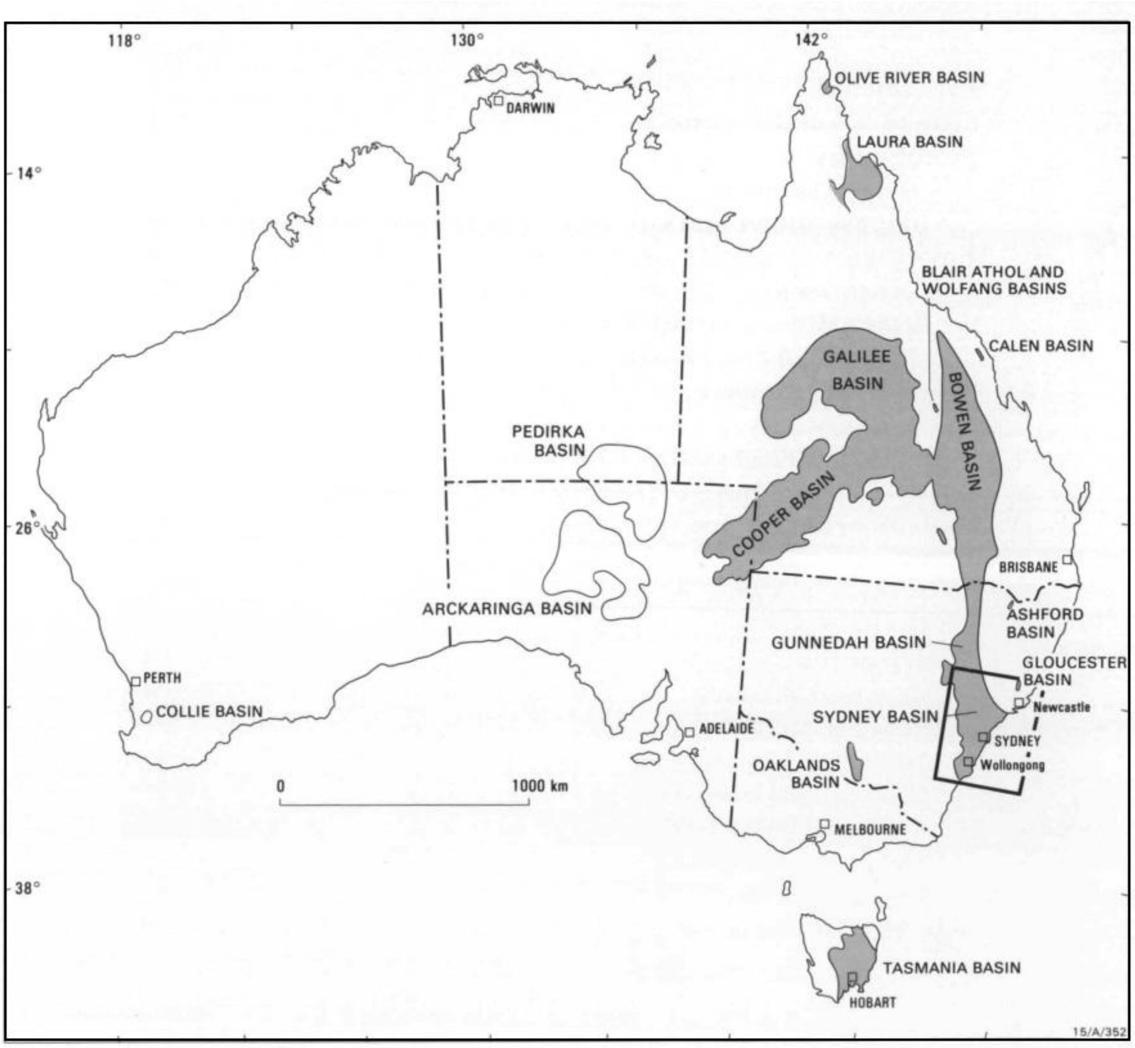


Figure 10 Geological basins in Australia (Sydney Basin highlighted) (Source: Volk 2011)

3.1. FORMATION AND STRATIGRAPHY

The basin was formed in a retro-arc foreland basin tectonic setting during the late Carboniferous-Permian-Triassic period (approximately 300-200 million years ago) as a result of continental rifting. The Sydney Basin was deposited behind the New England Fold Belt to the northeast which developed as an active convergent margin arc from the Devonian (~400 mya) through to the Triassic (~200 mya) before the eastern margin of Gondwana (New Zealand and the Lord Howe Rise – together referred to as “Zealandia”) rifted away about 85 mya creating the Tasman Sea (Veevers, 2012). A significant proportion of the sediment entering the Sydney Basin was derived from the then actively forming New England Fold Belt to the east as well as sediment eroded from the supercontinent – Gondwana, to the west (Scheibner, 1999). At its thickest, the basin currently consists of around 3000 m of sedimentary rock, the thickest of which lies west of Sydney, where the Cumberland Plain is identified as the depocentre, gently inclining towards the basin edge. Minor localised igneous intrusions and basalts have been identified throughout the basin (Reynolds, 1976, Bembrick et al., 1980, Hutton et al., 1990, Bamberry, 1991, Dehghani, 1994, Stewart and Alder, 1995, Hutton, 1999, Haworth, 2003, Volk et al., 2011).

The Sydney Basin is separated from the Gunnedah Basin in its north-eastern extent by the Mt Corricudgy Anticline, a basement ridge that was developed before sedimentation took place. Dominant structural features of the basin include numerous faults, anticlines, synclines and monoclines which typically trend north-south. The basin is divided into a number of structural subdivisions (Figure 11), with the Illawarra and Woronora Plateaus in the Southern Coalfield the regions of most importance for this study (Bembrick et al., 1973, Reynolds, 1976).

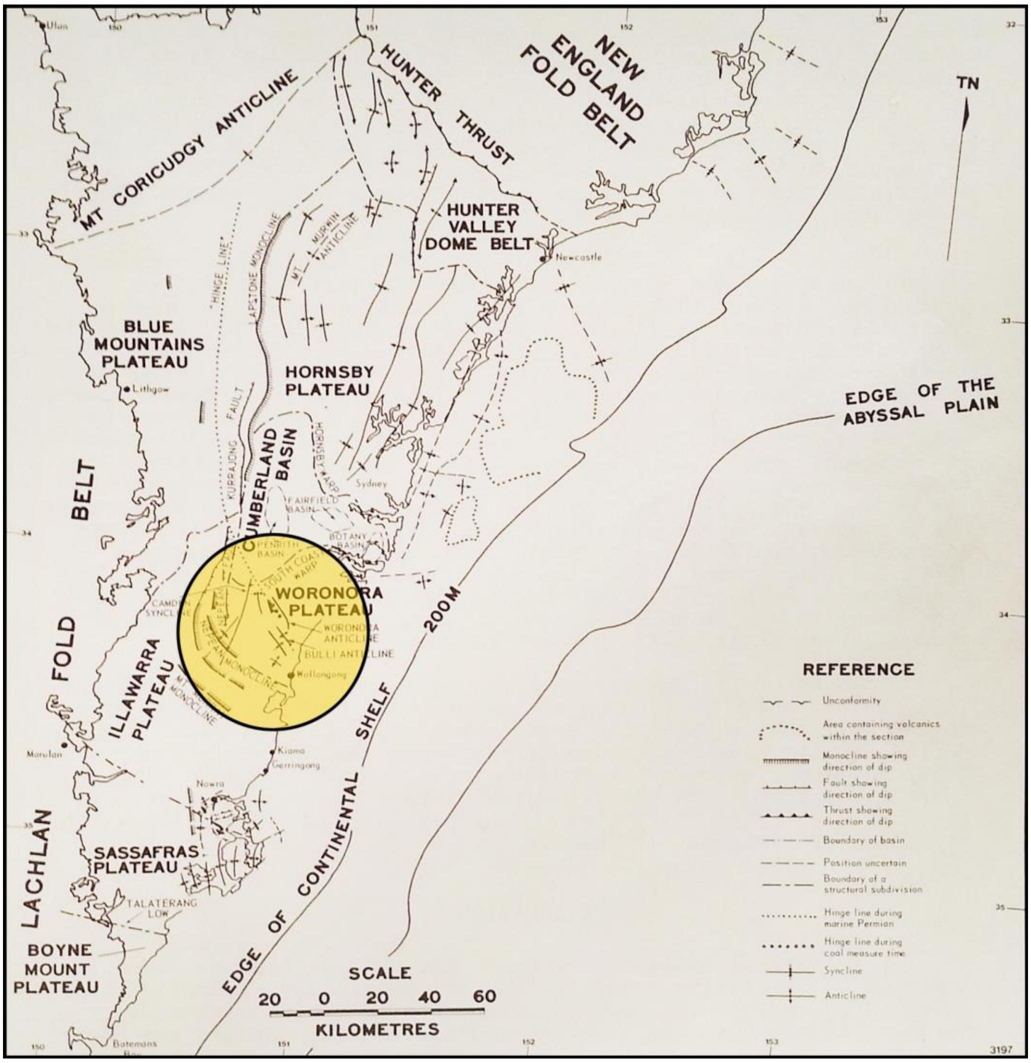


Figure 11 Structural subdivision of the Sydney Basin with area of interest highlighted (after Bembrick et al., 1973)

The stratigraphy of the Sydney Basin is dominated by six major units shown in (Figure 12) which gradually thin from the centre of the basin to the margins. Overlying the intensely folded Paleozoic basement lie the marine sediments and coal measures of the Talaterang and Shoalhaven Groups, which progressively thin from around 1000 metres at the coast near Nowra to approximately 45 metres thick near Tallong 50 kilometres west.

The Talaterang Group is made up of the Clyde Coal Measures and the shallow marine Wasp Head Formation. Overlying the Talaterang Group is the 300 to 900 metre thick Shoalhaven Group, typically lithic sandstones with interbedded beds of shale or mudstone deposited in a marine or marine-influenced environment. The group consists of the basal Pebbly Beach Formation, the Snapper Point Formation, the Wandrawandian Siltstone, the fluvially deposited Nowra Sandstone, the Berry Siltstone, and capping the sequence - the Budgong Sandstone (Bowman, 1973, Runnegar, 1973, Eyles et al., 1998).

On the western margins of the southern Sydney Basin where the basin meets the Lachlan Fold Belt, the Talaterang Group and Pebbly Beach formation are not present, with the basal outcrop formed by the Snapper Point Formation. At the top of the Shoalhaven Group, alternating layers of sandstones and siltstones are capped by volcanics, and are interbedded with the upper Budgong Sandstone and the base of the Illawarra Coal Measures (Bembrick et al., 1980, Carr and Jones, 2001).

Above the Shoalhaven Group is the economically significant Illawarra Coal Measures. This 240 m thick deltaic sequence consists of lithic sandstone formations interbedded with smaller formations of coal, sediments and shale. The maximum thickness of the coal measures is about 520 m in the northern section of the coalfield (Bowman, 1973, Hutton et al., 1990, Hutton, 2009).

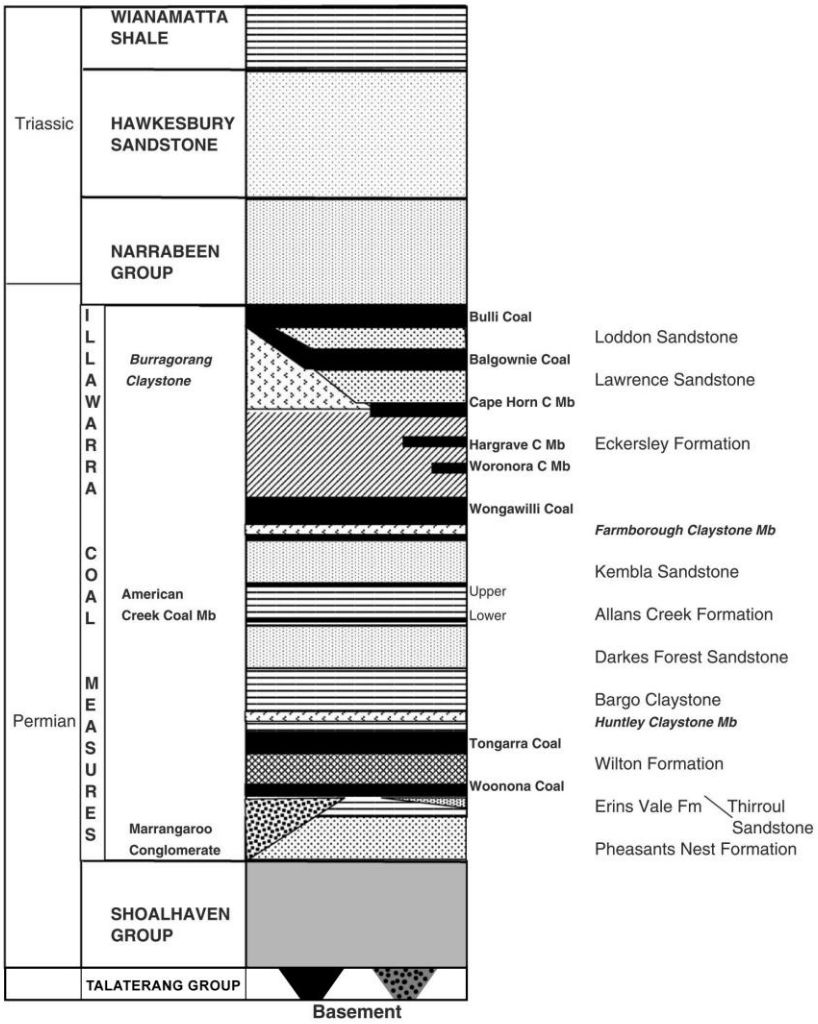


Figure 12 Overall stratigraphy of the Sydney Basin (not to scale) (after Grevenitz et al., 2003, Geological Survey of NSW, 2012, NSW Geological Survey, 1985)

The erosional surface at the top of the Bulli Seam is overlain by the Triassic sequence, namely the Narrabeen Group and Hawkesbury Sandstone. The Narrabeen Group comprises lithic to quartz lithic sandstones, shales and claystones and has a thickness ranging from 300 to 500 metres. This group also contains the Bald Hill Claystone unit, a largely continuous aquitard/aquiclude capping the Narrabeen Group. The Bald Hill claystone unit has been identified as an important impermeable unit in restricting the migration of water and gas into adjoining aquifer systems (Haworth, 2003).

Overlaying the Narrabeen Group is the Hawkesbury Sandstone, a group typically around 190 m thick in the southern region of the basin and particularly visible in outcrops across the entire Sydney Basin. The group consists of medium to coarse-grained quartzose sandstones and represents a return to a fluvial, braided river depositional environment. There are a number of mudstone lenses that appear throughout the sequence, but these are estimated to represent only 5% of the group (Bunny, 1972, Conaghan, 1977, Miall, 2006).

Above the Hawkesbury Sandstone, directly west of Sydney is the Wianamatta Group. This is the uppermost preserved unit of the Sydney Basin and is up to 300 metres thick. Thermal studies based on vitrinite reflectance (Middleton and Schmidt, 1982) suggests that coal seams were heated to temperatures of 250-300°C suggesting that at least 1 km of sediment has been removed from the upper portions of the basin, while apatite fission studies (Moore et al., 1986) suggest 1.5-2.5 km of erosion has taken place along coastal regions of the Sydney Basin. It is quite likely that the uppermost Wianamatta Group may have originally been much thicker and more extensive than its current limited distribution. The Wianamatta Group consists of two main units, the lower Ashfield Shale and the upper Bringelly Shale. The basal layer of the group is the Mittagong Formation, which rests unconformably on the Hawkesbury Sandstone. The thin Michinbury Sandstone (3 metres thick) represents a near shore depositional environment, and separates the lower Ashfield Shale from the overlying alluvial Bringelly Shale (Bunny, 1972, Herbert, 1976, Haworth, 2003).

Units of the Sydney Basin directly related to CSG accumulations are discussed in further detail in the following section of this thesis.

3.2. THE SOUTHERN COALFIELD

The Southern Coalfield is one of five major coalfields in the Sydney Basin, with the others being the Western Coalfield, the Central Coalfield, the Hunter Coalfield, and the Newcastle Coalfield (Figure 13). The Southern Coalfield comprises the southern portion of the Sydney Basin, covering an area south of Sydney almost to Batemans Bay, bounded in the west by the towns of Camden and Mittagong, and Helensburgh and Wollongong in the east. The present areas of active longwall coal mining and CSG development are typically located around the Hume Highway to the west and the Illawarra escarpment to the east (McNally and Evans, 2007, NSW Dept. Trade and Investment, 2012).

The first coal mining operation began in the region at Mt Keira in 1848, with more than 60 mines established in the region since that time. The high quality coking coal became one of the key drivers for economic development in the region, leading to the development of a vibrant local steel industry, port facilities, and railway lines linking Wollongong to Sydney. Although industries such as tourism and education have helped diversify the mix of commercial enterprise in the region, coal mining continues to play an important role in the Illawarra economy (ERMA, 2007).

The structure of the Southern Coalfield forms a broad syncline, which encloses the southern end of the Sydney Basin. Typically, units dip between 2-5 degrees to the NW with the numerous synclines and anticlines trending in a NW direction. Faulting is not considered to be intense and is often associated with folding, although some major faults have displacement of up to 90 metres and trend north-westerly (Hutton, 2009).

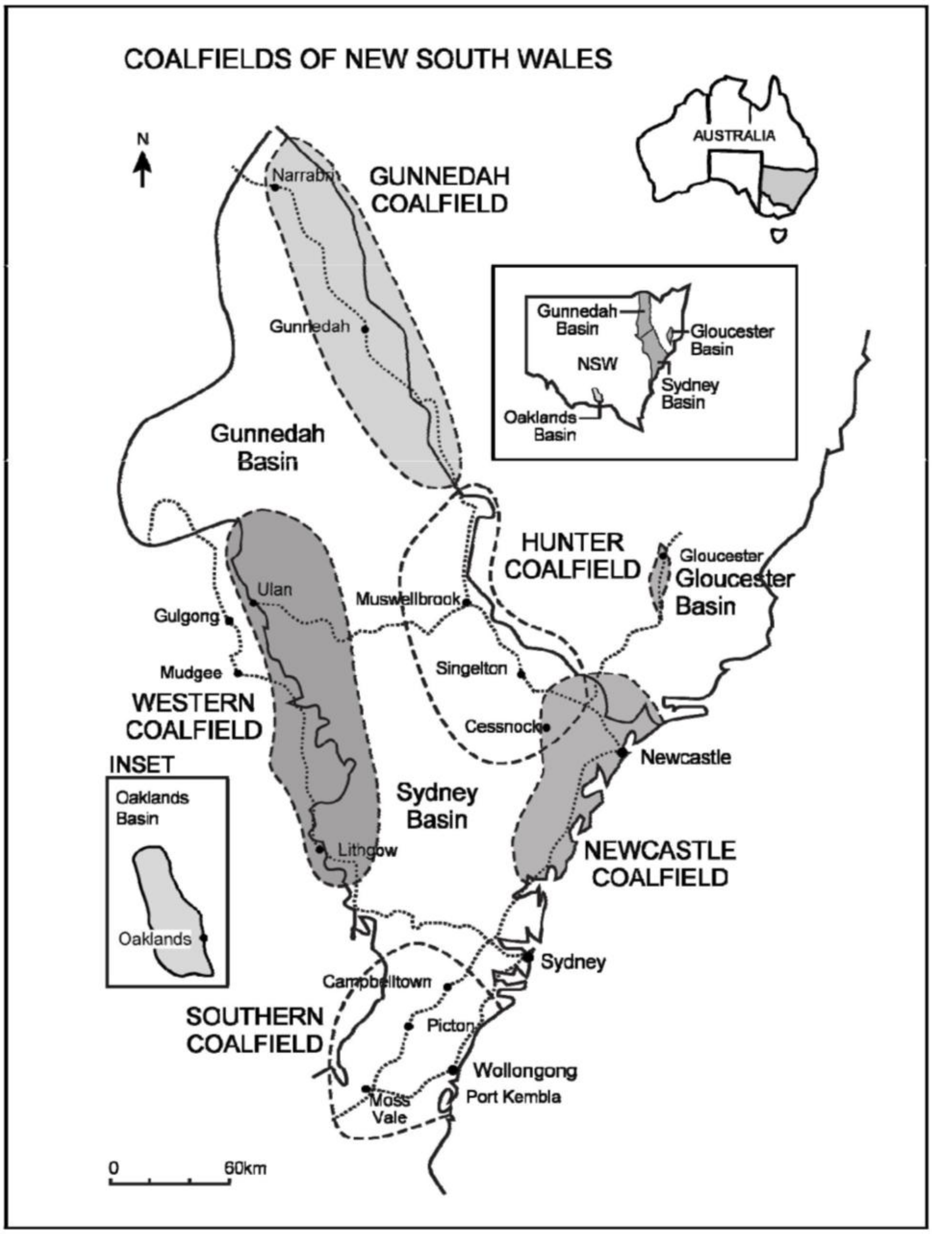


Figure 13 Coalfields of NSW (Holla and Barclay, 2000)

The topography of the region is a rugged sandstone plateau intersected by steep V-shaped gorges, which in some sections exhibit a rectilinear drainage pattern characterized by dominant joints and lineaments. These lineaments, which can be the exposed surface of igneous dykes or clusters of ‘master’ joints and can sometimes be greater than 1 kilometre in length, are occasionally linked with regions of sub-surface rock mass permeability and lateral stress. The soils on the sandstone plateau surface are generally thin, with bare rock shelves frequently exposed in creek beds. The combination of thin soils, exposed rock shelves and relatively wide-spaced jointing, tends to intensify surface strains and cause noticeable vertical fractures in areas that have been undermined (Bunny, 1972, Sherwin and Holmes, 1986, McNally and Evans, 2007).

3.3. THE MAJOR SEQUENCES OF THE SOUTHERN COALFIELD

The major sequences of the Southern Coalfield requiring further discussion in this study are the Illawarra Coal Measures, and the Triassic sequence of the Narrabeen Group and Hawkesbury Sandstone.

3.3.1. ILLAWARRA COAL MEASURES

The geological units of major economic significance in the Southern Coalfield are the late Permian lllawarra Coal Measures, a 240 metre thick deltaic sequence that sit above the Shoalhaven Group and beneath the Hawkesbury Sandstone and Narrabeen Groups. The Illawarra Coal Measures (Figure 14) are divided into two subgroups, the basal Cumberland Subgroup containing both the Pheasants Nest Formation and Erins Vale Formation; and the Sydney Subgroup which contains all the economic coal seams (Bulli, Balgownie, Wongawilli, and Tongarra seams). The coal measures appear above sea level approximately 20 kilometres to the north of Wollongong, undulating over the escarpment where the full outcrop is exposed near Wollongong. The outcrop continues in a southerly direction for approximately 40 kilometres, turning westward to track the northern side of the Shoalhaven River valleys (Bowman, 1973, Hutton et al., 1990, Hutton, 2009).

The Bulli Seam in particular has become the main target for CSG exploration and development in the region, with greenfield CSG production near the Camden region and goaf methane at the Appin and Tower collieries operating for 10 years and 16 years respectively. Nearer to Wollongong in the Helensburgh/Darkes Forest region, Apex Energy has submitted plans to develop CSG from the collapsed coal workings (goaf) of the Metropolitan Colliery.

