Hydrogeological role of Narrabeen Group fractures following coal seam gas extraction in the Southern Coalfields of NSW.

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Hydrogeological role of Narrabeen Group fractures following coal seam gas extraction in the Southern Coalfields of NSW.

Abstract

Coal seam gas extraction is a relatively young and rapidly developing industry. Many members of Government and the general public have expressed concern about the potential negative environmental impacts of coal seam gas extraction and its associated processes. Gaps in knowledge, such as the role of fractures in facilitating fluid flow, and their potential to impact groundwater, need to be further investigated in order to properly assess the risks associated with coal seam gas extraction.

With this in mind, this study was conducted to determine the ability of fractures within the Narrabeen Group in the Southern Coalfields of New South Wales, to facilitate fluid flow following coal seam gas extraction. The upper limit of fracture hydraulic conductivity in the modelled conditions was determined, and limitations of this potential were identified. The ability of Narrabeen Group fractures to contribute to environmental degradation following coal seam gas extraction was also assessed.

Outcrops of Narrabeen Group units were studied in order to constrain the density and extent of systematic fracturing. The micro scale characteristics of these fracture planes were recorded by examining core samples from the Camden Region, and literature was consulted in order to identify the parameters of a 'worst case scenario' following coal seam gas extraction.

The observed fractures have the potential to conduct environmentally significant quantities of water, up to 38.9 litres per day over a 25m² area, which equates to 199% of the 'Long-term average annual extraction limit' set by the NSW Office of Water. This potential is limited by the micro-scale characteristics of fracture planes, including the effects of infill minerals, multiple interruptions to laminar flow, and the potential for rheological sealing of fracture planes in three claystone aquitards present in the group. The results suggest that while there is potential for the existent fractures to facilitate fluid flow and the associated environmental impacts, the likelihood that these impacts will be realised to any significant extent is limited. It is suggested that further research continue with the micro scale characteristics of fracture planes, the potential of Narrabeen Group claystones to seal fresh fractures via rheological deformation, and the degree of subsidence following coal seam gas extraction.

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Degree Name

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Department

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Brian Jones

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Hydrogeological role of Narrabeen Group fractures following coal seam gas extraction in the Southern Coalfields of NSW.

Bachelor of Science (Honours)

By

Kieran Jay Lowe

A thesis submitted in part fulfilment of the requirements of the Honours degree of Bachelor of Science in the School of earth and environmental sciences, University of Wollongong

October 2014
Dedicated to Dwayne Johnson
The Information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged, and has not been submitted in part, or otherwise, for any other degree or qualification.

Signed: [Signature] Date 10/10/14
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Thankyou.
Chapter 1

Introduction

1.1 General Background

Coal seam gas (CSG) is a contentious issue of late. Members of the general public and the government, generally disconnected from the world of mining, now seem to hold a stance on the issue of coal seam gas. This has largely been guided by the extreme success of documentaries on the effects of similar extraction methods on the environment in America. These concerns have been projected onto the Australian public with ferocious effectiveness. The spotlight surrounding this extraction method has resulted in the intense scrutiny of coal seam gas activities by all levels of Australian governments. This extraction method, which on the surface seems to hold environmental advantages over traditional coal mining has had a polarising effect on Australian communities. The reason coal seam gas is so controversial is because of its potential effects on groundwater, and the environment through gas extraction and associated processes. Groundwater is relied upon by our community and the environment in the Sydney Basin. On the Illawarra Plateau, many creeks and ecosystems rely on groundwater for baseline flows, and the maintenance of habitats (New South Wales Department of Environment and Heritage 2011). On the Cumberland Plain, groundwater is used by the community for irrigation of crops, the watering of livestock and in some cases, for drinking water. Traditional coal mining in the region has had a particularly poor track record in preventing the degradation of the environment. Mining in the Southern Coalfield has resulted in a plethora of environmental impacts that have degraded surface habitats and destroyed ecosystems (Reynolds 1976, Judell 1984, McNalley & Evans 2007). These impacts are important, as coal seam gas extraction draws parallels with the hydrogeological impacts of traditional coal mining on surrounding strata.

Due to the introduction of relatively new technology that increases the economy of coal seam gas extraction, such as horizontal drilling and hydraulic fracking, coal seam
gas exploration is occurring at increasing pace (O'Kane 2013). A preliminary report by the New South Wales Chief Scientist and Engineer Mary O'Kane (2013) entitled, "An Independent Review of Coal Seam Gas Activities in New South Wales", flagged fluid flow through fractures following coal seam gas extraction as an unknown in the coal seam gas equation. Little is known about the role of fractures, and their potential impact on hydrogeological regimes following the extraction of water and gas from subsurface coal deposits. With pressure mounting from community groups and industry, Australian governments are finding it difficult to source reliable information on the potential impacts of coal seam gas extraction in order to properly guide their policies.