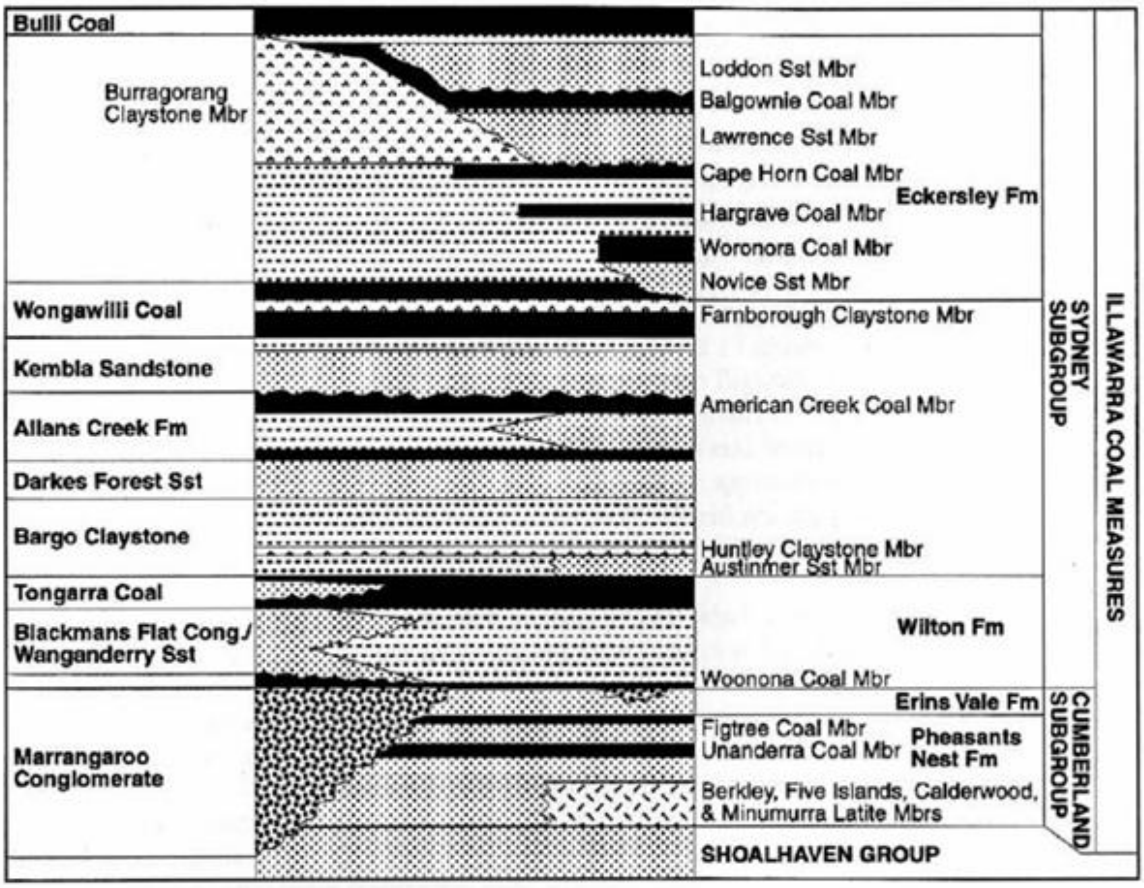


Figure 14 Stratigraphy of the Illawarra Coal Measures, southern Sydney Basin (From: Hutton and Bamberry, 1999)

The Bulli Seam is stratigraphically the top seam in the Illawarra Coal Measures and represents the majority of the coal reserves. The seam is generally two to three metres thick, apart from the northern section of the coalfield where it increases to around 5 metres. It comprises interbanded dull and bright coal plies, with sub-bands of siderite and claystone. The seam is medium ash (8-9% in the east, and increasing westward), medium volatile matter (21.5 to 27.5%, air dry) and has relatively low sulphur content.

In terms of potential for CSG development, the Sydney Basin and Illawarra Coal Measures represent an enormous reservoir for methane, with gas contents in many areas in excess of 18 m^3 per tonne, with the gas consisting predominantly of methane (up to 95%), with ethane concentrations up to 5% at greater depth (Faiz and Hutton, 1995).

3.3.2. THE TRIASSIC SEQUENCE

The Triassic sequence of the Southern Coalfield (i.e; the Narrabeen Group and Hawkesbury Sandstone) is mainly sandstone, with finer-grained rocks at depth. The combined sequence varies in thickness from about 100 metres at the Illawarra escarpment to 400-500 m towards the longwall mines to the west, dipping to the NW at a very low angle. Both major groups are intruded in places by basaltic and syenitic plugs, sills and dykes. These intrusions into the sequence may act as channels for surface water to migrate down to seam level, and depending on the intensity of weathering and fracturing, can act as groundwater dams, or vertical aquifers. It is generally accepted that although natural faults are present, they do not have a great impact on groundwater (Bunny, 1972, Sherwin and Holmes, 1986, McNally and Evans, 2007). A cross-section of the full sequence is provided in Figure 15.

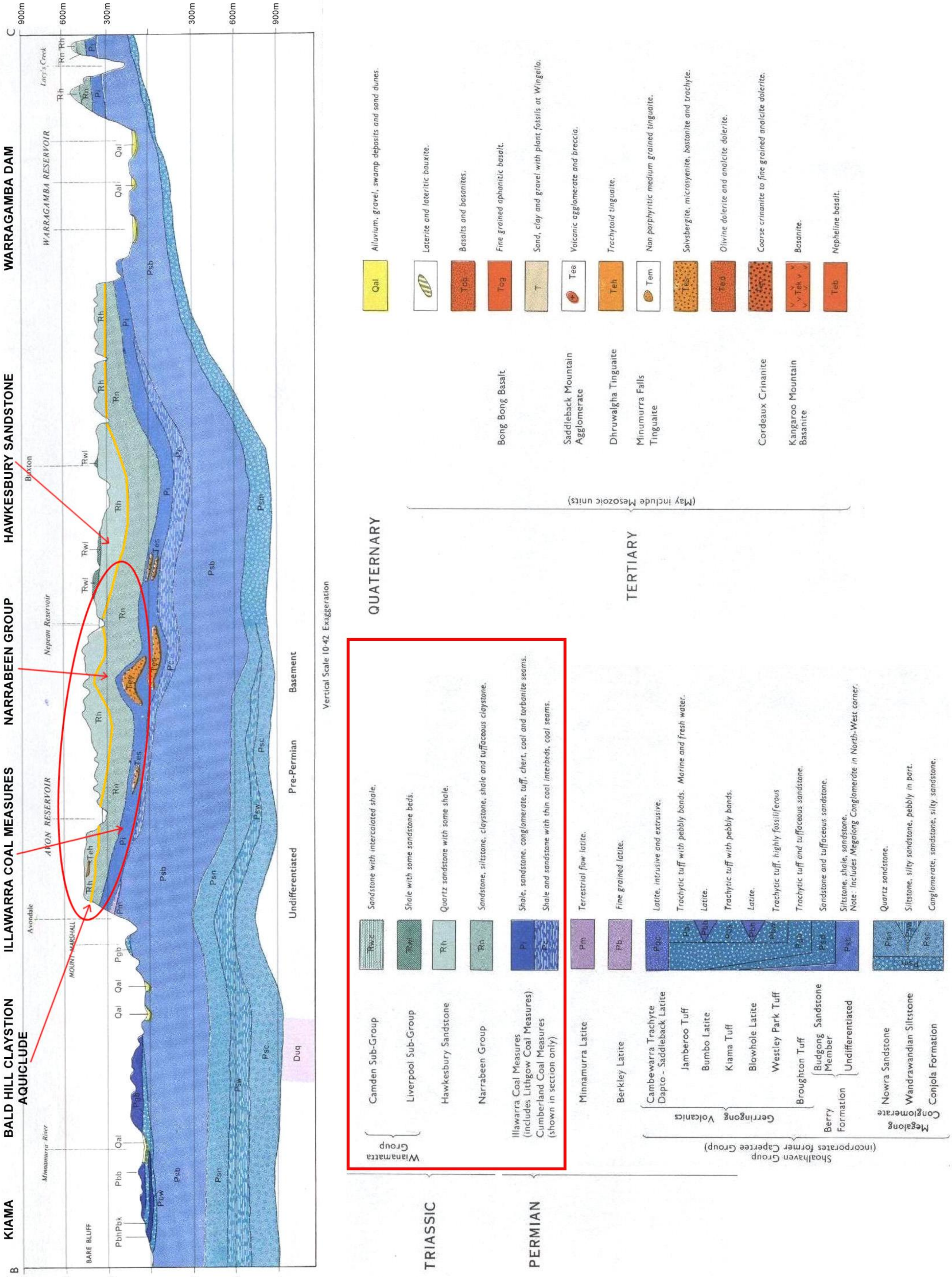


Figure 15 Cross-section of the Southern Coalfield (SE to NW)
Source: Geological Survey of NSW

3.3.3. NARRABEEN GROUP

The overall thickness of the Narrabeen Group in the Southern Coalfield is about 300 metres, of which 200 metres is the Bulgo Sandstone and 24 metres is the overlying Bald Hill Claystone. The Bald Hill Claystone is generally thought to act as a confining or sealing layer (aquiclude) between the Bulgo and overlying Hawkesbury Sandstone. Assessments of both groups show that the Narrabeen Group differs from the Hawkesbury Sandstone in the following ways:

- bedding in the Narrabeen Group is typically more continuous (shale beds often extend horizontally further than 100 metres),
- the Narrabeen Group displays minimal cross bedding, and
- cliff lines in the Narrabeen Group are less visible. (McKibben and Smith, 2000, McNally and Evans, 2007)

The group is also characterised by its petrological features:

- Grains of the Narrabeen Group sandstones are a mix of quartz and lithic fragments, rather than purely quartz. The sand-sized lithic fragments make up around 20-30% of the clastic part of the unit, and are not as well sorted as in the Hawkesbury Sandstone.
- Unweathered Narrabeen Group sandstones are typically more cemented, denser and less porous than the Hawkesbury Sandstone, and the cement is principally carbonate (more siderite than calcite).
- Unweathered rock is light to dark grey in colour due to the fine siderite cement and can be found 1 to 2 metres below the surface. Hawkesbury Sandstone is by contrast

often weathered and orange-brown to depths of 30 metres and greater (McKibben and Smith, 2000, McNally and Evans, 2007)

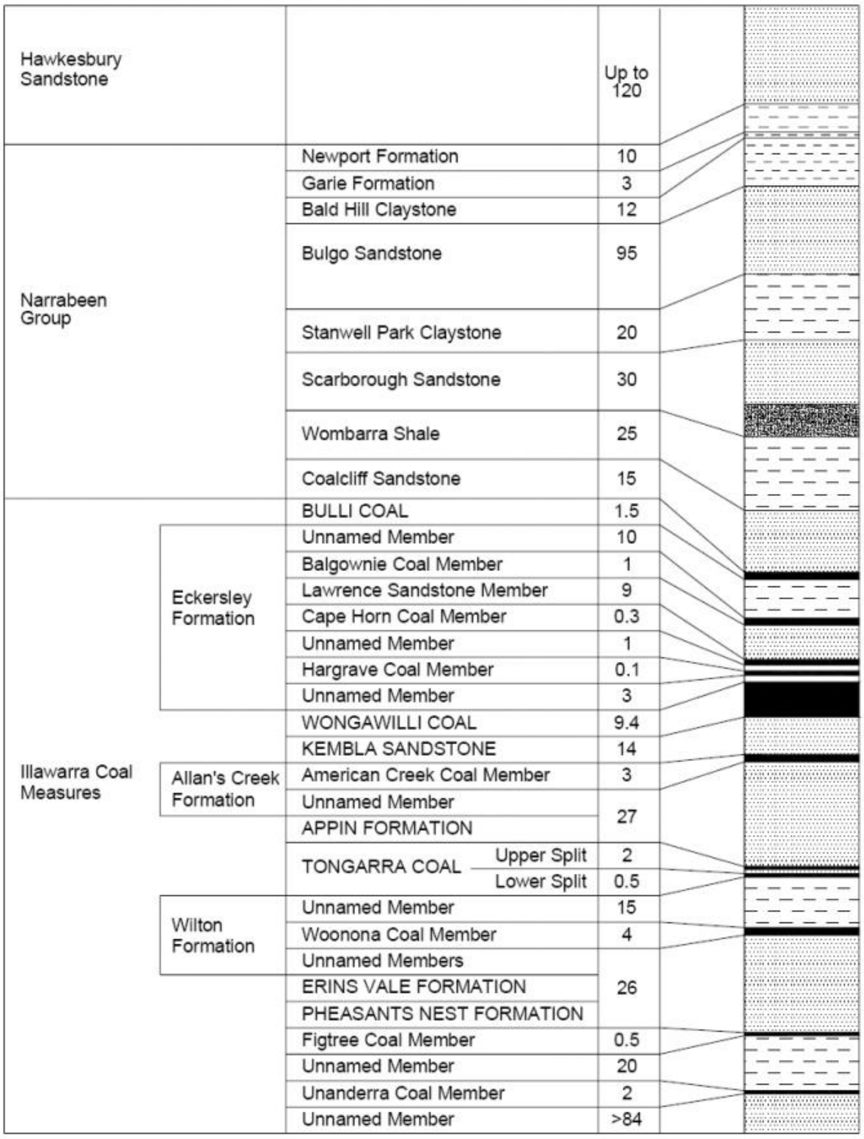
3.3.4. HAWKESBURY SANDSTONE

The Hawkesbury Sandstone is a quartz sandstone unit composed of very thick beds of heavily compacted sand or sandrock, with a small quantity (about 5%) of shale in discontinuous beds 1 to 3 metres thick. The width of the Hawkesbury Sandstone in the Southern Coalfield varies depending on the amount of erosion, but is typically 100 to 200 metres thick, with some sections up to 300 metres thick (Figure 16). The individual sandstone beds are generally 1 to 10 metres thick, but continue laterally for only 100 to 300 metres. For this reason, the sandstone beds are described as being ‘lenticular’. Their joints are sub-vertical and normally spaced slightly wider than the bedding planes (Bunny, 1972, Conaghan, 1977, Miall, 2006, McNally and Evans, 2007)

Groundwater flow is generally down joints and laterally across the bedding planes, creating numerous perched water tables after rain. There is also a certain amount of variability in the degree of cementation between layers, resulting in some beds outcropping more than others. This is also likely to lead to variations in the distribution of perched water tables and differences in hydraulic conductivity (permeability) between layers (McNally and Evans, 2007).

The mineral content of the Hawksebury Sandstone is relatively consistent, being made up of:

- Quartz (typically 60-75%). Mostly detrital, but includes secondary silica produced from compressed quartz grains.
- Clay (typically 20-30%). Mostly kaolinite, but with small amounts of illite-smectite and illite-mica (sericite).



Hawkesbury Sandstone				Up to 120
Narrabeen Group		Newport Formation		10
		Garie Formation		3
		Bald Hill Claystone		12
		Bulgo Sandstone		95
		Stanwell Park Claystone		20
		Scarborough Sandstone		30
		Wombarra Shale		25
		Coalcliff Sandstone		15
Illawarra Coal Measures		BULLI COAL		1.5
	Eckersley Formation	Unnamed Member		10
		Balgownie Coal Member		1
		Lawrence Sandstone Member		9
		Cape Horn Coal Member		0.3
		Unnamed Member		1
		Hargrave Coal Member		0.1
		Unnamed Member		3
		WONGAWILLI COAL		9.4
		KEMBLA SANDSTONE		14
	Allan's Creek Formation	American Creek Coal Member		3
		Unnamed Member		27
		APPIN FORMATION		
		TONGARRA COAL	Upper Split	2
			Lower Split	0.5
	Wilton Formation	Unnamed Member		15
		Woonona Coal Member		4
		Unnamed Members		26
		ERINS VALE FORMATION		
		PHEASANTS NEST FORMATION		
		Figtree Coal Member		0.5
		Unnamed Member		20
		Unanderra Coal Member		2
		Unnamed Member		>84

Figure 16 Stratigraphic column for the Southern Coalfield (NSW Government, 2008)

- Siderite (iron carbonate), (typically 3-5%). Usually appears as a very fine intergranular material, and not continuous cement. Imparts a grey tone on fresh sandstone and light brown/pink colouring on weathering.

- Iron oxides (limonite, hematite, goethite), (typically 1–4%). Derived as a weathering product from siderite, and along with siderite, may be the source for some of the rust-coloured groundwater in the region (McKibben and Smith, 2000, McNally and Evans, 2007).

3.4. HYDROGEOLOGY OF THE SOUTHERN COALFIELD

One of the reasons that CSG development has come under intense scrutiny are the potential impacts on groundwater and surface water systems. It is therefore important to discuss these systems as they relate to the Southern Coalfield.

As shown in Figure 17, the typical representation of the hydrogeologic cycle is described as a sequence of higher permeability units called aquifers, confined by units of lower permeability called aquitards (Reynolds, 1976).

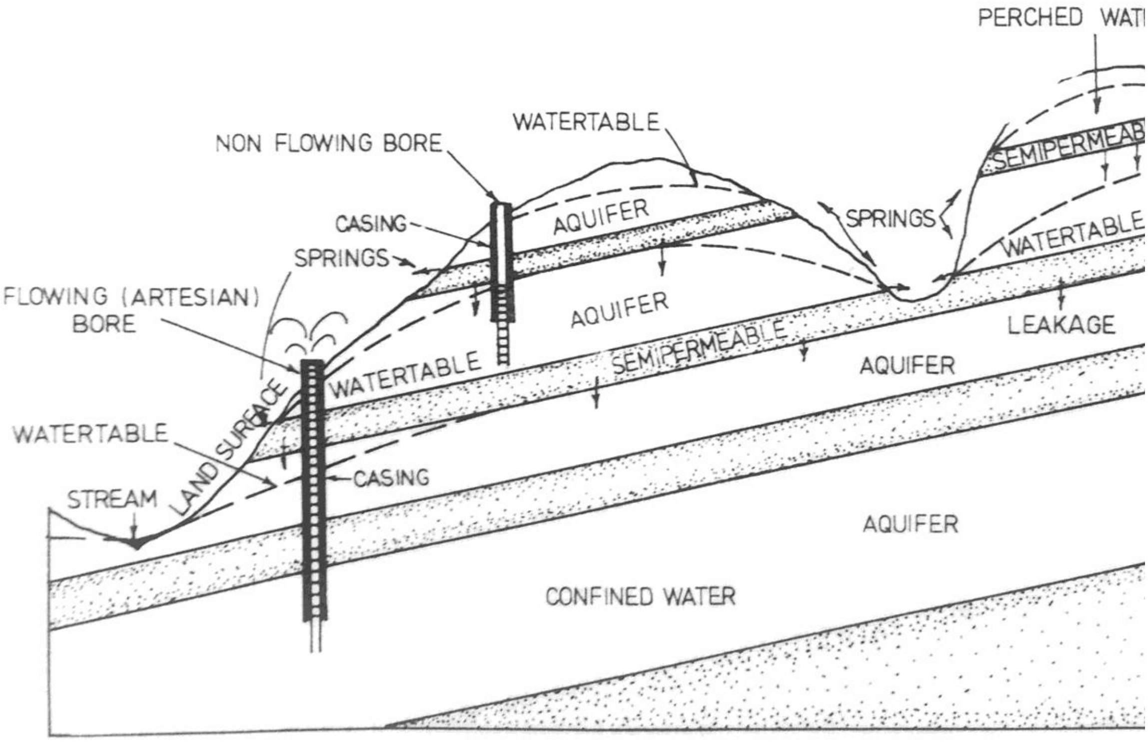


Figure 17 Typical hydrogeologic system (Source: Reynolds, 1976)

In the Southern Coalfield however, there is general consensus that both the natural hydrologic systems and the impacts of coal mining and water storage have created a hydrogeologic cycle more complex than the traditional representation. There is not scope in this report to analyse the system in all its complexity, however a number of the significant characteristics are provided below.

Perched aquifers and vertical groundwater flow down joints and through sandstones.

The proposed model of the groundwater system in the Southern Coalfield is provided by Reynolds (Figure 18) which shows a system of perched aquifers and low permeability layers, with groundwater flowing down joints and horizontally across bedding planes. The system is typically *anisotropic*, meaning that horizontal groundwater flow is significantly greater than vertical flow. While vertical flow is typically minimal in the region, it has been suggested by Judell et al., (1984) that subsidence from longwall mining can create fractures that lead to an increase in vertical flow. The overall result is the movement of groundwater stepping downwards through a ladder-like network of numerous semi-isolated aquifers, (some of which may be impacted by the effects of longwall mining) linked by zones of higher permeability such as joints and cleaner sandstones (Reynolds, 1976, Judell et al., 1984, Soliman et al., 1997, Stone, 1999, Nonner, 2003, NSW Government, 2008). The variability of cementation between layers also results in some beds outcropping more than others, thereby leading to further variations in the distribution of perched water tables and permeability, particularly within the Hawkesbury Sandstone (McNally and Evans, 2007).

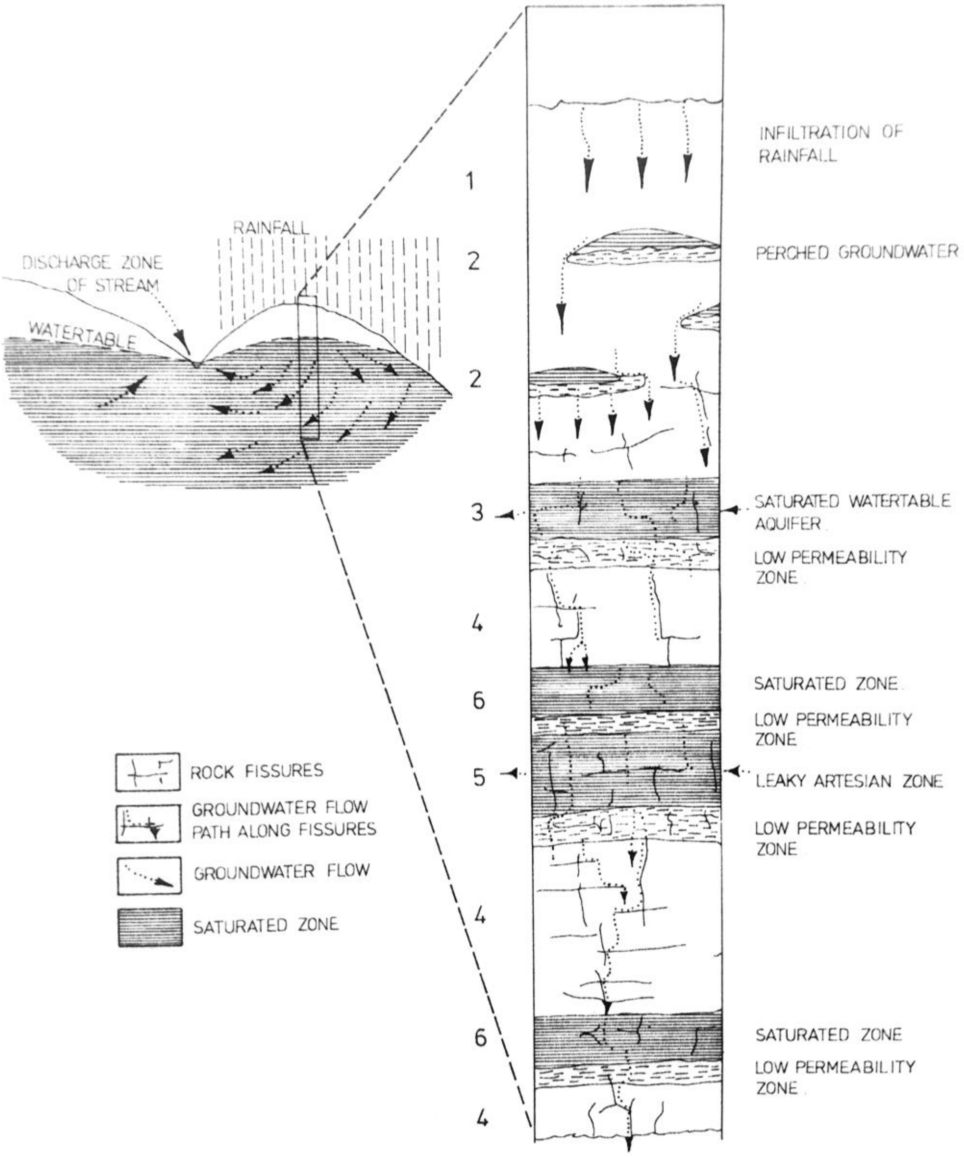


Figure 18 Proposed hydrogeological model of the Southern Coalfield (Reynolds, 1976)

Significant differences in permeability between surface sediments and deeper rocks.

The permeability of the shallow unconsolidated, soils, swamps and alluvial deposits (moderate to high permeability) is significantly higher than the permeability of the deeper consolidated rocks such as the Hawkesbury Sandstone and Narrabeen Group (low permeability). Consequently, groundwater flows through the soils and regolith much faster than it flows through the consolidated rocks. It therefore follows that the contributions of groundwater flow into the creeks and rivers within the region are significantly greater from the swamps and regolith than from the deeper rocks such as the Hawkesbury Sandstone and Narrabeen Group. Accordingly, the age of the groundwater that originates from the surficial sediment is quite young, while groundwater that comes from the deeper rocks is typically extremely old, typically in the range of 5,000 to 10,000 years in parts of the Hawkesbury Sandstone (McKibben and Smith, 2000, NSW Government, 2008)

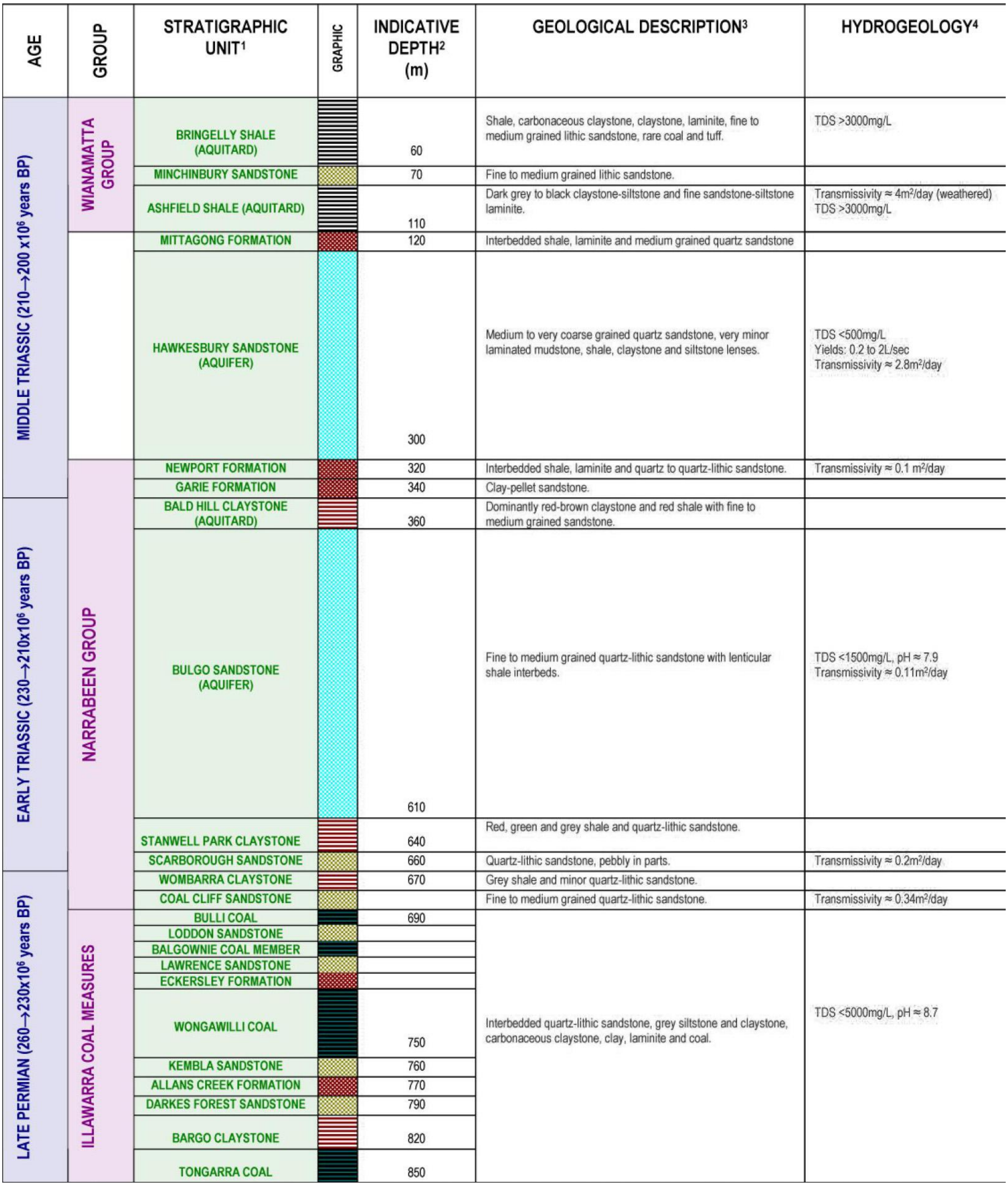
The Hawkesbury Sandstone – aquifer characteristics

The basic chemistry of groundwater is essentially the consequence of interactions between groundwater and rock over geologic time. Normally, natural uncontaminated groundwater will exhibit chemical stability within a narrow and predictable range, typically attributable to recharge processes. However, changes in groundwater flow paths, or reductions in recharge rates possibly caused by natural or induced fracturing of sandstone aquifers, may cause new rock/water reactions to take place. This can lead to short-term changes in groundwater chemistry, although it would be expected that conditions will tend towards stabilisation over time, with the groundwater chemistry tending towards the profile before conditions were altered (NSW Government, 2008, Karsten et al., 2008, Nonner, 2003, Stone, 1999).

In the Southern Coalfield, the Hawkesbury Sandstone is of great significance to groundwater, surface water and topography. The unit is highly resistant to weathering, and therefore the dominant topographical features of valleys and cliffs are concentrated on the sandstone's naturally occurring faults and joints. It also hosts a multi-layered system of subaquifers (perched water tables), connected by vertical joints and discontinuities in horizontal bedding planes (McKibben and Smith, 2000, McNally and Evans, 2007).

As an aquifer, it is typically only exploited for its water in a few areas such as the Southern Highlands where well yields can be as high as 40 litres per second, although typical yields are usually 0.2 to 2 litres per second (Figure 19)(Sydney Catchment Authority, 2006).

The water quality of the Hawkesbury Sandstone is generally potable close to recharge areas with total dissolved salts (TDS) less than 500 milligrams per litre, but salinity increases towards the centre of the Sydney Basin with TDS often greater than 10,000 milligrams per litre. The unit's porosity and hydraulic conductivity are typically secondary in origin, principally as a result of jointing and solution cavities (sandstone karsts). Permeability for the Hawkesbury Sandstone tends to be highly variable, especially in areas that have experienced subsidence from longwall mining, and therefore it is difficult to make general associations across the whole Southern Coalfield, although transmissivities of 2.8m^2 per day are typical (McKibben and Smith, 2000, McNally and Evans, 2007, Hammond, 2007, Moore and Nawrocki, 1980).



AGE	GROUP	STRATIGRAPHIC UNIT[1]	GRAPHIC	INDICATIVE DEPTH[2] (m)	GEOLOGICAL DESCRIPTION[3]	HYDROGEOLOGY[4]
MIDDLE TRIASSIC (210→200 x10^6 years BP)	WIANAMATTA GROUP	BRINGELLY SHALE (AQUITARD)		60	Shale, carbonaceous claystone, claystone, laminite, fine to medium grained lithic sandstone, rare coal and tuff.	TDS >3000mg/L
		MINCHINBURY SANDSTONE		70	Fine to medium grained lithic sandstone.	
		ASHFIELD SHALE (AQUITARD)		110	Dark grey to black claystone-siltstone and fine sandstone-siltstone laminite.	Transmissivity ≈ 4m^2/day (weathered) TDS >3000mg/L
		MITTAGONG FORMATION		120	Interbedded shale, laminite and medium grained quartz sandstone	
		HAWKESBURY SANDSTONE (AQUIFER)		300	Medium to very coarse grained quartz sandstone, very minor laminated mudstone, shale, claystone and siltstone lenses.	TDS <500mg/L Yields: 0.2 to 2L/sec Transmissivity ≈ 2.8m^2/day
	NARRABEEN GROUP	NEWPORT FORMATION		320	Interbedded shale, laminite and quartz to quartz-lithic sandstone.	Transmissivity ≈ 0.1 m^2/day
		GARIE FORMATION		340	Clay-pellet sandstone.	
EARLY TRIASSIC (230→210x10^6 years BP)		BALD HILL CLAYSTONE (AQUITARD)		360	Dominantly red-brown claystone and red shale with fine to medium grained sandstone.	
		BULGO SANDSTONE (AQUIFER)		610	Fine to medium grained quartz-lithic sandstone with lenticular shale interbeds.	TDS <1500mg/L, pH ≈ 7.9 Transmissivity ≈ 0.11m^2/day
		STANWELL PARK CLAYSTONE		640	Red, green and grey shale and quartz-lithic sandstone.	
		SCARBOROUGH SANDSTONE		660	Quartz-lithic sandstone, pebbly in parts.	Transmissivity ≈ 0.2m^2/day
LATE PERMIAN (260→230x10^6 years BP)		WOMBARRA CLAYSTONE		670	Grey shale and minor quartz-lithic sandstone.	
		COAL CLIFF SANDSTONE			Fine to medium grained quartz-lithic sandstone.	Transmissivity ≈ 0.34m^2/day
	ILLAWARRA COAL MEASURES	BULLI COAL		690	Interbedded quartz-lithic sandstone, grey siltstone and claystone, carbonaceous claystone, clay, laminite and coal.	TDS <5000mg/L, pH ≈ 8.7
		LODDON SANDSTONE				
		BALGOWNIE COAL MEMBER				
		LAWRENCE SANDSTONE				
		ECKERSLEY FORMATION				
		WONGAWILLI COAL		750		
		KEMBLA SANDSTONE		760		
		ALLANS CREEK FORMATION		770		
		DARKES FOREST SANDSTONE		790		
		BARGO CLAYSTONE		820		
		TONGARRA COAL		850		

Figure 19 Simplified stratigraphy of the Southern Coalfield showing typical hydrogeological characteristics (Source: Sydney Catchment Authority, 2007a)

[1]Regionally significant aquifers and aquitards indicated. References: [2](Harvest Scientific Services, 2001), Camden Coalbed Methane Project EIS (indicative depths to maximum 850m based on bore logs from Camden area); [3](NSW Geological Survey, 1985), Wollongong-Port Hacking 1:100,000 Geological Sheet; [4](Beavis, 1976), Engineering Geology; [4](McKibben and Smith, 2000), Sandstone Hydrogeology of the Sydney Region; [4](OEC, 1999), Cordeaux Colliery Strata Reinjection Project Review of Environmental Factors.

The Bald Hill Claystone

The Southern Coalfield contains a number of claystone and siltstone aquitards that restrict the movement of groundwater and gas between adjacent strata. The Bald Hill Claystone is possibly one of the more important aquitards in the Southern Coalfield because it occurs below the main aquifer in the region, the Hawkesbury Sandstone. It is generally accepted that the presence of the claystone restricts the exchange of groundwater and gas between the Hawkesbury Sandstone and the underlying Bulgo Sandstone (NSW Government, 2008, McKibben and Smith, 2000). This is significant for CSG development since wells are drilled through the both the Hawkesbury Sandstone aquifer and Bald Hill Claystone aquitard to reach the coal seams below. Migration of gas and fluids may occur if for example, well integrity was not maintained, or if the claystone was to be significantly fractured (Faiz and Hutton, 1995).

Rivers, rainfall, recharge and runoff

Rivers and streams of the Southern Coalfield tend to flow in a north-west direction away from the coast, typically following the bedding plane of the underlying sandstone bedrock. Rainfall that occurs in the region drains into to the network of creeks, streams and rivers, and recharge to any unconsolidated materials and underlying consolidated sandstone strata. This drainage network also acts on a regional level to relieve groundwater pressures and limit the elevation of the groundwater table to stream levels within the valleys and gorges. In areas away from the valleys and gorges, rainfall continues to recharge the system by creating an elevated water table and sustaining groundwater flows toward the creeks and rivers (McNally and Evans, 2007, Sydney Catchment Authority, 2007b)

Natural recharge in the region is complex, with aquifer systems recharged by rainfall over geologic time, and groundwater in the upper surfaces typically responding quicker than the deeper aquifers. Rates of recharge in the system are also affected by the local permeability of the rocks (including induced fractures from subsidence), in addition to natural evaporation and evapotranspiration. Recharge rates will also vary depending on local site characteristics. For example, in the upland areas where swamps exist runoff may be restricted. These upland swamps also act as water stores and provide a base flow component to creeks and streams.

During rainfall events, perching of the water table can be expected particularly in the upland swamps and the regolith, as rainwater infiltrates slowly through the profile. Groundwater flow can be enhanced along structural defects and are often observed as hanging swamps in many of the steep gorges, and are important in supporting groundwater dependent ecosystems.

Areas that have rock outcrops or thin regolith profiles will normally experience fast runoff, unless natural or induced fractures allow permeability and porosity to increase. These regions of fast runoff will typically not contribute significantly to groundwater recharge (McNally and Evans, 2007, Sydney Catchment Authority, 2007b, Hammond, 2007).

3.5. EFFECTS OF LONGWALL MINING

Adding further complexity to understanding the possible impacts of CSG development in the Southern Coalfield is the fact that much of the region has been subjected to decades of coal mining. It is therefore important to recognise that analysing potential impacts of CSG development in the region requires an understanding not only of the natural systems, but of the effects of human land use, particularly longwall mining. The Sydney Catchment Authority estimates that by 2030, over 90% of the Special Areas will have been undermined by either longwall or bord and pillar techniques (Sydney Catchment Authority, 2007b). There is no intention in this thesis to analyse in detail the potential effects of longwall mining as these impacts have been thoroughly analysed in previous studies. However, it is important to recognise that significant impacts on the natural systems in the Southern Coalfield have occurred largely as a consequence of coal mining.

In 2007, the NSW Government established an independent inquiry to investigate the past and potential impacts of mine subsidence on significant natural features in the Southern Coalfield. The subsequent report identified many past and future environmental impacts of both mining and other land uses in the region including:

- Cracking of stream beds and loss or redirection of surface water flows.
- Deterioration in surface water quality (particularly in springs).
- Reduction in groundwater quality (fresher water in shallow aquifers mixes with more saline water in deeper aquifers, or by reactions of oxygenated surface water with exposed rock that).
- Loss of ecosystem functionality.
- Damage to perched aquifers within seams creating new groundwater flow regimes.

- Lowering of water levels in wells.
- Significant possibility of degradation to valley infill swamps , swamp water and associated vegetation.
- Reduction in water quality from poorly controlled runoff.
- Artificial regulation of stream flows resulting in impacts on water flow, water quality, ecosystem function and aquatic ecology.
- Dams, weirs and other water supply infrastructure resulting in loss of habitat loss through loss of connectivity, storage, changes to water temperature and dissolved oxygen, and impacts on threatened species.

(NSW Government, 2008)

The existence of the Sydney Catchment Authority ‘Special Areas’ and the significant level of protection given to them, are designed to ensure impacts such as those outlined above are minimised. The water catchments are explained in further detail in the following section.

3.6. WATER CATCHMENTS

The 2008 report on the Impacts of Underground Coal Mining on Natural Features in the Southern Coalfield stated that the single most important land use in the Southern Coalfield is as a water catchment, with the region supplying over 4 million people in Sydney, the Illawarra and Southern Highlands with approximately 1.4 gigalitres of drinking water each day. This water supply system is managed by the Sydney Catchment Authority (SCA) and covers over 16,000 km^2, with 2.5 million megalitres of water stored in 21 dams. In addition to managing the catchments and dams, the SCA also owns 1,440 km^2 of land, and is responsible for associated infrastructure such as pumping stations, weirs, pipelines, tunnels and canals (NSW Government, 2008, Sydney Water, 2011).

The catchments on the southern and western fringes of the Sydney metropolitan area are known as the ‘outer catchments’, and are the source of the raw water stored in the SCA’s dams. The outer catchments host a wide variety of land uses; surface and underground mining, quarrying, urban development, rural residential, intensive agriculture, industry, grazing, State forests, national parks and State conservation areas. The largest sub-catchment is the Upper Nepean River system (**Error! Reference source not found.**), comprising the Upper Nepean River and most of its major tributaries - the Avon, Cordeaux, Cataract and Burke Rivers. The Georges, Woronora and Hacking Rivers host smaller, separate sub-catchments. All of these rivers are to some degree regulated by having their natural flows managed by major dams and/or small weirs, particularly the Upper Nepean River system which contains the Cataract, Cordeaux, Avon and Nepean Dams.

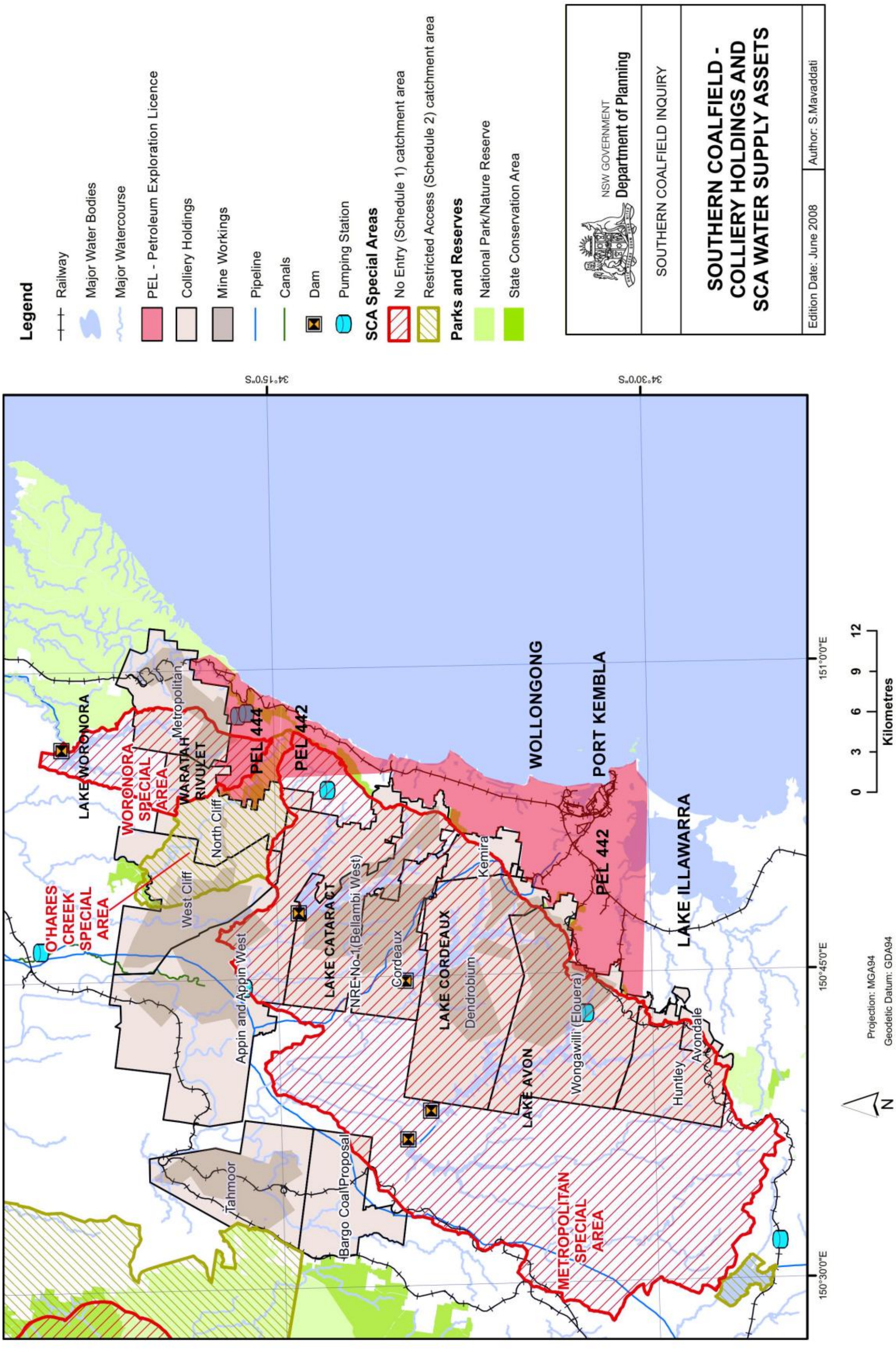


Figure 20 Southern Coalfield - Petroleum exploration, SCA supply assets, colliery holdings and workings (adapted from Southern Coalfield Inquiry report, 2008)

The Avon Dam is of particular importance to Wollongong as it is the principal source of water for the Illawarra. The Sutherland region however relies principally on drinking water from the Woronora Dam located on the Woronora River, which impounds parts of Waratah Rivulet.

The map in Figure 20 shows the Upper Nepean River system along with mining holdings, current petroleum exploration applications, and the Sydney Catchment Authority (SCA) supply assets and special areas. The 'Special Areas' surrounding SCA dams and storages (shown on the map by the red and lime green hatched regions) are lands declared under the Sydney Water Catchment Management Act 1998 for their ecological integrity and value in protecting the quality of the raw water. They are subject to extra management measures to protect water quality and are a critical element in protecting drinking water quality, with fines of up to $11,000 for trespassing into the areas on foot. The Special Areas basically function as a filtration system for inflowing water entering storages by reducing the nutrient and sediment load (SCA, 2007b). The three special areas located in close proximity to the Illawarra include:

- **Metropolitan Special Area** - includes all land draining to Pheasants Nest Weir on the Nepean River or Broughtons Pass Weir on the Cataract River (a total of 89,000 ha). This Special Area includes the Cataract Dam and the Cordeaux, Avon and Nepean dams which are all within the Upper Nepean catchment;

- **Woronora Special Area** - applies to the Woronora Dam catchment (7,600 ha) on the Woronora River; and

- **O’Hares Creek Special Area -** this area was proclaimed many years ago when a dam was proposed for O’Hares Creek. The plan for the dam was abandoned and the SCA has sought amendments to remove the Special Area classification for this area as it is not part of the water supply system.

It is important to recognise that mining is currently undertaken under much of the catchment, including SCA Special Areas. Petroleum exploration (PEL 444) is currently planned for parts of the Woronora Catchment, with some wells falling within SCA Special Areas. With such a considerable amount of underground mining in the region, it is not unreasonable to assume that future CSG development will likely involve the drilling and construction of gas wells in SCA Special Areas.

In its submission to the 2008 Southern Coalfield Inquiry, the SCA suggested that due to the lack of scientific data and baseline monitoring in the region, it was difficult to assess with any confidence the full range of potential impacts of mining on water resources in the Southern Coalfield (particularly groundwater resources). The SCA further advocated in its submission that it favoured a precautionary approach to any future mining in the region, using best practice risk assessment/management processes, backed up with comprehensive monitoring:

> ***“Until the reports from the science and research program become available, a risk management approach must be taken to applications for future mining in the most sensitive areas with the Metropolitan, O'Hares and Woronora Special Areas. “*** **(SCA, 2007b)**

It is also significant to note that the overarching aim of the *State Environmental Planning Policy (Sydney Drinking Water Catchment) 2011* is to provide for healthy water catchments that deliver high quality water while permitting development that is compatible with that goal. At the same time, the legislation also states that the consent authority (SCA) must not grant consent in a Special Area unless it is satisfied that the proposed development will have a *neutral or beneficial effect (NorBE)* on water quality. Determination of whether a particular development will have a neutral or beneficial effect on water quality is undertaken through the use of the NorBE Assessment Tool 2011.

4. COAL SEAM GAS

Coal seam gas (CSG) is a naturally occurring gas, predominantly methane (CH_4), found within the pores and fractures of all sub-surface coal seams typically at a depth of 300 to 1000 metres (Strąpoć et al., 2008, CSIRO, 2012, Freij-Ayoub, 2012). Also referred to as coal seam methane, coal bed methane or ‘sweet gas’, CSG is odourless and colourless, and is formed by the same chemical and physical processes that generate coal and oil, that being the microbial (biogenic) or thermal (thermogenic) decay of predominantly organic matter in oxygen-depleted environments over millions of years (Rutovicz et al., 2011, Moore, 2012, Freij-Ayoub, 2012). In Australia, CSG reserves are located in high volatile to medium volatile bituminous Permian coals of the Sydney and Bowen basins and subbituminous to high volatile bituminous Jurassic coals of the Surat Basin (Faiz, 2008). The gas is normally composed of more than 95% methane, and can also contain other hydrocarbons such as ethane, propane and butane, as well as carbon dioxide, carbon monoxide and nitrogen (CSIRO, 2012) . Once extracted, it can be used as a fuel in turbines to generate electricity, or compressed and transported in a natural gas pipeline for export or domestic use (Rutovicz et al., 2011).

4.1. HOW IS COAL SEAM GAS FORMED?

The process of coal seam gas development (Figure 21) begins in a wetland environment with predominantly organic plant material progressively accumulating at the base of a swamp, bog or marsh. As the burial and maturation process proceeds, physical and chemical processes begin to break down the plant debris forming thick peat beds. Over time, the organic debris is buried ever deeper and subjected to higher temperatures, with the overlaying sediment squeezing out the water, breaking-down the organic material into ever smaller fragments, and compacting the material into solid coal (Wang, 1996, Miller, 2004, Strąpoć et al., 2008)

The geochemical process that transforms peat into coal is known as coalification and can be expressed as:

PEAT → LIGNITE → SUBBITUMINOUS COAL → BITUMINOUS COAL → ANTHRACITE

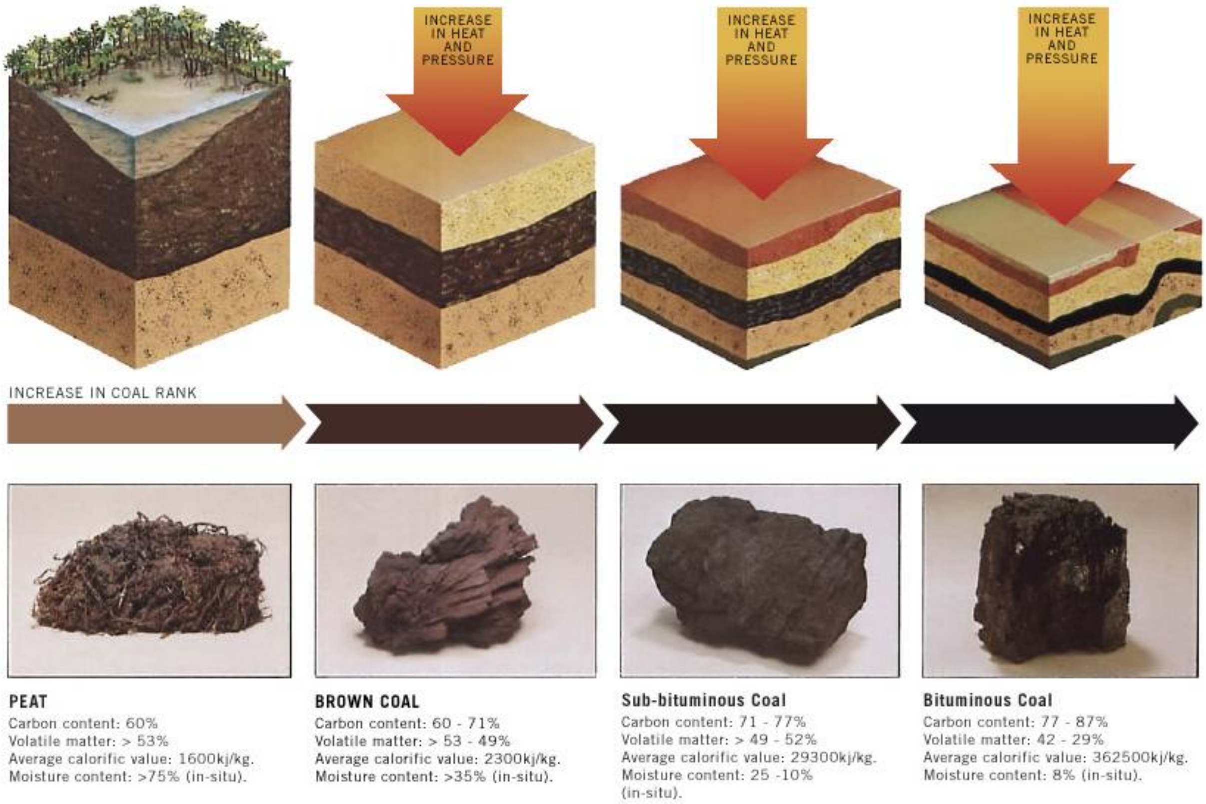


Figure 21 The process of coalification and increase in coal rank (Source: Australian Coal Association Research Program, 2012)

With increasing depth of burial and ongoing coalification, the coal rank increases, becoming ever richer in carbon, while continuing to release volatile matter such as water, carbon dioxide, and light hydrocarbons (including methane). As shown in Figure 22, coal seam methane content tends to increase with increasing rank, so that gas content is normally expected to increase with greater depth (Schoell, 1988, Coleman et al., 1995). Due to the nature of biogenic processes, low-rank coals typically contain mostly CH_4 and usually only small quantities of CO_2. However, in some reservoirs there may be some variation in CH_4 and CO_2 due to the kinetics of differential gas transport. These variations can influence the economic viability of particular regions (Cui et al., 2004).