Coal seam gas extraction in the Southern Coalfield, and in NSW in general, is currently limited to AGL's Camden Gas Project. However, exploration and the possibility of other coal seam gas mining activities are occurring all over the region. The Illawarra Coal Measures are the target of mining and extraction in the Southern Coalfields. The Permian and Triassic sediments of the Narrabeen Group, and the Hawkesbury Sandstone overlie these coal measures. The Hawkesbury Sandstone is the major source of groundwater in the Southern Coalfields, and the potential of coal seam gas extraction to draw water, through the Narrabeen Group, from this integral unit is of great importance. This is due to the dependence of the community and the environment on the Hawkesbury Sandstone for large volumes of clean, reliable water. Bradd et al. (2013) performed a preliminary analysis of coal seam gas impacts, using an existing fracture dataset for the Southern Coalfield to define a fracture density map as a surrogate for hydraulic conductivity. The scope of this study was limited, as the data set was of low resolution, including only large faults, and not background jointing densities. The resulting assessment was not a robust indicator of potential groundwater impacts. The authors suggested that more focused research with higher resolution would be useful in predicting the potential impacts of coal seam gas extraction on groundwater and the environment. In light of this approach, and the need for a similar study of finer resolution, this thesis will present another approach to the issue.
The aim of this study is to determine the density and hydrogeological characteristics of fractures in the Narrabeen Group, overlying the Illawarra Coal Measures in the Southern Coalfield. Specific attention will be paid to their potential impacts in the Camden region. Using the resulting information, examine the possible impacts of coal seam gas extraction on groundwater, and the environment. This will be conducted by

- Collecting available information on fracture direction, spacing, dip, and aperture, from outcrops of each unit overlying the Illawarra Coal Measures.

- Examining core samples, to constrain ranges of fracture aperture, rugosity, and concretion

- Calculating hydraulic parameters, and potential flow of each unit

- Examining results in order to assess the impact of coal seam gas extraction processes on the movement of groundwater, and the potential contamination of aquifers.

The resulting information will place an upper limit constraint on the ability of fractures to facilitate fluid flow following coal seam gas extraction, in the Southern Coalfield. The resulting data will represent worst-case scenario conditions, following the full extraction of gas and water from the Bulli Coal seam, the highest, and most economically significant seam within the Illawarra Coal measures. The results will be discussed in light of their ability to conduct water at maximum potential, and the realities that would govern whether those potentials are realised.
Chapter 2
Background

2.1 Coal seam gas

2.1.1 Introduction

Coal seam gas is a naturally occurring gas, generally between 95 and 97% methane (CH$_4$), which is derived from within the matrix of subsurface coal deposits. Coal seam gas is generally limited to seams between 300 and 1000m depth (CSIRO 2012). The majority of the gas is adsorbed to the coal matrix, on micro pores called macerals. Because of the large surface area of these features, up to 115 square metres of gas per gram of coal can be stored within a seam (Moore 2012). Gas can also be held in modes similar to traditional gas reservoirs, under pressure in fractures, and dissolved in pore water (Ward & Kelly 2013).

Coal is a carbonaceous sedimentary rock, formed from lithified plant debris deposited in ancient peat swamps. Compression, de-watering, and heating associated with burial, causes changes in the texture and the chemical composition of the peat and associated strata, resulting in the formation of coal (O'Kane 2013, Ward & Kelly 2013). A number of factors including extent of time, and overburden pressure, result in a spectrum of coal rankings. This process is known as coalification (Strapoc et al. 2008, Geoscience Australia 2013a) and progresses as shown in figure 2.1.
As the depth of burial increases, the overlying strata exert increasing pressure on the coal, condensing, dewatering and causing it to release volatiles such as carbon dioxide and methane. Thus, with increasing burial and age, methane levels within the coal matrix tend to increase (Schoell 1988).

Two main processes are largely responsible for coal seam gas, biogenic and thermogenic generation. Thermogenic generation occurs through the process of decomposition of coals, caused by heating and chemical changes associated with rank advance. Methane production is highest in medium volatile bituminous coals, and thus is associated with coals buried deeper in sedimentary sequences (Ward & Kelly 2013). Biogenic generation occurs by the action of microbes and is a by-product of the processing of coal by these microbes. These organisms are generally introduced to the system by groundwater of meteoric origin (Schoell 1988, Moore 2012), and are thus found at shallower depths and in any coal rank (Ward & Kelly 2013). Both of these processes are essentially different methods of breaking down longer hydrocarbon chains into smaller molecules.
The origin of coal seam gas, be it thermogenic or biogenic, can be determined via isotopic analysis (Whiticar 1996), however due to coal seam evolution, more than one origin may exist within a single seam sample.