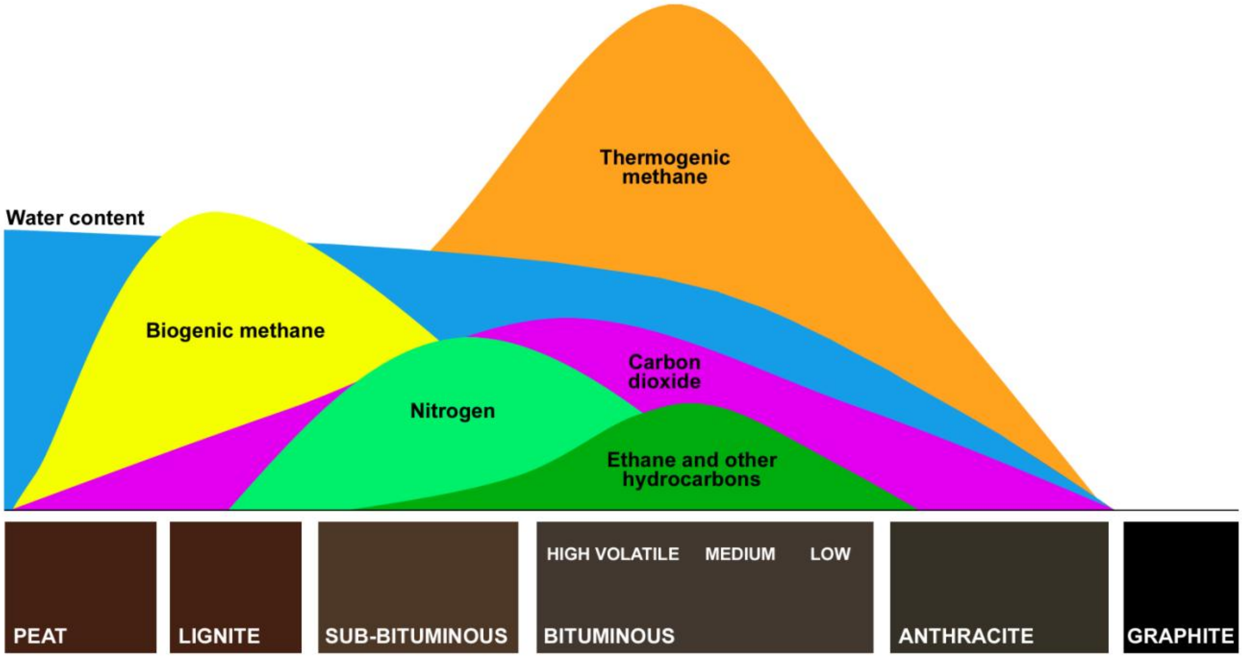


Figure 22 Gas and water content of coals
(Adapted from: ALL Consulting, 2003, Bryner, 2004)

In addition, some reservoirs contain a variety of gases whose relative concentrations vary significantly both vertically and laterally within the basin. This is particularly the case in the Sydney Basin where ethane proportions within the Bulli Seam vary significantly depending on depth (Faiz et al., 2003), and where shallow igneous intrusives have caused CO_2 concentrations to increase upwards through multiple seams (Faiz et al., 2007).

The burial process is also responsible for the formation of two distinct types of methane – biogenic and thermogenic (Figure 25). Biogenic methane is typically formed at shallow depths and low temperatures by anaerobic bacterial decomposition (Ahmed and Smith, 2001, Rice, 1993). Its composition is almost entirely methane. In contrast, thermogenic methane is formed at deeper depths and higher temperatures, and can contain significant concentrations of ethane, propane, butane and other hydrocarbons. This is an important consideration when attempting to understand potential sources of methane contamination in water bores, since biogenic methane can be found at relatively shallow depths and may naturally intersect the water table (Schoell, 1983, Faber et al., 1992, Berner and Faber, 1988, Schoell, 1988, Rice, 1993, Whiticar, 1994, Coleman et al., 1995, Ahmed and Smith, 2001).

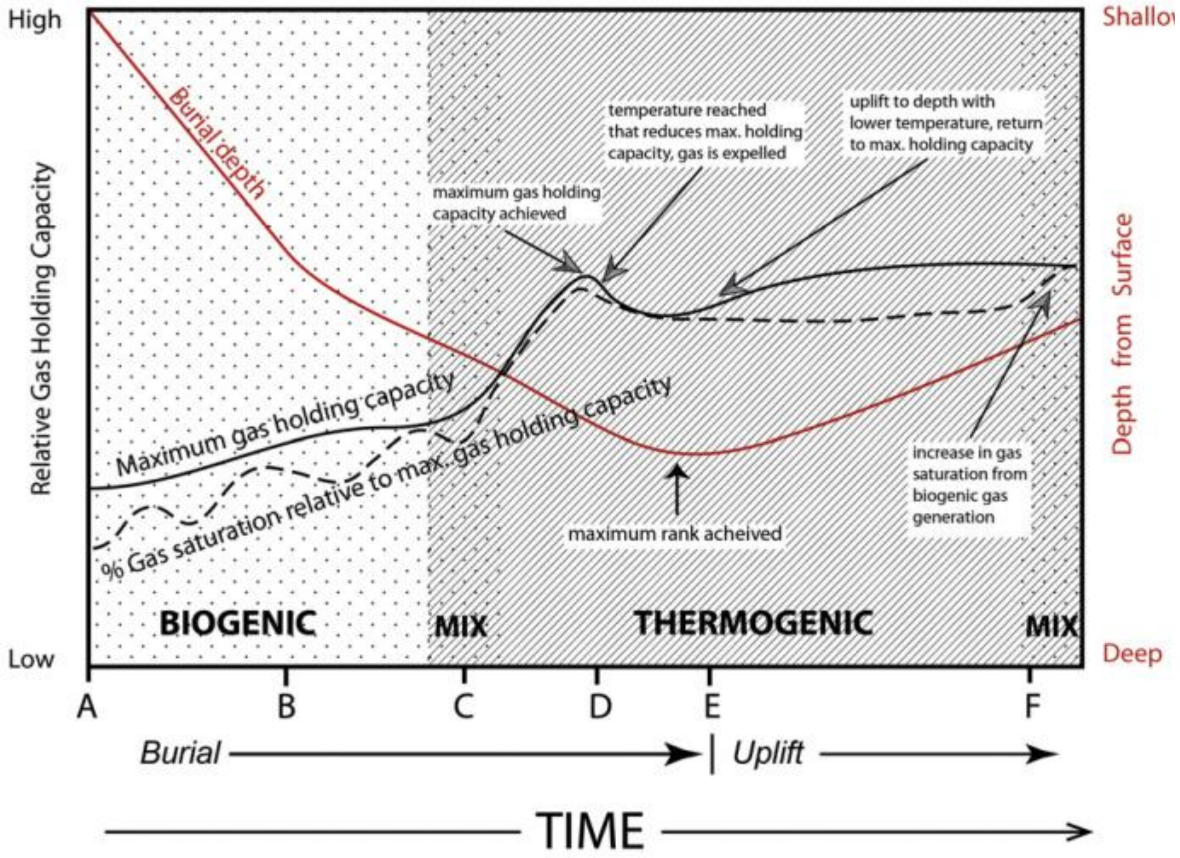


Figure 23 Time schematic of biogenic and thermogenic gas generation as related to burial and effect on gas saturation (Moore, 2012)

(A) Peat is formed and buried, primary biogenic gas gives way to secondary biogenic with depth.

(B) Continued burial and rank increase – moisture loss and and increase in maximum holding capacity. Gas saturation variable depending on local conditions.

(C) With burial and increased temperature, thermogenic gas is generated. Eventually, burial temperature will be rise to a point that biogenic gas generation will stop. Thermogenic gas saturation will be at its maximum and if geological conditions are right, could be 100%.

(D) Burial reaches a depth where temperature is so great that maximum holding capacity actually decreases (as per ideal gas law); gas is expelled but gas saturation remains the same. Maximum depth and maximum rank are achieved.

(E) With uplift, temperature decreases and maximum gas holding capacity increases. However, since some gas has been expelled, gas saturation gets concomitantly lower.

(F) In some cases if uplift is substantial and coal seams subcrop at the surface, biogenic enhancement may result in re-saturation of coal seams.

The presence of CSG has been known for many years and is particularly well understood within the underground coal mining industry, where the gas has proved to be particularly hazardous (Humphrey, 1960). A methane air mixture of 5-15% is typically explosive (Freij-Ayoub, 2012, Flores, 1998). To reduce the potential for explosions, miners have historically removed the gas by releasing it to the atmosphere (Christianovich, 1953, Ammosov and Eremin, 1960, Humphrey, 1960, Khodot, 1961, Cheng and Ding, 1971). CSG extraction essentially captures this natural gas and turns it into another energy source (Freij-Ayoub, 2012, Flores, 1998).

CSG is described as an unconventional natural gas, as opposed to a conventional natural gas. The basic difference between the two types is that unconventional gas is considered less economical or technically more challenging to extract than conventional gas. (CSIRO, 2012). Conventional natural gas is methane that migrates from where it forms, to create an underground reservoir (usually within a porous sandstone or limestone) beneath an impermeable rock stratum. The gas can then be discharged through a well under its own pressure. The basic differences between CSG and conventional natural gas are compared in Table 1 below.

Table 1 Comparison of CSG and Conventional Natural Gas (adapted from Rutovicz et al., 2011)

	COAL SEAM GAS	CONVENTIONAL NATURAL GAS
Geologic location	Coal seam. The gas is held to the surface of the coal by adsorption and hydrostatic pressure.	Sub-surface reservoir in sandstone or siltstone – easier to extract.
Depth	Typically 300-1000m[1]	Up to 5000m[1]
Pressure	Lower pressure (300-500kPa)[1]	Higher pressure (7,000 – 15,000kPa)[1]
Extraction	Need to depressurise coal seam by removing water.	Simpler technology - gas is released under its own pressure once the well is drilled.
Fracturing (such as hydraulic fracturing)	Often used but not always.	Possible for it to be used but typically not as often as CSG.
Composition in ground	Higher methane content > 95%[2] Less impurities[1]	Lower methane content ~ 90%[1]
Composition in pipe	Methane content 97%[2]	Methane content 90%[2]
Extraction techniques	Vertical, horizontal drilling, dewatering, hydraulic fracturing.	Vertical wells, hydraulic fracturing.
Well production	0.2 - 0.7 TJ/day for 5 to 15 years.[3,4]	10 to 20TJ/day for ~ 5 years[3]
Location of resources in Australia	The coal basins of Queensland, NSW and Victoria.	Western Australia, Victoria and eastern South Australia.

NOTES: 1. Kimber and Moran, 2004. 2. APPEA, 2011. 3. AGL Energy Ltd, 2011.
4. ALL Consulting, 2004.

Unconventional gas systems include CSG, shale gas, tight gas, deep gas and methane hydrates (Cleveland, 2004). CSG, shale gas and tight gas are found within complex geological structures where they were formed, with technological intervention required to release it from the rock (CSIRO, 2012). In the case of CSG, around 90% of the gas is stored in a near-liquid state mainly within the matrix of the coal, with the remainder held within the fractures (cleats) of the coal seams (U.S. EPA, 2009). Cleats refer to the natural fractures created by localised geological forces and the contraction of the buried organic matter under increasing heat and pressure. They have been described as the most important physical feature for gas flow in a CSG reservoir (Moore, 2012). The fractures in coal are termed either 'face cleats' or 'butt cleats', with the dominant fracture orientation referred to as 'face cleats' and the secondary, perpendicular fractures known as 'butt cleats' (**Error! Reference source not found.**).

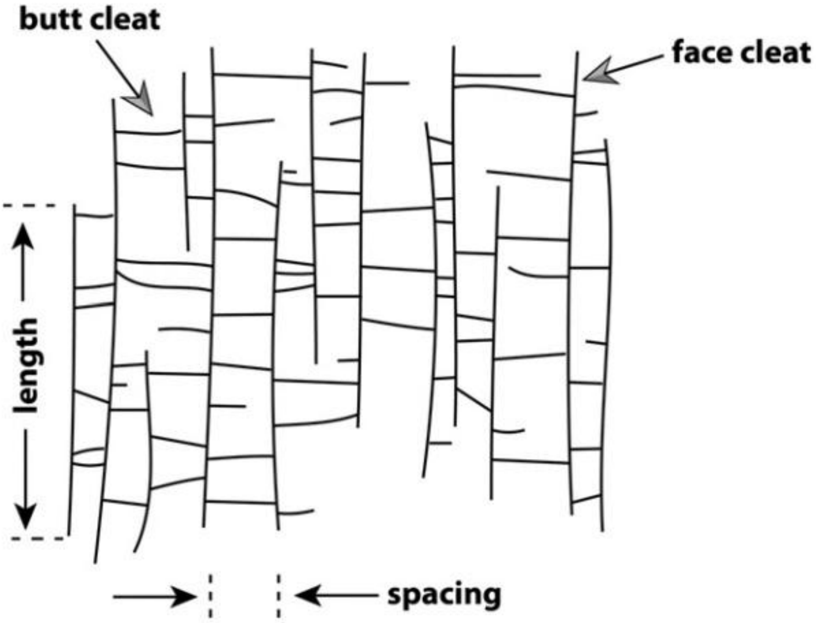


Figure 24 Schematic of face and butt cleats; view is looking down on the bedding plane. Note that face cleats are more continuous and butt cleats terminate at the face cleats (Moore, 2012)

The molecules of methane in a coal seam are held tightly within the large internal surface area of the coal by a combination of pressure from the overlaying rock, water in the seam, and a process called adsorption (Milewska-Duda et al., 2000). Adsorption refers to the physical adhesion of the gas molecules to the porous surface of the coal matrix via covalent bonding (Dallegge and Barker, 2000, Milewska-Duda et al., 2000, Rice, 1993). To extract the gas, the coal seam needs to be depressurized by removing the water. By removing the water and reducing hydrostatic pressure, the covalent bond between the methane and the coal is broken, allowing methane to desorb from the micropores of the matrix and be released through the cleats (Flores et al., 2008).

The concepts of permeability and porosity are of fundamental importance in understanding and assessing unconventional gas systems. Essentially, porosity refers to the amount of void space between the particles that make up the coal, while permeability is the degree to which these void spaces are interconnected. In terms of CSG development, permeability is important for determining the capacity for water and gas to flow through the reservoir and is generally determined by the number and width of the cleats and their continuity (Dabbous et al., 1974, Lingard et al., 1982). Typically, as overburden pressure increases with depth, the permeability of the coal can become restricted by closing the natural fractures in the rock (Somerton et al., 1975, Enever et al., 1999). Procedures such as hydraulic fracturing are often used (although not always) in CSG extraction to help increase the overall permeability of the seam and therefore increase the productivity of the well. The porosity of the coal determines a reservoirs capacity to contain gas on the surface of the coal matrix, and is determined by the size and number of pores, with most of the effective surface area of the coal – approximately 200 square metres per gram - being located inside the coal in its pores rather than on the outside surface of the coal (Chilangar et al., 2005)

4.2. DIFFERENCES BETWEEN CSG AND SHALE GAS

A substantial amount of the controversy surrounding unconventional gas development in the past few years has tended to concentrate on issues to do with shale gas, especially in the US (for example, the documentary Gaslands examines the issues surrounding shale gas development). It is important to be aware that there are important differences between shale gas and CSG. Firstly, shale gas is extracted from clay-rich sedimentary rock with extremely low permeability due to the fine-grained nature of the original sediments (Dewhurst et al., 1999). Current economic shale formations also contain almost no water and are usually found at depths of between 1200 to 3500 metres (Roth, 2011), often significantly deeper than coal seams which are typically found at depths of 300-1000 metres (GISERA, 2011, AGL Energy Limited, 2011a, Flores, 1998). Another key difference between CSG and shale gas is that since shale gas formations have low permeability, shale gas extraction always requires hydraulic fracturing, whereas with CSG this process is not always necessary (ALL Consulting, 2004). The decision to use hydraulic fracturing in CSG extraction is often site-specific, and determined by the natural permeability of the coal seam and to what extent well productivity can be increased by its use. It is also important to note that while shale gas supplied around 20% of US gas consumption in 2010 (Stevens, 2012), only a very small amount of shale production exists in Australia, with Santos Ltd announcing the first known commercial production of shale gas from the Cooper Basin in South Australia in October 2012 (ABC News, 2012).

It is not within the scope of this report to provide additional details on other types of unconventional gas, suffice to mention that CSG is just one of a number of unconventional gas types that are currently being extracted around the world to satisfy global demand.

4.3. CSG EXPLORATION

The history of commercial CSG development can be traced back to the United States in the 1970s, when the US Bureau of Mines attempted to improve mine safety by draining methane in advance of mining operations. CSG began to be produced in commercial quantities in the US during the 1980s, and grew rapidly from just a few dozen wells to almost 6,000 wells by 1992 (Moore, 2012).

CSG exploration began in Australia in 1976 in Queensland's Bowen Basin when two unsuccessful wells were drilled by Houston Oils and Minerals of Australia Incorporated (Geoscience Australia, 2012, Moore, 2012). In 1996, the first commercial coal mine methane operations began at the Moura mine in Queensland (owned by BHP Mitsui Coal Pty Ltd.) and also at BHP's Appin and Tower underground mines where methane drainage was used to power on-site gas-fired power stations (Freij-Ayoub, 2012). The first stand-alone commercial production of CSG commenced in December 1996 at Conoco's Dawson Valley Project which adjoined the Moura coal mine (Geoscience Australia, 2012). There has been significant growth in the industry since then, particularly in Queensland.

Typically, CSG developments move through two distinct stages – exploration and production. It is important to be mindful that in the current absence of a national legislative framework for CSG, that individual States have moved to develop their own policies and regulations in relation to CSG development. Furthermore, much of the legislation and regulations relating to planning and environmental assessment are currently under review in NSW, which may have some impact on the exploration and production processes outlined in this thesis.

In NSW, CSG exploration, assessment and production are principally regulated through the Petroleum (Onshore) Act 1991. This Act allows for the issuing of petroleum exploration licenses (PELs) and petroleum production leases (PPLs). The Act also stipulates that activities may require further assessment under other legislation such as the Environmental Planning and Assessment Act 1979 (NSW).

In terms of specific design, construction and environmental management standards relating to CSG exploration and development, companies in NSW are now governed by the guidelines outlined in the Codes of Practice for Coal Seam Gas – Well Integrity and Hydraulic Fracturing. These Codes of Practice were announced in September 2012, and are regulated by the NSW Department of Trade and Investment - Division of Resources and Energy (DRE) who authorise inspectors to ensure that companies are complying with regulations and work undertaken is of an acceptable standard (NSW Government, 2012b). The Codes of Practice outline certain mandatory requirements and best practice guidelines, and are meant to ensure that;

- the environment, particularly underground water is protected.
- risk to the public and workers is as low as reasonably practicable.
- any relevant Australian or International Standards, regulations and requirements are understood and implemented.

- appropriate design and construction techniques are used and ongoing monitoring is undertaken. (Queensland Government, 2011a)

Further information regarding the legislative framework and environmental assessment process is discussed in greater detail in Chapter 6 of this thesis. Consequently, the following section outlining the CSG development process assumes that all necessary environmental assessments and legal obligations have been satisfied, relevant codes of best practice are being followed, and permission obtained from the affected landholders and relevant authorities.

4.3.1. THE AIM OF CSG EXPLORATION

The fundamental aim of coal seam gas exploration is to find an assemblage of broadly distributed geological conditions favourable to the accumulation of natural gas that can be extracted economically (ABARES, 2010, Moore, 2012). Alongside that fundamental aim however, remains a significant challenge, and that challenge is in finding coal seams with a rank suitable for generating gas, but located at a depth that does not restrict permeability (Alberta Geologicial Survey, 2012). If a coal seam is of low porosity and permeability, then it will be difficult for the gas to move freely from the matrix of the coal seam into the cleats, and ultimately into the well head (Maracic et al., 2005). It therefore follows that many of the most productive CSG deposits have cleats permeable enough to let gas and water flow freely through them but located at a depth allowing for economic extraction (Australia Pacific LNG, 2012).

4.3.2. THE EXPLORATION PROCESS

This section provides a background on the exploration process as it occurs in many Australian CSG projects. Consequently, the major sources of information for this particular section has relied largely on Government agency and private company reports. Typically, once a company has satisfied all legal and environmental obligations required to carry out exploration, then the exploration process can continue through a number of stages including (Moore, 2012):

Investigating potential sites using computer based geological and geophysical techniques.

This is commonly referred to as making a desktop study and relies on an analysis of data generated from government, private company or academic sources. Site investigations may also be undertaken involving basic environmental checks, cultural heritage investigations, land use restrictions and desktop topographic analysis. If a particular site warrants further investigation, then the desktop study may also involve the planning of further analysis and drilling that might help in better understanding the coal and gas properties of the potential resource (AGL Energy Limited, 2011b, Queensland Government, 2011a).

Using land surveying techniques such as seismic to assess the potential size and extent of coal seams.

Geophysical surveying techniques such as seismic, magnetic, radiometric, gravity, induced polarisation and electromagnetic surveys may be used to further assess the potential resource. These surveys may utilise air-borne technologies or in the case of seismic surveys, often require the use of specialised vehicles (Figure 25) which may require minor vegetation clearing (such as grass slashing) for technical, safety and visibility reasons. Seismic analysis uses artificial sound waves produced from equipment mounted on a vehicle, with the underlying rock formations reflecting the waves back to the surface and received by geophones (Figure 26) at the surface. The surveys are used to generate a 2D image (Figure 27) of the sub-surface geology to assist in assessing the size and location of coal seams. Seismic studies can sometimes be used as a low impact alternative to drilling and can be conducted along existing roads in many areas. If the survey is considered successful, the company may choose to follow up with drilling of exploration core holes to further assess the resource (AGL Energy Limited, 2011b, Arrow Energy, 2011).

Figure 25 Basic seismic surveying vehicle (Arrow Energy)

Figure 26 Geophone receiver setup on surface. (AGL)

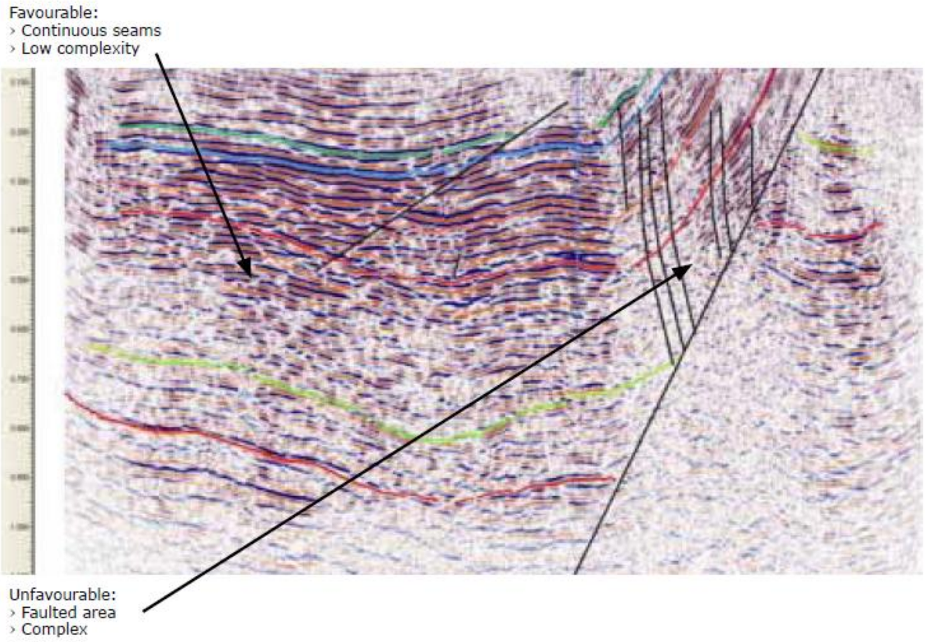


Figure 27 Example of the image produced from a 2D seismic survey (AGL)

Drilling core or chip holes to assess presence of coal and hydrocarbon accumulation.

Core and chip holes allow geologists to physically acquire rock and coal samples to assess the potential resource. They are not wells, and are unable to extract gas or water (APPEA, 2012a). Drilling core and chip holes require land access involving environmental assessments, site inspections, and landholder consultations prior to any work being undertaken (further details on the environmental assessment process is discussed in Chapter 6). The process of exploration drilling will generally take three to six weeks depending on the depth and type of exploration hole (Arrow Energy, 2011).

Depending on the underlying geology, drilling engineers may choose one method or a combination of methods to obtain the samples necessary for geological assessment. Common methods of CSG exploration drilling include:

- *Diamond drilling*: used to drill core holes. Core holes are typically 10cm to 30cm in diameter, producing core samples around 5cm to 10cm in diameter and divided into 1 metre lengths for easy analysis. Core holes require the use of a diamond bit with an opening that allows for a solid column of rock (core sample) to move up into the drill pipe and be recovered at the surface for assessment (Michna, 2012).

- *Rotary mud drilling*: often used for petroleum and deep stratigraphic drilling. Rotary mud drilling uses water and drilling fluids to lubricate the drill bit and return fine rock fragments to the surface. The drilling rigs are typically larger than for other methods and may require more support vehicles and site preparation. (NSW Government, 2012a).

- *Air drilling*: holes may be drilled using open hole percussion or the reverse circulation (RVC) process. An air-drilling rig is usually truck-mounted with one or two support vehicles. Both open hole percussion and reverse circulation drilling produce chips of rock that are brought to the surface by the compressed air. Air-drilling will often require less site preparation and rehabilitation than other drilling methods. RVC drilling tends to be faster and significantly less expensive than diamond core drilling (Michna, 2012).

Due to the significant costs involved in drilling, the sites identified for sample drilling would typically be considered carefully. Sites chosen are typically a few kilometres apart, flat, easy to access, and with consideration to potential environmental impacts (Santos Limited, 2010).

Once permission has been obtained to undertake drilling activity, the process of core and/or chip hole drilling will begin with preparation of the site (known as a ‘lease’) where an area of around 80m x 80m (maximum) is fenced, graded and prepared for drilling activity (Figure 28 28). Top soil is normally removed and kept for later rehabilitation. This preparation stage will typically take around three days (Santos Limited, 2010). Once the lease is prepared, two or three sump ponds for drilling fluids are excavated and lined with heavy plastic. Each sump is typically 5-10,000 litres each with a one metre buffer (freeboard) from maximum fluid height to land surface maintained during drilling operations (Santos Limited, 2010). Another hole known as a ‘cellar’ will also be dug approximately 2m square and 2m deep to house the Blow Out Preventer (BOP). The BOP is a safety mechanism to seal the well and minimise the risk of unplanned flow from the well or a build-up of pressure (Queensland Government, 2011a).

Figure 28 Typical core hole drilling site (Santos)

One of the potential environmental issues in regards to drilling and well construction is the risk of cross aquifer contamination. To reduce this risk, drilling engineers will run one or two layers (depending on depth) of steel casing from the surface through the alluvial and weathered material to solid rock and cement them in place (see Figures 29, 30 and 31). Cement Bond Logs (CBLs) are run to ensure the integrity of the cementing job (Dart Energy, 2012). The steel casings are then pressure tested to ensure that the concrete and casings are sufficiently sealed and able to prevent drilling fluids and water from lower aquifers mixing with water in upper aquifers (Santos Limited, 2010). When the casings and cement are in place, the BOP is placed at the top of the core hole, sealing the well to prevent overflow in the event of excess pressure. Once the BOP has been installed, drilling can continue using the coring method, extracting long columns of rock for assessment at the surface.

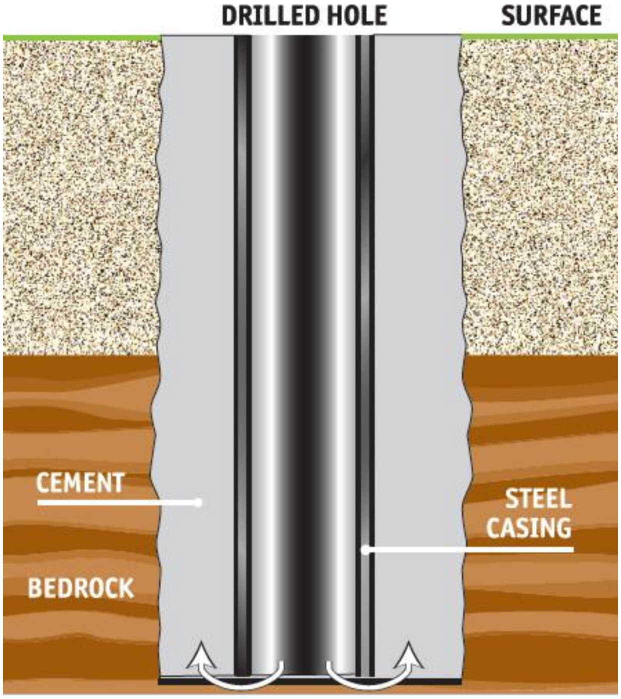


Figure 29 Surface casing - cement pumped up hole between the rock and casing.

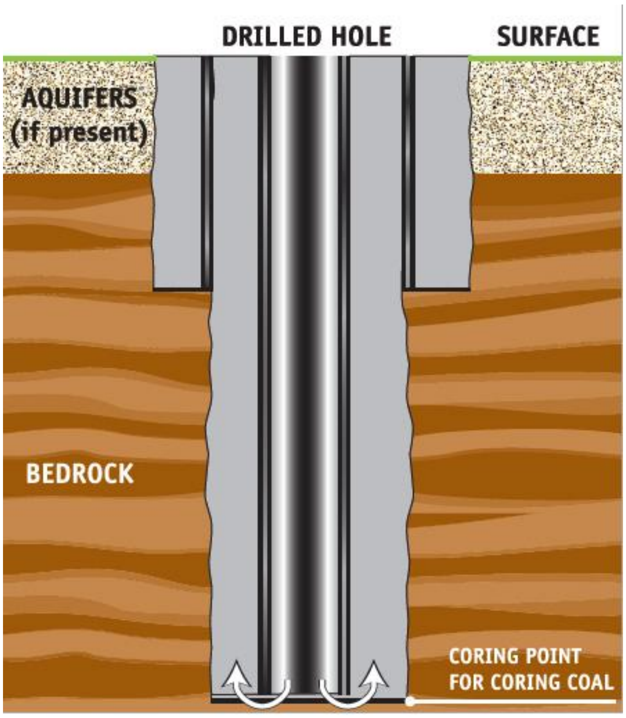


Figure 30 Intermediate casing - double layer of cement and steel to help prevent aquifer contamination.

Figure 31 Cross section of double steel casing (AGL).

Another important environmental consideration in exploration drilling are the use of drilling fluids. Drilling fluids are dispersed down the drill string and back up the annulus (void space) between the drill string and hole wall. Standard drilling fluids used in the industry are typically water-based (fresh water or based on salt brine), with potassium chloride a principal component. Organic polymers, clays, viscosifiers and additives may also be used, with biodegradable substances preferred (Queensland Government, 2011a). The fluids are used to lubricate the drilling assembly, remove cuttings, maintain pressure, and stabilise the hole, and therefore maximum retention of drilling fluid is desirable. Normal drilling fluid loss is estimated at approximately 5 to 6% of total volume used, with most of the drilling fluids and cuttings returned back to the drilling sumps (Santos Limited, 2012). Once in the sumps, the solid drill cuttings settle to the bottom and the liquid recirculated back down the assembly.

In NSW, the drilling fluid and additives are outlined in the Codes of Practice for CSG – Well Integrity and are considered in the Review of Environmental factors. In addition, drilling fluids are considered ‘wastes’ once taken off site and are subject to the Protection of the Environment Operations (Waste) Regulation 2005.

On completion of drilling and assessment, the hole is tested and logged. Unless the hole is required for further exploration testing or monitoring (such as installing a piezometer to monitor groundwater levels), it will be sealed completely (Figure 32) from the surface to the base of the hole with cement according to regulatory requirements (AGL Energy Limited, 2011b). The steel casing (filled with cement) is then cut off 1.5 metres below the surface and sealed with a metal identification plate and the well location reported to the relevant authorities (Santos Limited, 2010). If required, drilling fluids and cuttings are transported to a disposal facility and sump liners removed (and re-used if possible). The site is then rehabilitated with the stored topsoil being replaced, the ground seeded and fencing removed.

Figure 32 Cross section of abandoned double steel casing (AGL)

4.3.3. PILOT WELL TESTING

Pilot well testing is essentially small-scale gas production and the last step in the exploration process before full-scale gas production is undertaken (APPEA, 2012a). It is used to make a final determination as to the economic viability of the development, in addition to obtaining further information about permeability, gas volume, flow rates, water volumes, reservoir pressure and gas composition characteristics (AGL Energy Limited, 2011b, Dart Energy, 2012). Pilot testing also provides companies with a method of trialling the gas project, since an individual well is just one part of an often much larger network linked together by pipelines to a gas processing facility. This particular stage of the development process is also the first time where water is pumped off the coal seams, depressurising the seam and releasing the gas (Cameron, 2012). This makes pilot testing important in assessing the likely impacts of CSG production on local aquifers by physically measuring how much water is pumped from the wells (APPEA, 2012a).

The design of a CSG pilot project follows the same basic principles of core hole design, however it will often include multiples wells (often two to five) in close proximity, spaced approximately 100 to 500 metres apart depending on the location (Arrow Energy, 2011, Santos Limited, 2010). This means that the area of land cleared for an individual pilot well is similar to the area cleared in a single core hole drilling project, however multiple wells will require multiple drilling pads to be constructed. The main additions to a pilot well are the installation of pump and wellhead facilities to separate the gas and water produced by the well, and the construction of a water tank or pond to store produced water (explained in greater detail in the following section explaining gas production methods).

For pilot testing, the operator needs to provide a way for the gas to get from the formation into the well. This process is called perforation and involves a special gun shooting several small holes through the casing. These holes, or perforations, pierce the casing and cement surrounding the casing, and extend a short distance into the producing formation. Formation fluids, which including gas and water, flow through these perforations and into the well (Figure 33).

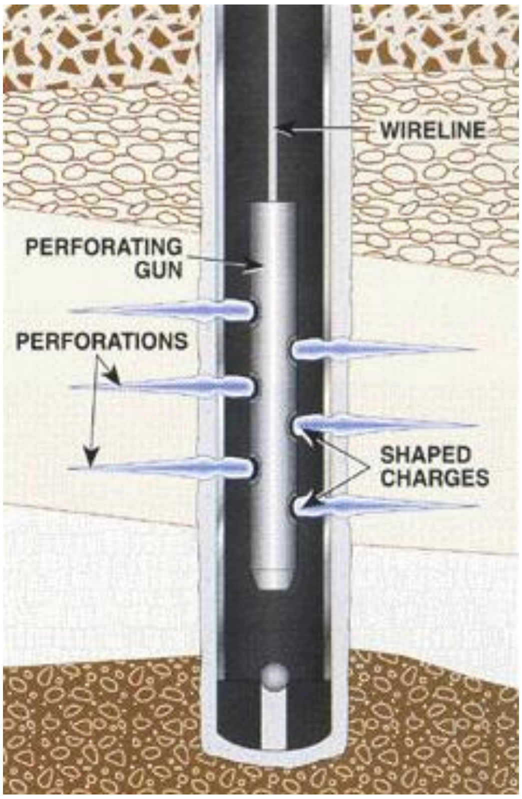


Figure 33 Obtaining connection between well and formation with perforating gun (Source: Blue Ridge Group)

It should also be remembered that since pilot testing is basically a small scale version of full production, some of the production methods used for obtaining optimum gas flow rates (including the use of hydraulic fracturing and horizontal drilling) may be undertaken in the pilot testing stage of the project. These techniques are explained in further detail in the next section of this report.

A pilot testing program may run anywhere from a few months to a couple of years depending on the project. During this period, water volumes, water levels, gas flow rates, pressures and compositions are monitored and reported in accordance with regulatory obligations.

4.4. CSG PRODUCTION

If the pilot testing program is considered successful and the project thought to be economically viable, the next step in the process will involve extracting and processing the gas for commercial sale. This stage of development is known as the production phase, and in terms of the NSW approvals process, is considered separate to exploration. The environmental approvals process for the production phase is explained further in Chapter 6.

CSG gas projects can vary in size from just a few wells through to hundreds or even thousands of wells. For example, AGL Energy's Camden Gas Project in NSW has 89 producing wells with a total gas production rate of approximately 17 terajoules (TJ) per day, supplying approximately 5% of gas Sydney's gas market (AGL Energy Limited, 2012a). This equates to a potential chemical energy equivalent of approximately 30 barrels of oil per day per well. In Queensland, thousands of CSG wells in the Bowen and Surat Basins are being drilled as part of the QCLNG Project, which will transport CSG via pipeline to Curtis Island near Gladstone for ultimate conversion to LNG and export to Asia (Figure 34).

The major developer QGC expects to drill around 6000 wells over more than 4500 sq km of tenements over the next 20 years in the Surat and Bowen Basins in southern Queensland, with more than 800 wells already drilled around the towns of Tara, Condamine and Miles (Figure 35). In Australia, as of the first quarter 2012 there were a total of 2,177 wells in production, with another 1,226 wells in the exploration or pilot testing phase of development (APPEA, 2012b).

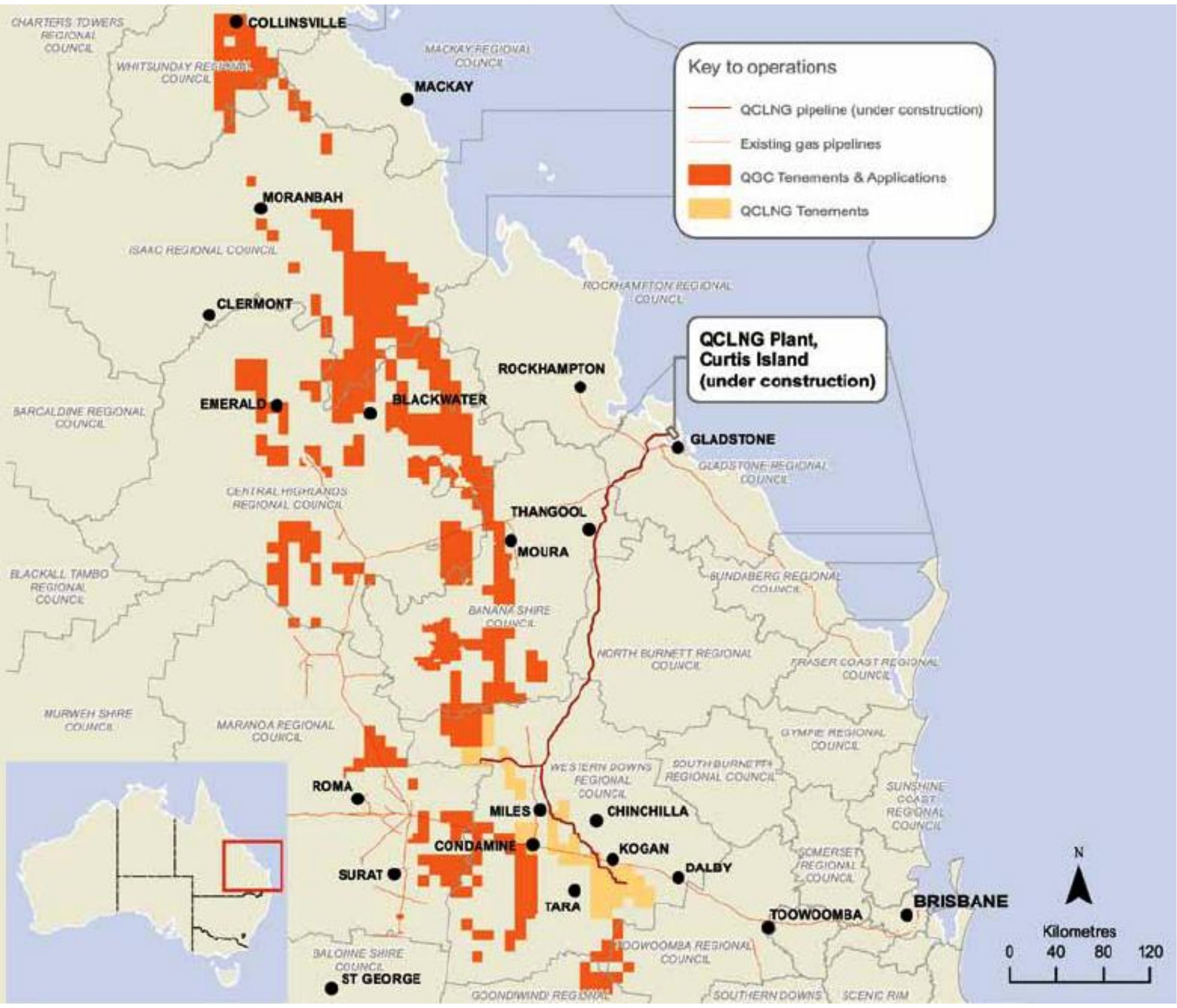


Figure 34 Overview of the QCLNG project in Queensland

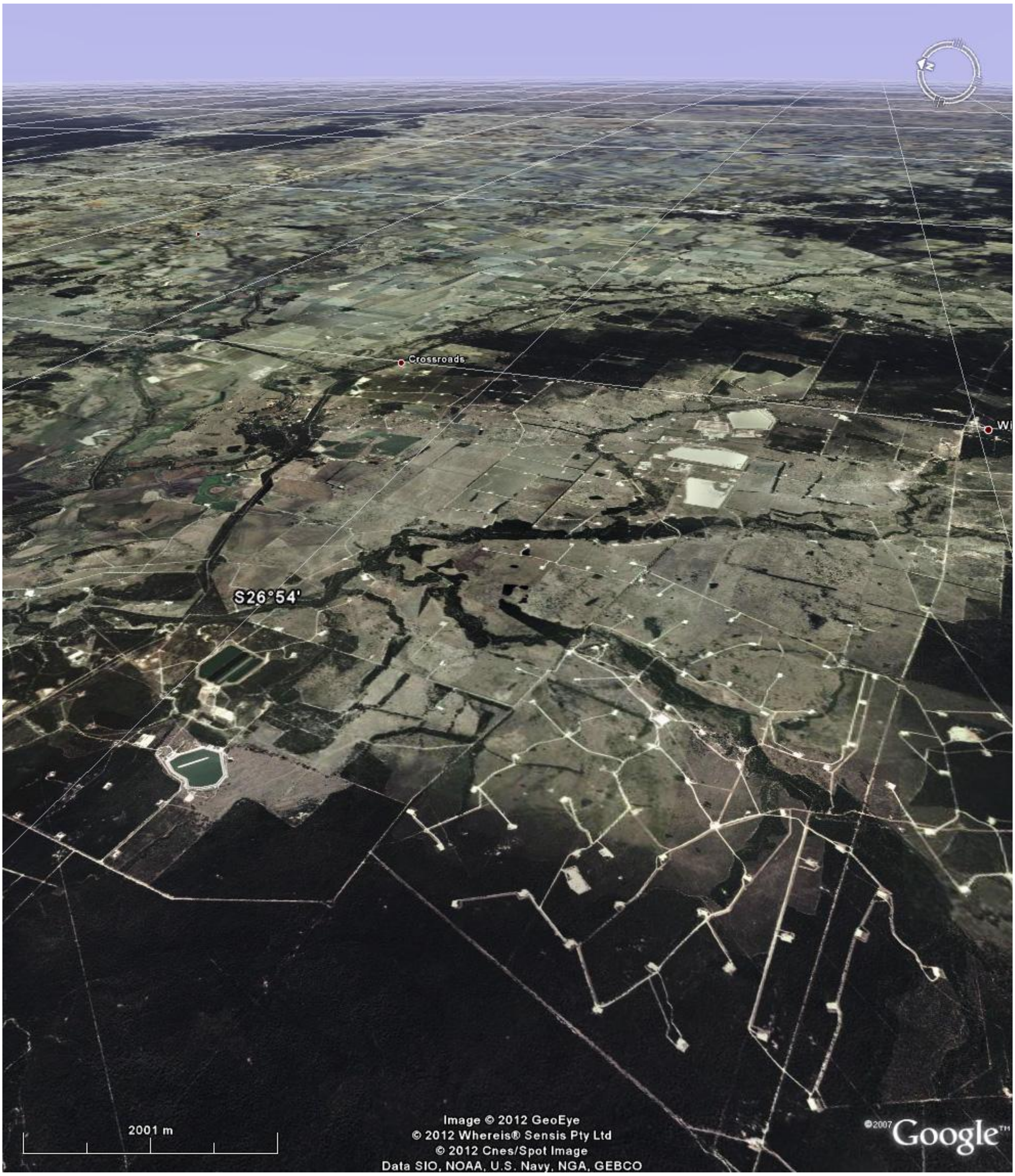


Figure 35 Satellite image of CSG development near Tara, Queensland.

4.4.1. EXTRACTION TECHNIQUES

Coal seam gas is held in place within coal seams by a combination of pressure from the overlaying rock, water in the seam, and adsorption of the gas molecules to the surface of the coal. To release the gas, the water must be extracted by drilling a well into the target coal seam, reducing the pressure and allowing the gas to flow. The gas is then processed at the well head to remove the water and piped to nearby compression plants for injection into gas transmission pipelines. Once operational, an individual coal seam gas well may produce gas for between 10 to 20 years (NSW Government, 2011).

Each coal seam gas well needs to be constructed according to the relevant regulations. One of the major concerns raised in regards to well construction is the possibility of cross-aquifer contamination. In NSW, wells are cased with steel and cemented to the surface, isolating the well from surrounding geological layers (AGL Energy Limited, 2012a). Well construction is regulated in NSW by the Code of Practice for Coal Seam Gas Well Integrity released by the NSW Government in September 2012. The Code of Practice outlines mandatory requirements and recommendations for CSG development, from exploration through to well abandonment. The Code of Practice further states that well design and construction “must ensure that no leaks occur through or between any casing strings. The fluids produced from the well must travel directly from the producing zone to the surface inside the well conduit, without contamination of groundwater or other aquifer resources, and avoiding leakage” (NSW Government, 2012d). Figures illustrating current well construction requirements are shown in Figures 36 and 37.

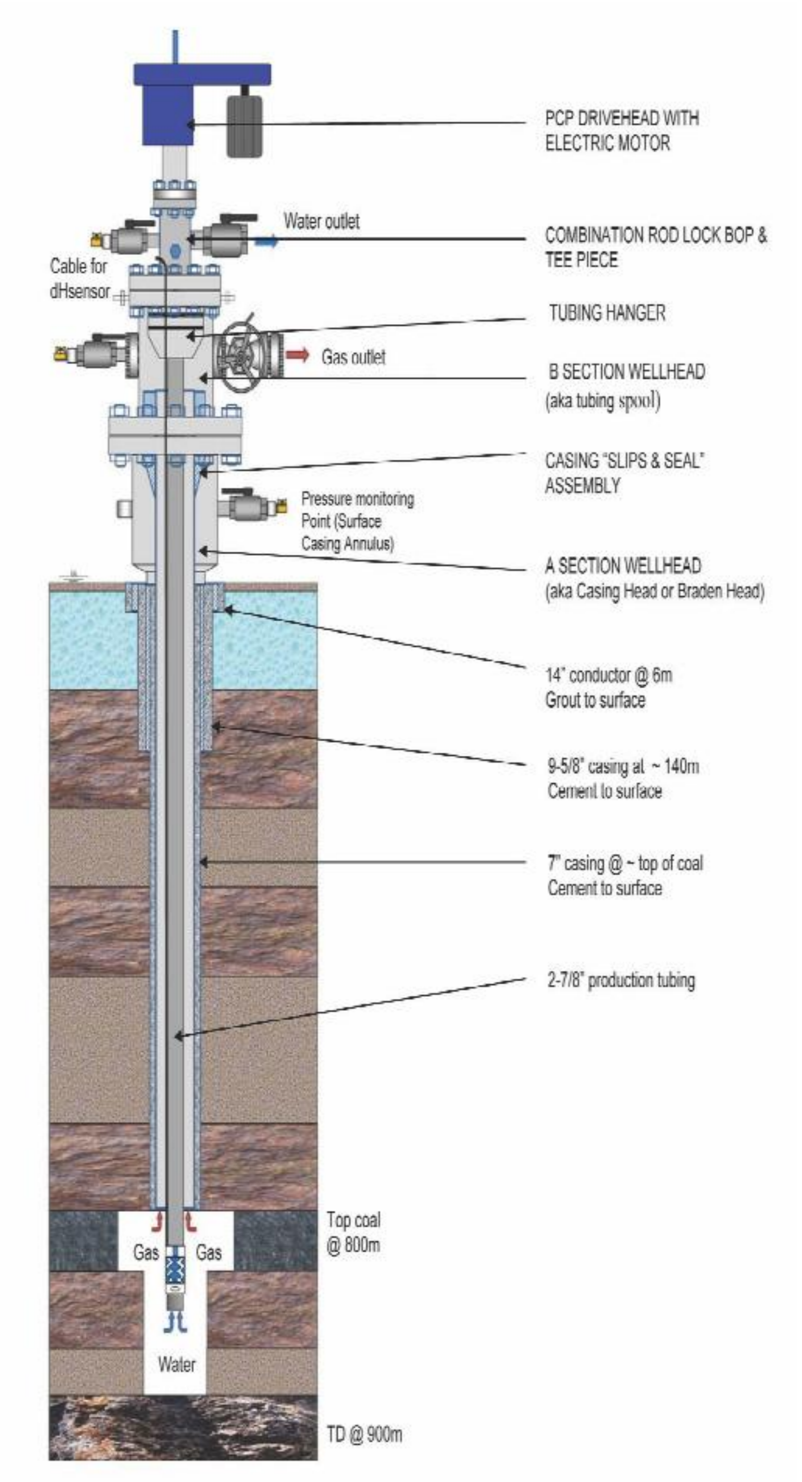


Figure 36 Typical vertical well.
Note: Section A would normally be set below ground level but is shown above ground level for illustration purposes only (Source: New South Wales Parliament Legislative Council, 2012, Karsten et al., 2008, Beavis, 1976)

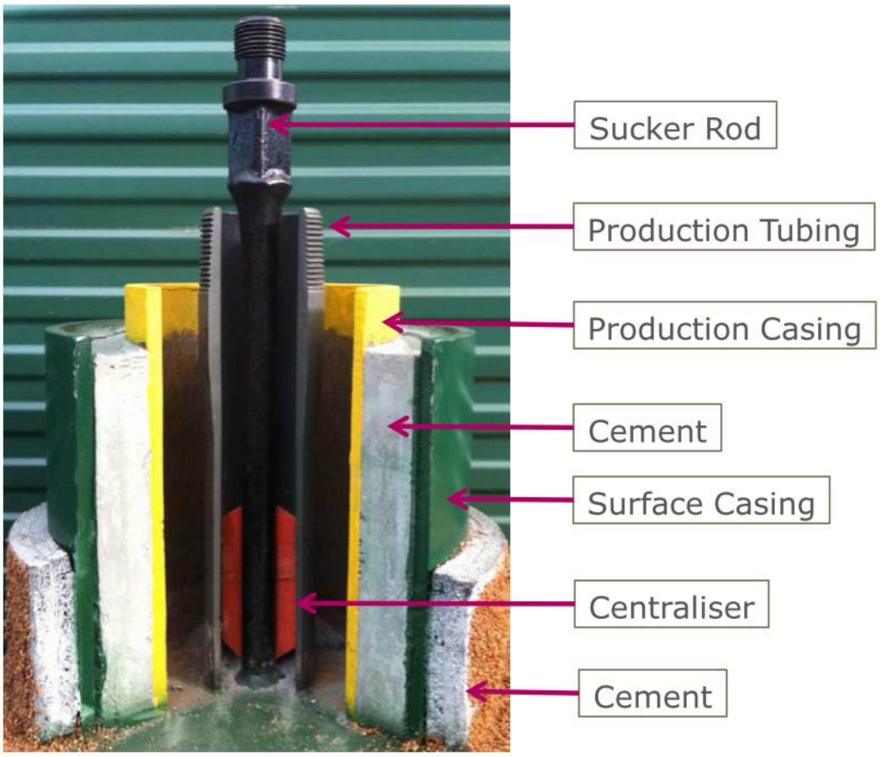


Figure 37 Cross-section of well (Source: AGL, 2012a)

There are a number of techniques available for gas operators to extract CSG. The main methods used include vertical wells, horizontal drilling (including directional and multilateral drilling), dewatering and hydraulic fracturing. The actual technique used in each well may involve one or a combination of methods, and will depend on the geology, economics and physical constraints of the site. Individual wells can take from just a few days to 8 weeks to set up, drill and complete depending on the technique/s used. The main techniques used in CSG extraction are summarised in Table 2 below.

Table 2 Summary of common CSG extraction techniques (Rutovicz et al., 2011)

VERTICAL WELLS	• Typically the cheapest method. The well is cased with steel pipe and cemented to the surface, isolating the well from surrounding geological layers. • Each well requires one surface well-pad to be constructed, therefore projects using only vertical drilling typically require multiple surface sites. • Likely to require fracturing to stimulate gas production. • Drainage radius of 200-400m • Drilling and completion is usually 7 – 10 days.
HORIZONTAL DRILLING	• Includes directional and multilateral drilling. • Less likely to require hydraulic fracturing than vertical drilling. • Allows for a sub-surface network (or 'web') of as many as 6 wells per location. This enables the extraction of gas in multiple directions along the target coal seam. • The web of underground wells can be constructed from one drill pad. Therefore, horizontal drilling can be less surface-intensive than vertical drilling. • Drainage radius of 1500-2500m. • Drilling and completion is usually 3 – 4 weeks.
DEWATERING	• Allows the seam to depressurise allowing the gas to move through the natural cleats in the coal. • The ratio of water to gas will vary depending on the site and age of the well. Typically volumes of water decrease gradually over the life of the well.
HYDRAULIC FRACTURING	• 'Fraccing' or 'stimulation' aids the extraction of gas by increasing the permeability of the coal. • The most common technique is hydraulic fracturing which uses water and sand, a viscofying agent such as guar gel, and other chemicals. • The use of fracking is not always required – depends on geology. • Other types of fracking include using petroleum gels and gases such as air and carbon dioxide.

4.4.2. VERTICAL, HORIZONTAL AND DIRECTIONAL DRILLING

Historically, vertical wells have been the most utilised type of well used in CSG extraction. This is because the techniques are similar to those used for many years in the conventional oil and gas exploration industry and is typically the cheapest method (Kimber and Moran, 2004). Once the drill pad has been constructed, vertical wells will normally take between seven to ten days from the start of drilling to completion (AGL Energy Limited, 2012a). Vertical wells also typically require hydraulic fracturing to stimulate water and gas production. One of the major disadvantages (when compared to horizontal drilling) is that each vertical well requires its own well pad. This often creates gas projects where well pads are located just a few hundred metres apart, resulting in a closely-spaced grid of wells at the surface (Moore, 2012, Freij-Ayoub, 2012).

With improvements in drilling technology, horizontal drilling (including directional and multilateral drilling) have become more commonly used in CSG extraction (Rutovicz et al., 2011). These techniques provide the gas operator with the ability to operate multiple wells (as many as six) from one drill pad, enabling the extraction of gas in multiple directions along the target coal seam (AGL Energy Limited, 2012a). Horizontal wells also significantly increases contact with the coal seam, with bore lengths extending up to 2000 metres out from the well pad. This allows gas rates to be significantly increased compared to vertical wells, which are restricted to a drainage radius of just 200 to 400 metres (Rutovicz et al., 2011).

Horizontal wells also provide another obvious advantage over vertical wells by reducing the number of individual well pads required over a particular area at the surface.

The horizontal drilling technique may also provide the advantage of reducing the need for hydraulic fracturing, since the simple action of drilling along the seam can be enough to increase permeability and stimulate gas and water extraction (Final Report NSW Inquiry into CSG 2012). Basically, although horizontal wells are initially more expensive to construct than vertical wells, they typically allow for more sustained production of methane (U.S. Department of Energy, 1999), reduce the number of wells required, reduce land use on the surface, and can often improve the economic viability of the project.

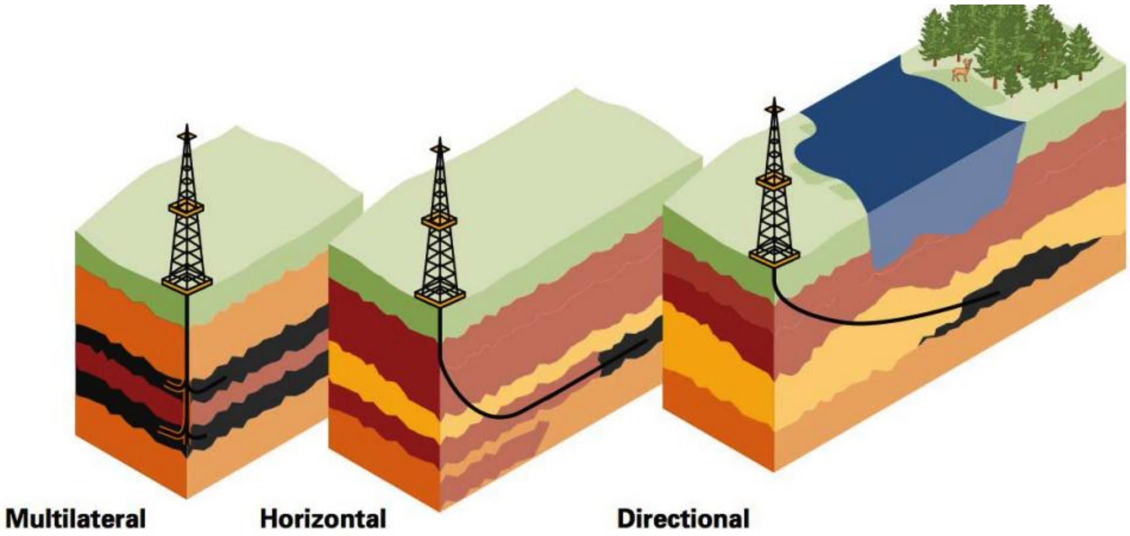


Figure 38 Representation of various CSG drilling techniques
(Source: U.S. Department of Energy, 1999)

4.4.3. DEWATERING

Water is an important consideration in CSG development (Flores, 1998). Prior to drilling into the coal seam, the subsurface system is basically in a state of equilibrium, with the gas being held in place by the pressure from the overlying strata and water in the seam. As described earlier in this report, to extract the gas, the coal seam needs to be depressurized by removing the water. Once the pressure in the coal seam is reduced, the gas is desorbed from the surface of the coal matrix and diffused into the cleats (Rice, 1993, Flores, 1998).

Consideration must also be given to the typical changes in water and gas production over the life of a CSG project. For vertical wells the volumes of water produced will typically decline gradually over time, until the methane rate reaches the peak value (Figure 39). The dewatering curves for horizontal wells will often differ significantly to vertical wells, with the horizontal method dewatering the system at a more rapid rate (Maracic et al., 2005).

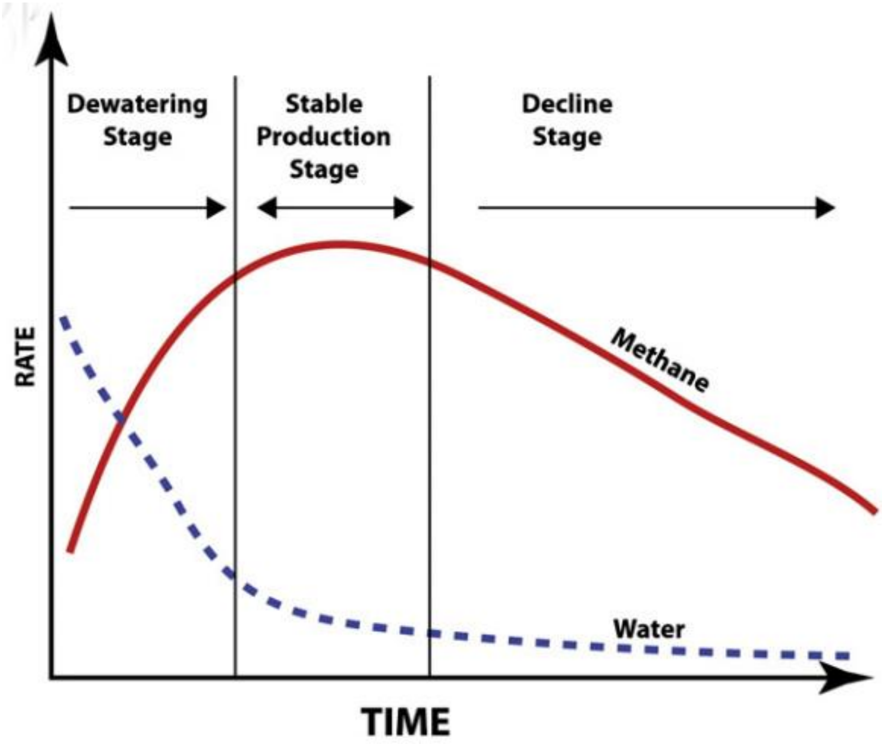


Figure 39 Typical CSG production profile showing gas and water rates (Source: Moore, 2012)

The amount of water produced from a coal seam can vary significantly, and the volume and quality of the produced water often plays an important role in determining the economic viability of the well. For example, as shown in Figure 40, volumes of produced water are typically lower for coastal Permian basin coals in NSW (Camden, Gloucester and Hunter) compared to the Surat or Bowen basin coals in Queensland (Athanasiadis, 2012).

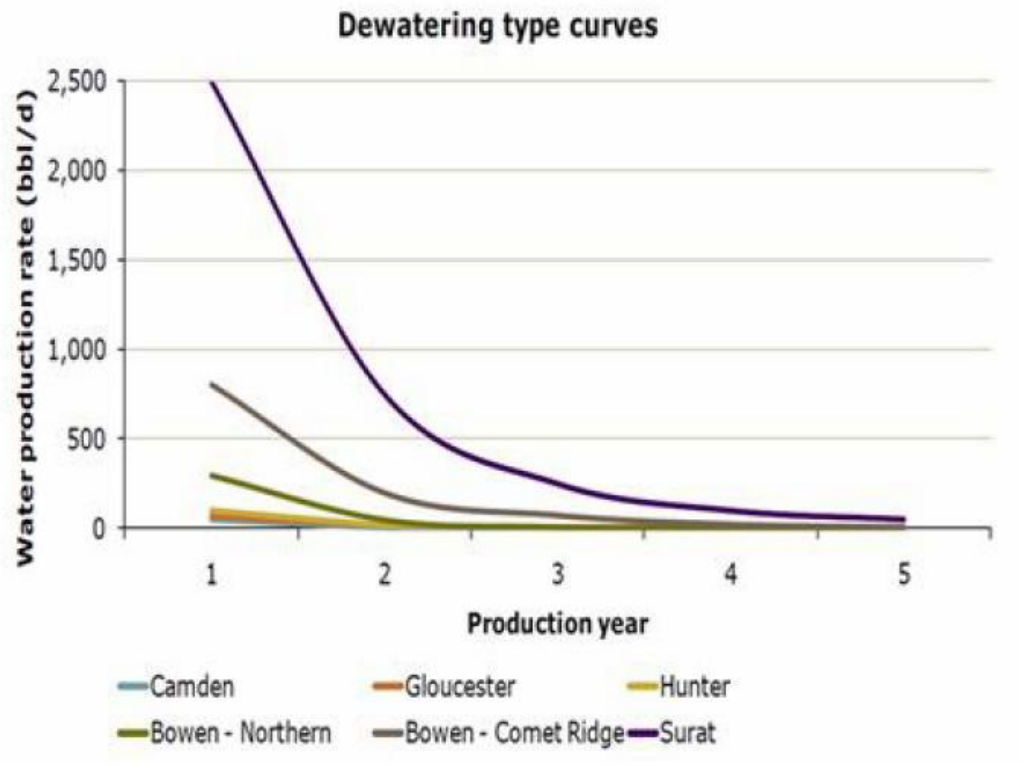


Figure 40 Dewatering curves for various CSG projects in Australia (Source: Athanasiadis, 2012)

To further illustrate the difference between projects, in the Surat Basin in Queensland, QGC reported that for the 12 months to June 2011 its Codie-Lauren field near Dalby extracted a total of 7.46 petajoules of gas using 104 wells, with a produced water volume of approximately 450 million litres (Table 3). This meant each well was producing on average almost 12,000 litres of water per day. This compares this to AGL's Camden Gas Project in the Sydney Basin which extracted slightly less gas (5.5 to 6 petajoules per annum) using 89 wells, but did so with a total produced water volume of just 4.8 million litres. This meant each well was producing on average approximately 150 litres of water per day. This difference is equivalent to QGC's field producing enough water per year to fill 180 Olympic-size swimming pools, compared to the Camden project which would fill just 2 Olympic-size swimming pools.

Table 3 Comparison of Sydney Basin and Surat Basin CSG developments

	CAMDEN GAS PROJECT NSW	**CODIE-LAUREN QLD**
Company	AGL Energy Ltd	QGC Ltd (a BG Broup business)
Basin	Sydney (Southern coalfield)	Surat
Stratigraphic unit	Illawarra Coal measures	Walloon Coal measures
Number of wells	89	104
Gas (PJ)/annum	5.5 to 6.0	7.46 (year ending 2010-11)
Produced Water per annum (L)	4.8 million	450 million
L/well/day	~ 150	~ 12,000
Water processing methods	On-site water tanks emptied approximately once a month with water treated at water processing plant.	Large volumes of water necessitate the construction of storage dams and water processing facilities.

Handling and processing such significantly different volumes of water has important implications for each project. The Camden Gas Project is able to handle its small volumes of water by installing a small water tank next to the wellhead which is typically emptied approximately once a month.

The overall economic viability of a project can be affected if too much water needs to be removed. The removal, pumping, storage, treatment and disposal of produced water all require energy, which in the end can prove uneconomic for particular sites. At other times, dewatering is unsuccessful due to recharge from adjacent strata.

4.4.4. HYDRAULIC FRACTURING

Hydraulic fracturing (also known as ‘fraccing’) is the process by which a coal seam (or any other hydrocarbon-bearing deposit) can be ‘stimulated’ by forcing fluids at high pressure into the formation to create an artificial network of fractures. This increases the permeability of the seam, allowing more gas to flow to the wellhead and thereby increase the productivity of the well. Initial experiments using the technique were conducted in the US in 1947, with the first commercial use of the technology performed in Oklahoma in 1949 (Montgomery and Smith, 2010). Since then, hydraulic fracturing has been used extensively throughout the world to increase production in oil and gas wells , with the technique already used a million times in the US by 2002 (ALL Consulting, 2012).

The technique has recently come under intense scrutiny from governments, the public and non-governmental organisations due to possible environmental and human health impacts (Lloyd-Smith and Senjen, 2011). Some of these concerns include the volume of water the technique consumes; disclosure of fracture fluid chemical additives; possible surface and groundwater contamination from vertical fracture propagation; the treatment, recycling and disposal of produced water; onsite storage and handling of chemicals and wastes; and increased truck movements (ALL Consulting, 2012).

Figure 41 Typical CSG hydraulic fracturing operation in Gloucester, NSW (Source: AGL Energy Ltd)

The actual process of hydraulic fracturing involves pumping large volumes of a fluid (typically more than 98% sand and water) at high pressure down the well into the coal seam creating cleats or fissures that increase the permeability of the seam, allowing the gas to be released at a faster rate (Figure 41). The fluid is normally composed of water, a ‘proppant’ (usually sand) to hold the fractures open, and a chemical solution that will vary depending on the geology of the site (Rutovicz et al., 2011). A table outlining the types of chemicals and their uses is given in Table 4. It is worth noting that the use of BTEX chemicals (benzene, toluene, ethylbenzene, and xylene) in hydraulic fracturing has been prohibited in both NSW and Queensland.

It is also important to note that many of the additives used in hydraulic fracturing are quite common compounds. For example, guar gum is used as a gelling agent to increase the viscosity of the fraccing fluid and hold the sand in suspension and assist in keeping the fractures open. Guar gum is manufactured from the ground endosperm of guar beans, with India being the world's major producer, responsible for approximately 80% of the global market. Guar gum is also used extensively as a thickening agent in many food products. Gas CSG producers have indicated that the use of guar gum is part of a wider move towards increased use of food-grade chemical additives in hydraulic fracturing procedures (AGL Energy Limited, 2012a).

The categories and uses of typical chemicals used in hydraulic fracturing are outlined in the following table:

Table 4 Categories and uses of typical hydraulic fracturing chemicals

TYPE	MAIN COMPOUND(S)	PURPOSE	COMMON USES
Proppant	Sand	Used to hold the fractures open while the gas is released into the well.	Used in filtration, play sand.
Diluted acid	Hydrochloric acid or muriatic acid	Helps dissolve minerals and initiate cracks in the rock.	Swimming pool cleaner and chemical.
Biocides	Glutaraldehyde	Kills bacteria in the water that produce corrosive byproducts, and reduces risk of fouling	Disinfectant, sterilizer for medical and dental equipment
Breakers	Ammonium persulfate, Peroxodisulfate	Allows delayed breakdown of gel polymer chains	Bleaching agent in detergent and hair cosmetics, manufacture of household plastics.
Corrosion inhibitor	N,n-dimethyl formamide	Prevents well corrosion	Used in pharmaceuticals, acrylic fibres and plastics.
Clay stabilizer	salts, ie tetramethyl ammonium chloride	Reduces clay swelling around the well and enhance pre-fracture conditions.	
Crosslinker	Borate salts	Maintains fluid viscosity as temperatures increase.	Used in laundry detergents, hand soaps and cosmetics.
Friction reducer	Polyacrylimide	Minimises friction between fluid and pipe, by ‘slickening’ the water.	Water treatment, soil conditioning.
	Mineral oil		Make-up remover, laxatives and sugar sweets.
Gelling agents	Guar gum or hydroxyethyl cellulose	Increases thickness/ viscosity of the fluid to make it more ‘gel-like’. Helps hold sand in suspension and allow more of it to be carried into the fractures.	Food-grade thickener used in cosmetics, ice cream, toothpaste, and sauces.
Iron control	Citric acid	pH control - prevents precipitation of metal oxides.	Food additive, flavouring in food and beverages, eg: lemon juice ~7% Citric Acid
KCl	Potassium chloride	Creates a brine carrier fluid.	Low sodium table salt substitute.
Oxygen scavenger	Ammonium bisulfite	De-oxygenates water to protect pipes from corrosion.	Cosmetics, food and beverage processing, water treatment.
pH adjusting agent	Sodium or potassium carbonate	Maintains effectiveness of other components such as crosslinkers.	Washing soda, detergents, water softener, glass, soap, ceramics.
Scale inhibitor	Ethylene glycol	Prevents scale deposits and precipitation in pipe.	Automotive antifreeze, household cleansers, deicing and caulk.
Surfactants	Isopropanol	Increases viscosity of fracture fluid.	Glass cleaner, antiperspirant, hair coloring.

Note: the specific compounds used in a given fracturing operation will depend on company preference and site-specific characteristics of the target formation.
(Adapted from QLD DEHP, 2012, Independent Petroleum Association of America (IPAA), 2012)

A typical hydraulic fracturing operation on a vertical CSG well will normally take two to three days and consume around 200,000 to 600,000 litres of water and additives (Rutovicz et al., 2011, AGL Energy Limited, 2012a). The site will also require preparation similar to that used for a normal drilling operation, but may also require the construction of a storage dam depending on the volume of water produced by the well. The sand used for the operation is typically 20 to 40 mesh sand which is able to withstand the crush pressures and hold open the fractures for the gas to flow (AGL Energy Limited, 2012a).

It is also important to be aware of the differences between shale gas fraccing and CSG fraccing. For shale gas, hydraulic fracturing is required in practically every well due to the absence of natural fractures or cleats in the rock, and the depth of the formations (1200-3500 metres for shale compared to 200-100m for CSG). Hydraulic fracturing is not required for all CSG wells, with estimates suggesting less than half (10-40%) of vertical wells in Queensland will require hydraulic fracturing (Queensland Government, 2011b). The use of hydraulic fracturing in coal formations depends on the natural permeability of the formation and type of drilling used, i.e: horizontal drilling can often increase the area of the seam without the need for fraccing. Shale gas fraccing operations are also typically much larger operations than CSG procedures and occur over longer time periods. For example, shale fraccing typically requires 25,000 – 35,000 horsepower, compared to 4000 – 5,000 horsepower in CSG wells, and can take up to 30 days compared to 2 to 3 days for a CSG frac. A shale frac will also usually involve significantly greater volumes of water: typically around 1.6 megalitres compared to 200,000 to 600,000 litres for a CSG fracture. (AGL Energy Limited, 2012a, Wilkinson, 2011).

These differences in power and water volumes have significant implications for analysing one of the major criticisms of hydraulic fracturing – that being the vertical propagation of fractures into overlying aquifers. The consequences of fractures extending beyond the target coal seam include the possibility of fraccing fluids entering overlying strata, possible cross contamination of aquifers, excess water production, and inefficient depressurisation of the coal seam (Colmenares and Zoback, 2007).

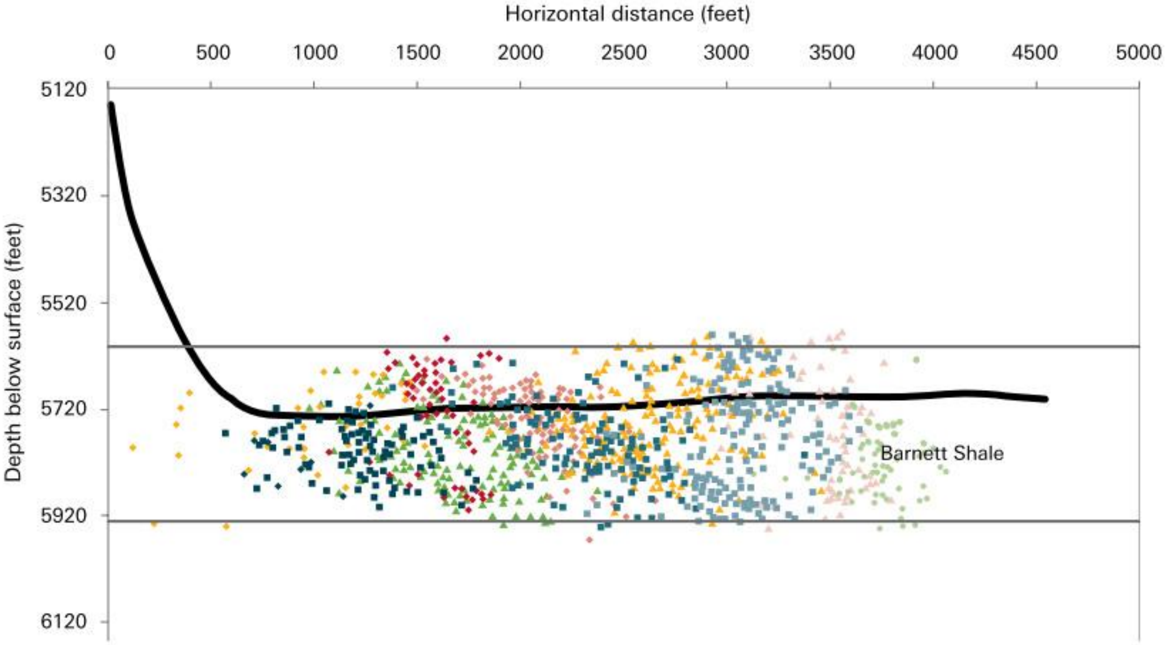


Figure 42 Horizontal view of microseismic events along a horizontal well (Zoback et al 2010)

Current research into the vertical propagation of hydraulic fractures in shale formations (Davies et al., 2012) report a maximum height of approximately 580 metres, with the probability of a fracture extending more than 350 metres vertically estimated at approximately 1%. It needs to be noted however that coal seams being targeted in the

Sydney Basin are generally only 2-3 metres thick (Bulli seam) and are overlain by much harder sandstone strata. This means that the pressures required to fracture the coal seam are not likely to generate fractures that extend significantly into the adjacent sequence.

To further strengthen regulations, the NSW Government published a Code of Practice for Coal Seam Gas Hydraulic Fracturing in September 2012. This document provides gas operators with mandatory and best practice guidelines with which to undertake hydraulic fracturing (NSW Government, 2012c).

4.5. POST-MINING METHANE (GOAF DRAINAGE)

Post-mining methane (or goaf drainage) is a particular type of CSG, relating specifically to the draining of methane resources from the voids and collapsed strata (known as the ‘goaf’) which remain after coal is extracted from an underground mine. The technique has been used at BHP’s Appin and Tower underground mines since 1996, where methane has been drained from the goaf and used to power mine operations and supplement local energy supplies (Final Report NSW Inquiry into CSG, 2012).

Longwall coal mining creates voids when coal is extracted. This de-stresses both overlying and underlying strata, creating fractures in the rock. Over time, economical reservoirs of methane can accumulate in the goaf, as methane from underlying coal seams migrates to regions of lower pressure. This is of particular relevance to CSG development in the southern region of the Sydney Basin due to extensive underground coal mining that has taken place in the region over the past 150 years.

Goaf methane reservoirs in the Illawarra region and other parts of the Sydney Basin have become attractive to gas operators for a number of reasons. These reasons include:

- Proximity to the Sydney gas market.
- Goaf methane extraction rarely requires the use of hydraulic fracturing, thereby eliminating an expensive component of the development process.
- An ability to partner with local industry (i.e; nearby coalmines).
- A history of coal mining in the region may provide some degree of social acceptance compared to greenfield sites where mining has not yet occurred.

For example, Apex Energy and partner Ormil Energy have put forward plans to develop goaf methane (in addition to unmined sections of the coal seam) in the Helensburgh/ Darkes Forest region of the Illawarra escarpment and also in the Burragorang/Nattai region west of Camden (Apex Energy Ltd, 2011). Both of these regions gave been mined extensively in the past and have potential for development of goaf methane resources.

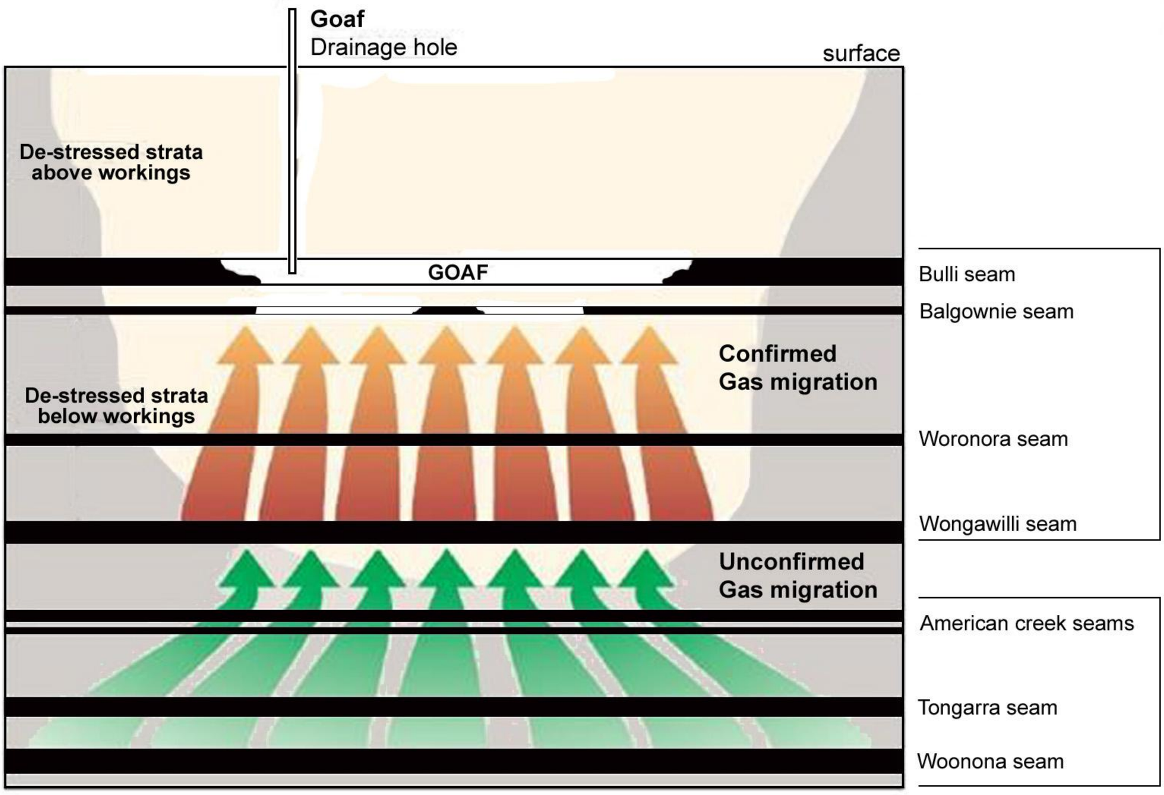


Figure 43 Schematic of post-mining goaf methane in the Helensburgh/ Darkes Forest region of the southern coalfield. (Source: Apex Energy website)

4.6. POTENTIAL ENVIRONMENTAL IMPACTS

Potential environmental impacts of CSG development have been summarised as follows:

- Groundwater effects - including depletion and contamination of aquifers.
- Fluctuations in water availability - from depressurization in nearby aquifers,
- Surface water effects - typically resulting from produced water disposal.
- Hazardous waste - from water treatment or drilling muds.
- Surface footprint of mining - including access roads, bushfire risk, habitat clearing, noise, night lighting, dust, traffic, noise, night time lighting, traffic, access routes, and dust.
- Greenhouse emissions of methane and CO_2 (known as 'fugitive emissions')
- Land use conflict - with agriculture, catchments, or high conservation value areas.
- Subsidence - from depressurisation and large-scale extraction of water.

  (Young, 2005, Rutovicz et al., 2011, New South Wales Parliament Legislative Council, 2012)

It is important to recognise that potential environmental impacts, especially those impacts relating to groundwater, are very often site-specific and typically determined by the hydrologic and geologic physiognomies of the target seam, the techniques used to extract the resource, the use or otherwise of procedures designed to mitigate potential environmental impacts, and the adherence to the legislative framework regulating CSG development. The following section provides further detail of the possible environmental impacts of CSG development.

4.7. EFFECTS OF CSG DEVELOPMENT ON WATER

It has been suggested that in Australia, coal seam gas is as much a water business as it is a gas business (Athanasiadis, 2012). Although issues relating to water use and gas production have been of concern in other countries, any natural resource development in Australia that may impact significantly on water resources is likely to come under intense scrutiny. The main concerns relating to water and CSG development have tended to focus on issues relating to aquifer depletion, aquifer contamination, and disposal of produced water (Nghiem et al., 2010, Freij-Ayoub, 2012, ALL Consulting, 2003, Chalmers et al., 2010).

4.7.1. AQUIFER CONTAMINATION

It is possible that aquifer contamination may occur from increasing flows between the coal seam and overlying aquifers when drilling is undertaken through aquifers (Rutovicz et al., 2011, McKibben and Smith, 2000). Well integrity is important to reducing this risk, and the NSW Government has attempted to mitigate this risk by issuing a Code of Practice specifically for well integrity. The aim of the *NSW Code of Practice - Well Integrity* is to ensure the environmentally safe production of gas and wellbore fluids by containing them inside the well, protecting groundwater resources, isolating the productive formations, and properly executing treatment/stimulation and well completion procedures (NSW Government, 2012d). One of the remaining concerns with the concept of well integrity is that it remains difficult to assess how particular methods of well construction improve well integrity over particularly long time periods (Duguid, 2009, Dusseault et al., 2000).

Contamination of aquifers can also occur during hydraulic fracturing operations if fractures were to propagate outside of the target coal seams, allowing migration of fraccing fluids from the coal seam into overlying formations (Osborn et al., 2011, Davies et al., 2012). Possible aquifer contamination from hydraulic fracturing has come under scrutiny due in part to the mixture of chemicals used in the procedure, but also from the possibility of methane and fluid migration out of the coal seam (Moore, 2012, Schon, 2011). Although hydraulic fracturing is not always required for CSG developments, and will typically be undertaken using lower pressures than in shale formations, there is still some degree of risk involved. In addition, since extraction techniques and fluids will vary depending on the geology of the site, this may be an area where regulation of chemicals and techniques used in hydraulic fracturing may minimise potential impacts.

4.7.2. AQUIFER DEPLETION

CSG extraction involves the dewatering and depressurisation of what is essentially a coal aquifer. Since projects typically involve many wells across a large area, dewatering and depressurisation may lead to the inflow of water from surrounding strata, possibly resulting in a major cumulative effect on surrounding aquifers (Holla and Barclay, 2000, Helmuth, 2008). To reduce these potential impacts on aquifers, an operator may decide to re-inject the produced water. This decision will depend on local site characteristics, and will take into account recharge times from adjacent aquifers and permeability of the coal seam and surrounding strata.

The cumulative effects of dewatering a coal seam depend on the surface-groundwater recharge regime and the degree of hydraulic connectivity between the target coal seam and the overlying and underlying aquifers. To a certain extent, hydraulic connectivity will be related to the volumes of produced water and the time taken to replenish the depleted aquifer (US Committee on Produced Water, 2010).

4.7.3. PRODUCED WATER

The process of dewatering coal seams and extracting gas can often result in significant volumes of waste water (known as 'produced water'). As discussed, the volumes of produced water can vary significantly with some wells producing just 150 litres per day compared to some wells producing 10-20,000 litres per day. It is also important to recognise that the produced water is often saline, giving rise to handling, treatment and disposal issues (Van Voast, 2003, Jackson and Reddy, 2007, Dahm et al., 2011). In addition, almost all CSG co-produced waters have similar chemistries. The waters are dominated by sodium (Na) and bicarbonate and devoid of calcium (Ca), magnesium (Mg) and sulphate (Van Voast, 2003). Together, water quality, volumes, treatment and disposal of produced water have emerged as one of the major environmental concerns in CSG development.

The possible environmental impacts of produced water include alterations of natural flow regimes if released to surface water system. This can have significant impacts on water quality in rivers, wetlands, and reservoirs (ALL Consulting, 2003). There are also risks associated with water treatment that removes all contaminants, and subsequently releasing this 'clean water' to a naturally turbid system (National Water Commission, 2010). At the same time as recognising potential environmental impacts of produced water, it is also important to recognise that the quality and quantity of produced water can vary significantly from one location to the next, with chemical composition determined principally by the geological characteristics of the particular coal seam (ALL Consulting, 2003).

One of the major issues in CSG development is the treatment and disposal of saline produced water. One of the common methods of measuring salinity is Electrical Conductivity (EC), and refers to the ability of water to conduct a current. EC is measured in µS/cm, and typically the higher the conductivity of water, the higher the salinity. EC measurements from the produced water from the Camden Gas project normally range between 7,000 and 15,000 µS/cm. As shown in Table 5, this is too high for use in irrigation and therefore the produced water from Camden is transported off site via truck and disposed of at a water processing facility. Other characteristics of the produced water from the Camden Gas project include:

- a pH level of about 7-8.5,
- typically low levels of heavy metals,
- approximately 50,000 years of age (AGL Energy Limited, 2012b).

Despite the relatively high EC of water at Camden, the small volumes of produced water make management relatively straightforward. When large volumes are water are produced however, such as in Queensland, the produced water will often need to be processed and treated on-site, because transportation of such large volumes of water on trucks is not economically viable.

Table 5: Water quality guidelines (Source: DPI Victoria, 1999)

EC RANGE (µS/cm)	**USEFULNESS OF WATER**
0-800 Rainwater (2-100) Drinking Water (10-1,600)	• Good drinking water for humans (provided there is no organic pollution and not too much suspended clay material) • Generally good for irrigation, though above 300 µS/cm, some care must be taken, particularly with overhead sprinklers which may cause leaf scorch on some salt sensitive plants. • Suitable for all livestock.
800 – 2,500 Brackish Water	• Can be consumed by humans although most would prefer water in the lower half of this range if available. • When used for irrigation, requires special management including suitable soils, good drainage and consideration of salt tolerance of plants.
2,500 – 10,000	• Not recommended for human consumption, although water up to 3000 µS/cm could be drunk if nothing else was available. • Not normally suitable for irrigation, though water up to 6000 µS/cm can be used on very salt tolerant crops with special management techniques. Over 6000 µS/cm, occasional emergency irrigation may be possible with care, or if sufficient low salinity water is available, this could be mixed with the high salinity water to obtain an acceptable supply. • When used for drinking water by poultry and pigs, the salinity should be limited to about 6000 µS/cm. Most other stock can use water up to 10,000 µS/cm. • High magnesium levels can cause stock health problems in this range.
Over 10,000	• Not suitable for human consumption or irrigation • Not suitable for pigs, poultry or any lactating animals. Beef cattle can use water up to 17,000 µS/cm and adult dry sheep can tolerate 23,000 µS/cm. However it is possible that waters below these EC levels could contain unacceptable concentrations of particular ions. Detailed chemical analysis should therefore be considered before using high salinity water for stock. • Water up to 50,000 µS/cm (the salinity of the sea), can be used to flush toilets provided corrosion in the cistern can be controlled.

In an attempt to deal with the issue of produced water, the Queensland Government has provided guidelines on the use of produced water:

Category 1 – preferred management options:

- injection where detrimental impact is unlikely
- untreated use where detrimental impact is unlikely
- treatment to an agreed standard for agricultural, industrial and potable uses (aquaculture, coal washing, dust suppression, industrial use, and irrigation).

Category 2 – non-preferred management options:

- disposal via evaporation dams
- disposal via injection where detrimental impact is likely
- disposal to surface waters
- disposal to land. (DERM2011a):

The treatment of the produced water to an acceptable level removes the salts from the water, however an issue remains as to storage and disposal of the removed salts and concentrated brine. This remains one of the significant challenges to CSG development where large volumes of produced water are extracted (Freij-Ayoub, 2012, Nghiem et al., 2010, Athanasiadis, 2012)

5. CSG LEGISLATION

CSG development in Australia has grown strongly since the commencement of the first commercial project in 1996, with development in Queensland over the past decade being particularly rapid. It has been indicated that the development of a regulatory framework has struggled to keep pace with the development and unique characteristics of the CSG industry. For example, the NSW Environmental Defender's Office suggested in 2011 that many aspects of the regulatory framework for the industry are outdated and insufficient to produce sound environmental outcomes (EDO NSW, 2011).

5.1 NEW REGULATIONS IN NSW - STRATEGIC REGIONAL LAND USE POLICY (SRLUP)

At the time of writing this report, the NSW Government under Premier Barry O'Farrell is currently seeking to create a new development and planning system for NSW, through modifications to the *Environmental Planning and Assessment Act 1979* and *Environmental Planning and Assessment Regulation 2000*. It is therefore important to recognise that the regulations and legislation outlined in this chapter may undergo significant changes in the near future.

In addition to the ongoing review of the State's planning system, in September 2012 the NSW Government released the **Strategic Regional Land Use Policy**. This policy sets out a range of initiatives to try and balance mining and CSG development with the protection of agricultural land and water resources. Once established, the plans will not be legally binding as such, but are likely to be implemented through legally binding mechanisms such as local environmental plans (LEPs), State Environmental Planning Policies (SEPPs) and other legislation (EDO NSW, 2012).

Key elements of the **Strategic Regional Land Use Policy** include:

- **Creation of a Land and Water Commissioner**

  The creation of a Land and Water Commissioner to manage exploration activities, including land access agreements between farmers and miners as well as provide advice on exploration activities proposed on Strategic Agricultural Land. The Commissioner will review any exploration approval and advise government and the community whether the assessment process has occurred in accordance with the regulation, policy and Acts. The Commissioner will also supervise standard land access agreements, collate and publish remuneration information relating to land access agreements, and help negotiate future agreements.

- **Mapping of 'Strategic Agricultural Land'**

  The Government has begun mapping agricultural land throughout the State and assigning a biophysical value based on its soil type, access to water, or value to a particular industry such as wine-making or horse breeding.

- **Agricultural Impact Statements**

  Developers will be required to prepare an Agricultural Impact Statement (AIS)at the exploration stage of development.

- **The Gateway**

  'The Gateway' is the assessment process that a proposed mining or CSG development will need to go through before a development can be assessed by the Planning and Assessment Commission. The Gateway involves an independent, scientific assessment by 'The Gateway Panel' on the agricultural and water impacts of a proposed mining or CSG production project. The Gateway Panel will consist of independent experts in fields such as agricultural science, water and mining and will be appointed by the Minister for Planning and Infrastructure Expert. Advice on aquifer impacts will be obtained from the Minister for Primary Industries and the Commonwealth Independent Expert Scientific Committee to assist in the assessment. A Gateway Certificate (with possible conditions) can then be submitted to the Planning and Assessment Commission for final determination.

- **Aquifer Interference Regulation**

  This policy requires any exploration activities taking more than three megalitres per year to hold a water access licence. The policy also outlines how the volumes of water taken as part of an aquifer interference activity will be accounted for and sets out the assessment considerations to safeguard groundwater systems. In addition, the policy outlines minimal impact considerations of proposals which are to be assessed by the NSW Office of Water.

- **Codes of Practice for the CSG Industry – Hydraulic Fracturing and Well Integrity**

  The Codes of Practice provide CSG developers and drilling companies with a set of mandatory requirements and best practice guidelines on hydraulic fracturing, and the construction and abandonment of wells. Before the introduction of these Codes of Practice, drilling companies had been guided by best practice guidelines issued by the American Petroleum Institute.

In addition to developing these policies and regulations, the Government has also prohibited the use of BTEX chemicals in drilling and hydraulic fracturing, banned the use of evaporation ponds for the disposal of produced water, and removed the five-year royalty-free period for CSG producers (NSW Government, 2012e).

The Strategic Regional Land Use Policy is intended to sit alongside the existing legislative framework which is outlined below:

5.2 CURRENT LEGISLATIVE FRAMEWORK IN NSW

One of the most important things to understand about mineral rights in Australia is that ownership of land does not give landholders ownership of the minerals below the ground. All petroleum, helium and carbon dioxide existing in a natural state on or below the surface of any land in the State is the property of the Crown, and therefore the Government can allow third parties to explore for and extract CSG (*Petroleum (Onshore) Act 1991* (NSW) s. 6).

CSG exploration and development in NSW comes under the direction of the Minister for Resources and Energy who is responsible for issuing licenses and leases to develop or explore for CSG. Many CSG activities also require development consent, which will require assessment by the Department of Planning and Infrastructure. The Planning and Assessment

Commission (PAC) may also assist the Minister for Planning and Infrastructure to assess certain applications, and in some cases replaces the Minister for Planning as the decision maker.

5.3. TYPES OF CSG APPROVALS

The Minister for Resources and Energy can issue four types of licenses for CSG exploration and production. These include a:

- Petroleum exploration license - PEL
- Petroleum assessment lease - PAL
- Special Prospecting Authority – SPA; and
- Petroleum production lease – PPL

CSG development typically involves petroleum exploration licenses PELs, and petroleum production leases PPLs, and these are explained in greater detail below.

5.3.1. PETROLEUM EXPLORATION LICENCE (PEL)

A Petroleum Exploration Licence (PEL) gives the holder the exclusive right to explore for CSG within the area specified in the licence for no longer than 6 years, with renewals granted at the discretion of the Minister. Exploration can include a relatively wide range of activities including accessing the site on foot and collecting samples for analysis, geophysical surveying, seismic surveying, drilling core holes, and pilot testing of gas production. Exploration activities that require drilling often require development consent. Other approvals may also be required by the CSG operator such as permits to clear native vegetation, a licence to extract water, or an environment protection licence to authorise pollution. There is currently no legal requirement for the public to be notified of a CSG exploration licence application.

Exploring for CSG in National Parks is essentially prohibited as it is unlawful under the *National Parks and Wildlife Act* 1974 (NSW) to prospect or mine minerals in a National Park. However, some National Parks do not include the land beneath the surface, and therefore there is some ambiguity as to whether extracting CSG from under a National Park is lawful or not (Environmental Defender's Office NSW, 2012) . Typically, exploration for CSG cannot be undertaken in ‘exempted areas’ such as National Parks and State Forests, unless the Minister for Resources and Energy grants an exempted area consent. Exploration in State Conservation Areas will also require agreement from the Environment Minister under the *National Parks and Wildlife Act* 1974 (NSW). In addition, exploration is prohibited on the *surface* of land within 200 metres of a house, 50 metres of a garden, vineyard or orchard, or on any improvement, *unless* written consent is obtained from the landholder.

If development consent is required, an environmental assessment will be required to be undertaken by a consultant paid for by the applicant. This environmental assessment will be undertaken under the pertinent regulations of the *Environmental Planning and Assessment Act 1979* (NSW). Typically the environmental process is the same process that applies for State significant developments.

If development consent is not required, a review of environmental factors (REF) will need to be undertaken by the applicant. An REF is essentially a basic review of environmental impacts. If the REF uncovers significant environmental impacts, then the applicant is required to prepare an environmental impact statement (EIS). An EIS provides a more comprehensive investigation of the environmental impacts. The applicant may also be obliged to prepare a Species Impact Statement if the REF reveals a significant impact on threatened species, populations, and ecological communities and their habitats.

Determinations on granting exploration licenses are ultimately made by the Minister for Resources and Energy, with consideration given to the need to conserve and protect:

- flora, fauna, fish, fisheries and scenic attractions, and
- features of Aboriginal, architectural, archaeological, historical or geological interest in or on the land over which the petroleum title is sought.

If development consent is required, the Minister for Planning (or local council) will need to consider:

- local environmental plans (LEPs) or State environmental planning policy (SEPPs).
- provisions included in any planning agreement.
- provisions included in any coastal zone management plan.
- the suitability of the site for the development,
- the public interest.
- submissions made in accordance with the Act or regulations,
- likely environmental, social and economic impacts of the development.

If an exploration licence is granted, there will often be certain legally binding conditions attached. These conditions may relate to pilot testing, cultivated land, conservation and protection of ecological or cultural items, and rehabilitation of affected land.

5.3.2. PETROLEUM ASSESSMENT LEASES (PALs)

Assessment leases are designed to allow the lease holder to retain rights over an area in which a significant petroleum deposit has been identified, but may not be commercially viable to extract now, yet could possibly be viable in the future. Assessment lease holders have the right to prospect for and assess any CSG deposit on the land comprised in the lease and can be granted for no longer than 6 years.

5.3.3. SPECIAL PROSPECTING AUTHORITIES (SPAs)

Special prospecting authorities allow the holder exclusive rights to conduct speculative geological, geophysical or geochemical surveys or scientific investigations on the land covered by the authority. The initial term of a special prospecting authority is a term (not exceeding 12 months) fixed by the Minister.

5.3.4. PETROLEUM PRODUCTION LEASES (PPLs)

A petroleum production lease (PPL) is granted by the Minister for Resources and Energy and is usually granted for a period of up to 21 years. A PPL gives the holder the right to conduct petroleum mining / CSG production in the area specified in the lease. Production may involve the construction of infrastructure necessary for production to be undertaken, including building roads and pipelines, drilling production wells, clearing vegetation, building gas processing plants, and constructing dams to store produced water. Typically production leases are only granted to applicants who have held a PEL or PAL and complied with the terms of the license or lease. Prior to granting a PPL, the Minister will normally consult with a range of government agencies, local councils, the general public, and the Director-General of Planning.

The approvals process for granting a PPL typically involves proponents applying for development consent and the production lease in parallel. Applicants are typically granted development consent prior to applying for a PPL. CSG production is automatically considered a State significant development, and therefore is assessed under the applicable regulations in the *Environmental Planning and Assessment Act 1979* (NSW).

Similar to applying for an exploration licence, other approvals such as a permit to clear native vegetation, a licence to authorise pollution, and a water use licence may be required. Mining and CSG production applications also require aquifer interference approval from the NSW Office of Water.

5.4. LANDHOLDER RIGHTS

One of the major considerations in regards to landholder rights and CSG development is the fact that in Australia, landholders do not own the minerals or gas below the ground. These resources are owned by the Crown. This means that if a third party obtains permission from the Government, then it can undertake exploration and production with or without the permission of the landholder. The legislative framework is designed to strike some kind of balance between the interests of the landholder, the developer and the Government.

In regards to PELs, there is currently no legal requirement for the public to be notified of a CSG licence application. PALs however, must be advertised in a State or regional newspaper within 21 days of applying for the assessment lease, with councils providing the applicant with details of affected landholders. If development consent is required as part of a PEL or PAL application, the application must be advertised on the Department of Planning and Infrastructure's website.

It is also important for landholders to be aware that exploration is prohibited on the *surface* of land within 200 metres of a house, 50 metres of a garden, vineyard or orchard, or on any improvement, *unless* written consent is obtained from the landholder. If a licence holder causes environmental damage, or engages in unauthorised activities the landholder may get an injunction to stop the activities.

In regards to access arrangements, the licence holder must negotiate an access arrangement with the landholder before undertaking any activities. Landholders are entitled to compensation for land that is likely to be affected by the licence holder. The amount of compensation payable is typically negotiated between the two parties as part of the access arrangement. The landholder may refuse to negotiate an access arrangement, however if after 28 days no arrangement has been agreed, then the licence holder may seek the appointment of an arbitrator. If the parties cannot agree on the appointment of the arbitrator, the Director-General of Primary Industries can select an arbitrator from the Arbitration Panel who will make the final decision as to access. If arbitration fails, either party can challenge the decision in the land and Environment Court which will give a final determination.

6. LITERATURE ANALYSIS

The rapid pace of CSG development, particularly in Australia, has led to concerns within the community, at all levels of government, and in academic circles about a lack of independent scientific research into potential environmental effects of the industry. At a national level, the Federal Government has responded to these concerns by setting up the Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining (IIESC) in 2011 to help ensure that potential impacts of coal seam gas and large coal mining activities are informed by substantially improved science and independent expert advice. The ultimate aim of the IIESC is to provide greater confidence to communities where coal seam gas development is occurring, by providing independent scientific expert advice to state governments on the direct and cumulative impacts of proposed developments, and where the science is uncertain, the committee aims to address the inadequacies. In late 2011, the Australian Government, along with the Queensland, New South Wales, South Australia and Victoria signed the National Partnership Agreement. This agreement signalled a commitment by the states to take into account the advice of the Independent Expert Scientific Committee when making regulatory decisions (IIESC, 2012).

At a state level, in 2011 the NSW State Government established a Legislative Council Inquiry to report on the environmental, health, economic and social impacts of coal seam gas activities. The inquiry took evidence from approximately 130 witnesses, and received over 900 individual submissions from concerned citizens, academics, community groups, councils and government agencies. In its final report, the committee makes a number of comments and recommendations about the gaps in knowledge relating to potential environmental impacts of CSG development. For example, in its comments on potential impacts on water resources, the committee states that:

> *… more data needs to be gathered, and more studies need to be done… in order to understand the science underpinning our water systems. In particular, we need more data on specific water systems and the interconnectivity of aquifers, if any, in these systems, and the potential cumulative impacts of multiple coal seam gas projects. The Committee agrees with the conclusion reached by Geoscience Australia that the Commonwealth and State Governments must take concerted action as a matter of urgency to develop models of cumulative impacts.*
>
> (Final report, NSW Inquiry into CSG, 2012)

One of the components in this report is to develop a risk matrix for some of the potential environmental impacts of CSG development in the Illawarra. This component is provided in the next section. The major potential environmental effects of CSG can be summarised as:

- Groundwater effects, which may include depletion or contamination of surrounding aquifers,
- Subsidence as a result of large scale extraction of produced water and depressurization of the coal seam,
- Well integrity
- Changes in water availability from depressurization in adjacent aquifers,
- Surface water effects, generally arising from disposal of produced water,
- Hazardous waste, resulting from either treatment of produced water or drilling muds,
- The surface footprint of the mining process, including noise, night time lighting, traffic, access routes, and dust.
- Direct greenhouse gas emissions (known as ‘fugitive’ emissions) of methane or CO2.

6.1 RISK ANALYSIS MATRIX

Analysis of risk: CSG development and potential environmental impacts in the Illawarra.

The following table outlines the risk analysis matrix used to assess potential environmental impacts of CSG development in the Illawarra (Southern Coalfield) based on published scientific literature. A number of assumptions apply to this analysis:

1. Potential CSG projects in the Illawarra will *likely* involve development in specially restricted areas of the water catchment.
2. Potential CSG projects in the Illawarra are *unlikely* to use hydraulic fracturing (CSG projects will potentially use horizontal drilling and gofe methane drainage from collapsed mine workings, due to extensive coal mining in the region).
3. Much of the literature cited in this analysis relates to shale gas operations. The differences between shale gas and CSG development need to be well understood to assess potential risk.

		CONSEQUENCES			
		SEVERE Severe disruption and environmental impacts.	**MAJOR** Major disruption and environmental impacts	**MODERATE** Moderate disruption and environmental impacts.	**MINOR** Minor problem handled by normal day to day processes.
LIKELIHOOD	**Almost certain**	**Extreme**	**Extreme**	**High**	**Moderate**
	Likely	**Extreme**	**High**	**Moderate**	**Moderate**
	Unlikely	**High**	**Moderate**	**Moderate**	**Low**
	Rare	**Moderate**	**Moderate**	**Low**	**Negligible**

POTENTIAL IMPACT	KEY LITERATURE & MAJOR FINDINGS	LIKELIHOOD	CONSEQUENCES	RISK
Fractures caused by hydraulic fracturing extend beyond the target coal seam and into adjoining aquifers, causing gas and fluid to migrate.	**(Davies et al., 2012)** ***Hydraulic fractures: How far can they go?*** Maximum reported height of an upward propagating hydraulic fracture is ~ 588 m. Maximum height for natural hydraulic fracture networks is ~ 1106 m. The probability of a stimulated and natural hydraulic fracture extending vertically >500m is ~1% and ~15% respectively. **(The Royal Society and The Royal Academy of Engineering, 2012)** ***Shale gas extraction in the UK: a review of hydraulic fracturing.*** Fracture propagation is an unlikely cause of contamination. The risk of fractures propagating to reach overlying aquifers is very low provided that shale gas extraction takes place at depths of many hundreds of metres or several kilometres. Pressure conditions for contaminants to flow are very unlikely to be met. **(Maxwell et al., 2002)** ***Microseismic Imaging of Hydraulic Fracture Complexity in the Barnett Shale*** **(Fisher and Warpinski, 2012)** ***Hydraulic Fracture-Height Growth: Real Data*** Both papers show the complexity of fracture growth. **(Osborn et al., 2011)** ***Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing.*** Methane concentrations in drinking water wells increased with proximity to nearest gas well. **(Saba and Orzechowski, 2011)** ***Lack of data to support a relationship between methane contamination of drinking water wells and hydraulic fracturing*.** **(Schon, 2011)** ***Hydraulic fracturing not responsible for methane migration.*** Both papers dispute the findings of Osborn et al.	**RARE** **Rationale:** Hydraulic fracturing unlikely to be used in the Illawarra region due to the use of horizontal drilling and goaf drainage. Pressures required to fracture coal are significantly less than pressures required to fracture deep shale. Even if hydraulic fracturing was used, fractures would be unlikely to extend beyond target coal seam.	**MAJOR** **Rationale:** The consequences of contamination are major for any development that may cause long-term damage to the water catchment. contaminate the water supply.	**MODERATE**

POTENTIAL IMPACT	KEY LITERATURE & FINDINGS	LIKELIHOOD	CONSEQUENCES	RISK
Cross-aquifer contamination resulting from well leakage.	There is much research relating to well integrity, particularly studies relating to cement technologies and subsurface greenhouse gas storage. Key literature includes: **(Duguid, 2009)** ***An estimate of the time to degrade the cement sheath in a well exposed to carbonated brine.*** Rate of well degradation will depend on the quality of the cement and the quality of the cementing job within a well. For a well that has good zonal isolation and no pathways for flow the mechanism for attack will likely be diffusion and the rate of degradation will be between 30,000 and 700,000 years to degrade 25 mm of neat paste in a sandstone reservoir, and possibly longer to destroy the cement passing through the cap rock. **(van der Kuip et al., 2011)** ***High-level integrity assessment of abandoned well.*** Review of abandonment regulations showed plug lengths vary greatly from a minimum of 15 m in Alberta to 100 m in some European countries. Considering that diffusion of CO_2 in the cement controls degradation, results of these studies shows that up to a few meters of cement may be affected in 10,000 years. **(Dusseault et al., 2000)** ***Why Oilwells Leak: Cement Behavior and Long-Term Consequences*** Thousands of old wells in the US leak gas to the surface, and into shallow aquifers. Sulphurous compounds and methane can make household water non-potable. Methane from leaking wells is widely known in aquifers and the concentration of the gases in the shallow aquifers will increase with time. **(The Royal Society and The Royal Academy of Engineering, 2012)** ***Shale gas extraction in the UK: a review of hydraulic fracturing.*** The probability of well failure is low for a single well if it is designed, constructed and abandoned according to best practice. Likely causes of possible environmental contamination include faulty wells. Ensuring well integrity must remain the highest priority to prevent contamination. **(Crow et al., 2010)** ***Wellbore integrity analysis of a natural CO2 producer*** Evidence from this investigation suggests that Portland-based cement systems can be used effectively in creating suitable barrier systems for long-term CO2 storage operations, if good practices are employed during well construction. Examples of required good practices include: centralization of casing and efficient borehole mud removal for cement placement.	**UNKNOWN** **Rationale:** The likelihood of well integrity being compromised is hard to assess, although the new Code of Practice for Well Integrity will assist in ensuring drilling companies follow best practice guidelines. Greater certainty in regards to the degradation properties of well construction materials and techniques would allow for improved risk assessment.	**MAJOR** **Rationale:** There are major consequences for any development that has the potential to cause long-term damage to an important water catchment.	**UNKNOWN**

POTENTIAL IMPACT	KEY LITERATURE & FINDINGS	LIKELIHOOD	CONSEQUENCES	RISK
The overall greenhouse gas footprint of CSG production is greater than the GHG footprint of coal.	Again, much of the research on the life-cycle greenhouse gas footprint of natural gas relates to shale gas. The recent report by Saddler (2012) to the Department of Climate Change and Energy Efficiency has identified a significant gap in knowledge with regards to greenhouse gas emissions from CSG production. **(Saddler, 2012)** ***Review of literature on international best practice for estimating greenhouse gas emissions from coal seam gas production.*** There is at present no published data on methane emissions from CSG production in Australia. There is also no systematic program currently underway to measure emissions (apart from CSG producers). There is effectively no public information about methane emissions associated with unconventional gas production in Australia. This is a matter of some public policy concern, given the projected large growth in production of CSG. More information about methane emissions associated with CSG production is required. The US national greenhouse gas inventory methodology does not distinguish between shale gas and CSG. **(Howarth et al., 2011)** ***Methane and the greenhouse-gas footprint of natural gas from shale formations.*** Compared to coal, the footprint of shale gas is at least 20% greater and perhaps more than twice as great on the 20-year horizon and is comparable when compared over 100 years. **(Burnham et al., 2011)** ***Life-Cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal, and Petroleum*** Disputes the claims of Howarth et al. Asserts that shale gas life-cycle emissions are 6% lower than conventional natural gas, 23% lower than gasoline, and 33% lower than coal. **(Cathles et al., 2012)** ***A commentary on "The greenhouse-gas footprint of natural gas in shale formations" by R.W. Howarth, R. Santoro, and Anthony Ingraffea.*** Also disputes the claims of Howarth et al. Using more reasonable leakage rates and bases of comparison, shale gas has a GHG footprint that is half and perhaps a third that of coal. **(Stephenson et al., 2011)** ***Modeling the Relative GHG Emissions of Conventional and Shale Gas Production.*** In all cases considered, the emissions of shale gas power-generation are significantly lower than those of coal.	**UNKNOWN** **Rationale:** There is no published data on methane emissions from CSG production in Australia. Research has tended to be focussed on shale gas and US emissions. The US research suggests life-cycle emissions of shale gas are significantly lower than that of coal. Research is now required with a focus on CSG production in Australia.	**MAJOR** **Rationale:** If it is proved that the greenhouse gas footprint of CSG is greater than the GHG footprint of coal, then the claim of CSG as an attractive low-emissions alternative to coal would come into question.	**UNKNOWN**

POTENTIAL IMPACT	KEY LITERATURE & FINDINGS	LIKELIHOOD	CONSEQUENCES	RISK
Produced water adversely impacts on environment.	**(Van Voast, 2003)** ***Geochemical signature of formation waters associated with coalbed methane.*** Almost all CSG co-produced waters have similar chemistries. The waters are dominated by sodium (Na) and bicarbonate and devoid of calcium (Ca), magnesium (Mg) and sulphate (except when marine-derived sediments are proximal to the coal deposits). **(Freij-Ayoub, 2012)** ***Opportunities and challenges to coal bed methane production in Australia.*** Water purity and the quantity produced determine the means and cost of water management option. Water management options include: surface discharge; underground injection; impoundment with no re-use (evaporation, recharge); or beneficial uses such as irrigation. **(Nghiem et al., 2010)** ***Treatment of coal seam gas produced water for beneficial use in Australia: A review of best practices.*** Volume, pre-treatment and reverse osmosis concentrate management are the most challenging aspects of CSG water treatment. Further research is needed to address the issue of membrane fouling and the treatment of the brine concentrate to achieve the ultimate goal of zero liquid discharge. **(Dahm et al., 2011)** ***A composite geochemical database for coalbed methane produced water quality in the Rocky Mountain Region*** Almost all co-produced water samples from CSG wells were outside the water quality standard for drinking water. **(Jackson and Reddy, 2007)** ***Geochemistry of coalbed natural gas (CBNG) produced water in Powder River Basin, Wyoming: salinity and sodicity*** Na, alkalinity, SAR and pH downstream from unlined impoundment ponds were significantly higher than background levels. **(ALL Consulting, 2003)** ***Handbook on Coal Bed Methane Produced Water: Management and Beneficial Use Alternatives*** Volumes of produced water are highly variable. Outlines various methods of treatment, including reinjection, irrigation, reverse osmosis, ion exchange, and evaporation.	**RARE** **Rationale:** The volumes of produced water in the Sydney Basin are typically much less than in Queensland. Management of water is therefore significantly easier.	**MAJOR** **Rationale:** Incidents that occur at sites within the water catchment are likely to have more serious consequences.	**MODERATE**

POTENTIAL IMPACT	KEY LITERATURE & FINDINGS	LIKELIHOOD	CONSEQUENCES	RISK
Increased bush fire risk.	Much of the land proposed for CSG development in the Illawarra is highly bush fire prone, ie: land that can support bush fire or could be subject to bushfire or ember attack. **(Wollongong City Council, 2005)** ***Illawarra Escarpment Strategic Management Plan*** Major fires have occurred on the Illawarra escarpment and adjacent areas in 1939, 1968, 1980, 1994, 1976 and 2001. (Bowman et al., 2011) ***The human dimension of fire regimes on Earth*** There remains uncertainty as to the most appropriate and sustainable strategies for managing flammable environments with increasing extreme fire weather. Improved knowledge of the following aspects of fire is needed: (1) a better understanding of past fire regimes, (2) how humans currently influence the regional variation in contemporary burning practices, (3) the underlying planning regulations and economic costs and benefits of different types of fire use, (4) social and political responses to risk of fire, and (5) the economic and ecological costs and benefits of fire. **(Wilkinson et al., 2006)** ***Impacts of water quality by sediments and nutrients released during extreme bushfires: Report No. 3. Post-fire sediment and nutrient redistribution to downstream water bodies, Nattai National Park.*** After severe bush fire events, the post-fire recover period of soil stability is 1-4 years. During the recovery phase, above average rainfall events will lead to erosion and subsequent downstream deposition of sediments and nutrients.	**LIKELY** **Rationale:** Intense bush fires in the region are quite common and are likely to occur again. Clearing and human impacts may increase the risks of fire. Gas pipelines are buried underground and well-heads can be remotely shut-off in case of fire.	**MAJOR/ MODERATE** **Rationale:**. Depending on the severity of the fire, impacts can range from catastrophic to negligible.	**HIGH / MODERATE**

7. DISCUSSION

The rapid emergence of CSG and shale gas development in the last few years has generated significant concern within many communities, particularly in Australia and the USA. The potential environmental impacts of CSG development encompass a broad suite of issues relating to groundwater, water catchments and agricultural land. In the Illawarra region, the unique characteristics of relatively pristine bushland and important water catchments have been co-existing with the impacts of longwall coal mining for many decades. However, many of the environmental impacts of the intensive coal mining are still not well understood, particularly in regards to the complex interactions between groundwater and surface water.

Similarly, many of the potential impacts of CSG development are not well understood and therefore significant knowledge gaps exist. The literature analysis in this study shows that significant knowledge gaps exist with regards to groundwater, well integrity, life-cycle greenhouse gas emissions and possible bushfire risks. However, It would appear that the contentious issue of hydraulic fracturing is perhaps not as relevant to the Illawarra region due to the fact that much of the region has already been extensively mined and the target collapsed coal seams (goaf) would be unlikely to require hydraulic fracturing. In addition, if hydraulic fracturing was used, recent research from Davies et al., (2012) suggests that propagation of fractures beyond the coal seam to an adjoining aquifer would not be likely due to the relatively low pressures.

Issues in regards to produced water are also not as relevant in the Illawarra, due to the relatively low water content of the Permian coals in the Southern Coalfield, when compared to the more saturated coal seams in the Surat and Bowen basins. Although the produced CSG water from the Sydney Basin is moderately saline (ranging between 7,000 and 15,000 µS/cm), the low volumes allow for the risk of spillage and surface contamination to be minimised.

Well integrity is perhaps another issue examined in the literature analysis that could benefit from further investigation, particularly with regards to greater certainty as to the longevity of individual wells.

A further gap in knowledge relating to life-cycle greenhouse gas emissions of CSG was highlighted in the analysis, with the report by Saddler (2012) indicating that the lack of data and information on this issue being of serious policy concern.

In addition, the lack of information and data relating to groundwater in the Southern Coalfield was highlighted in 2008 as being of significant concern, with recommendations that data gathering and analysis be improved (NSW Government, 2008). Improvements in this area of research since 2008 were not particularly noticeable, although the author is aware of current research attempting to consolidate data from the numerous agencies in order to generate a better understanding of groundwater in the Southern Coalfield.

There are of course other environmental considerations with CSG development including the ecological effects of clearing bushland, storage of chemicals, and the building of roads, pipelines and associated infrastructure. Although these are legitimate concerns, perhaps one of the major concerns in regards to CSG development in the Illawarra region is the frequency of intense bushfire. Literature relating bush fire to CSG development or gas pipelines was virtually non-existent, which perhaps signifies that this issue could benefit from further investigation.

8. CONCLUSION

CSG development in Australia has rapidly emerged over the past couple of years as one of the country's most highly contentious environmental issues. Concerns as to the possible impacts of CSG on agriculture, groundwater, and water catchments have generated considerable publicity and pressure on all levels of government to strike a balance between agriculture, the mining industry and the environment.

The overarching aim of this project was to objectively assess the current state of knowledge regarding CSG extraction and its potential environmental impacts so that local government can make informed decisions relating to future CSG developments. A critical review of available scientific, government and private company research formed the basis of this study, with gaps in knowledge relating to CSG developments in the Illawarra identified for further investigation.

Exploration and production techniques such as hydraulic fracturing were investigated, in addition to an analysis of the geology and hydrogeology of the Southern Coalfield, with particular reference to the potential impacts on groundwater and water catchments. A review of the current legislative framework was also undertaken, along with a discussion of the global and domestic economic conditions currently driving CSG development.

8.1. AVENUES FOR FURTHER RESEARCH

The rapid pace of coal seam gas development has led to a lack of independent scientific research. This has been recognised by the Federal Government who in 2011 established the Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining (IIESC) to provide advice, oversee bioregional assessments and direct research on potential water-related impacts of coal seam gas and/or large coal mining developments.

One of the key areas for further research is in assessing the potential for CSG to deplete or contaminate water resources, both groundwater and surface water. Further research into groundwater systems and 3D modelling of these systems at a regional scale would assist in understanding potential environmental effects.

Another key area for research is investigating the life-cycle greenhouse gas emissions of coal seam gas from exploration through to end use. Current research shows that natural gas does indeed burn cleaner than coal, but there is currently a lack of research into the total emissions generated in getting the resource to the end user. Research should include an investigation of pipe and ground leakage, methane entrained in produced water, emissions from the drilling, extraction and processing methods (including converting CSG to LNG), plus emissions from transportation, particularly overseas shipping. This would allow a more direct comparison between the greenhouse emissions of coal compared to natural gas.

It would also be worthwhile to conduct further research into the chemicals and techniques used to access and extract the gas, particularly the method of hydraulic fracturing. Companies are indicating that there is a shift towards using techniques and chemicals that lessen the risk to the environment, however further research and development on these issues would be beneficial to both the community and industry. Further research might also be beneficial in regards to seismic effects and subsidence.

Another important area of investigation is in the processing, handling and disposal of produced water. The CSG industry appears to be having some difficulty in dealing with this issue, particularly in Queensland, and therefore further research into filtration, brine processing, irrigation, re-injection, and storage are all possible areas that could benefit from further analysis.

A further area of research could be in investigating potential bushfire risks. This is particularly important in the Illawarra region, where CSG is planned for bushland areas, water catchments and near national parks. Extracting flammable gases, installing pipelines, clearing vegetation, and increasing traffic may increase the risk of fire, and further research into this would be valuable.

Another interesting area of research might look into the possibilities of treating the coal seam as a renewable resource, by stimulating the growth of bacteria within the seam, thereby generating biogenic methane. Some research into this has been undertaken already (Faiz et al., 2003), and it remains an interesting proposition that could be investigated further.

Other possible avenues of further research include investigations into the legislative framework, particularly assessments of the existing regime along with possible recommendations as to how legislation might be improved.

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