2.1.2 Extraction

Coal seam gas is extracted through wells drilled into target coal seams. These gas wells are specifically designed to be impermeable to water and gas along the well length, to prevent any leakage between the well and aquifers intersected during drilling. To do this, the wells are typically composed of three concentric concrete and steel layers (Figure 2.3).
Being under pressure due to overlying strata, the seam must first be de-pressurised before any methane can be extracted, this is necessary because the gas is held in adsorption by the hydrostatic pressure of the water within the pore space and cleat system. This depressurisation is achieved through dewatering of the coal seam. Being essentially an incompressible fluid, and existing under pressure, the water within the seam flows on its own to the surface, causing a rapid drop in reservoir pressure. This results in desorption of methane from the coal macerals, and allows the gas to disperse through the matrix to the cleat system, and other larger transport structures (Figure 2.4; (Loftin 2009, Moore 2012, Stammers 2012, O'Kane 2013).
When cleat systems are not sufficient to transport economic volumes of methane to a well, methods exist to enhance, or stimulate the methane recovery of that well. Hydraulic fracturing, or "fracking" is a coal seam stimulation process in which water, small concentrations of fracturing chemicals, and a proppant (most commonly coarse sand or glass beads) is pumped at high pressure into a coal seam. This is done in order to fracture the coal matrix, creating pathways for methane to diffuse into, allowing the gas to be extracted (Loftin 2009, Australian atlas of minerals resources mines and processing centres 2012, Cook 2012, Jeffery 2012, O'Kane 2013). The proppant is pumped into the fractures, created or widened by the fracking process, to hold the fractures open and maintain transitivity. The fracking fluid is then chemically thinned and allowed to flow back through the wellbore under its own pressure and that of the produced water, leaving the proppant in place. Care is taken in not allowing the fractures to propagate out of the seam into over or underlying strata such as aquifers, as this may make it impossible to de-pressurise the seam and allow gas to desorb (Cook 2012). However, controlling the propagation of fractures is still an immature science, and thus prediction and modelling can at times be ineffective (Loftin 2009)

In recent years, fracking has been the subject of significant controversy. Most of this
controversy is centred around contamination of beneficial aquifers by fracking chemicals (Lloyd-Smith & Senjen 2011, O’Kane 2013), and the possibility of these chemicals leaking into groundwater through rogue fractures created by the fracking process. Most objections have been aimed at the use of BTEX chemicals (benzene, toluene, ethyl benzene, and xylene), which have been used in the past by some CSG operations in the US. The use of BTEX is now banned in New South Wales and Queensland, due to adverse environmental effects.

Horizontal drilling is another method of coal seam stimulation, involving directing the borehole into a coal seam, so the bore runs parallel within it. Initially, a vertical hole is drilled to within a few hundred metres of the target seam. The drill is then rotated, and begins to turn along side the coal seam. Horizontal wells can extend anywhere up to 3km from the original vertical well (Carter 2013, AGL 2014a). Horizontal drilling increases the surface area of the well in contact with the coal, and thus allows for the extraction of CSG from a larger area. Vertical wells may only have 1-3 metres of production casing enclosed within a coal seam. However by drilling horizontally, a well can have it's entire horizontal length within the seam (Figure 2.5; (Carter 2013, AGL 2014a). This method is advantageous over vertical drilling, as one horizontal well can produce the same volume of gas that would otherwise need many vertical wells to release. In this way, horizontal drilling can lead to a decrease in surface disturbance. Drilling radiating horizontal wells from a single vertical point can also drastically limit surface disturbance (Figure 2.5).

Combining fracking and multi-directional horizontal drilling allows the production of much greater amounts of gas, with minimal effects on the environment, due to the reduction of wells required.
2.1.3 Extraction in NSW

Coal seam gas was first extracted and sold at the Sydney Harbour colliery in Balmain in the early 1900s. The gas was a by-product of seam de-gassing, a process in which gas is extracted from coal seams in order to limit the potential for explosions during traditional mining. The Sydney Harbour colliery was the first to market and sell the gas as an industrial and motor fuel. Modern exploration and production of coal seam gas began in Queensland in 1976 and 1996, respectively, with production in New South Wales commencing in 2001 with AGL’s Camden Gas Project. (Ward & Kelly 2013, AGL 2014a, New South Wales Department of Trade and Investment 2014).
While exploration has occurred predominantly in the Southern, Hunter and Newcastle Coalfields, production is still limited to AGLs Camden Gas Project. The Camden Gas Project includes 144 wells, with 95 producing gas, supplying around 5% of NSW gas needs (AGL 2014a). New exploration licences have recently been issued to Apex Energy, who is drilling in Darkes Forest, just West of the Royal National Park. It is likely that this region will be conducive to coal seam gas production in the near future.
2.1.4 Environmental impacts

The review of coal seam gas activities by the Chief Scientist and Engineer, identified areas of concern surrounding coal seam gas. Many of these issues can be grouped under a banner of environmental degradation (Figure 2.8).

![Figure 2.8 Most common CSG concerns submitted to Review (O’Kane 2013)](image)

However, the main issues identified by Stammers (2012), O’Kane (2013), Ward and Kelly (2013) and the New South Wales Department of Trade and Investment (2014) that may pose an immediate threat to the environment include:

- **Contamination of groundwater aquifers** - harmful chemicals occurring naturally within the coal seam, surrounding strata, or pumped in during the drilling/fracking process may leak into overlying aquifers due to disturbance caused by the extraction process. These chemicals may foul aquifers being utilized for human or livestock consumption, enter river systems and harm aquatic life, or degrade the surface environment.
• **Depletion or drainage of groundwater aquifers** - inversion of hydraulic gradients caused by depressurising the coal seam, may cause water to be drawn from overlying aquifers into the coal seam. Many of these aquifers in NSW are used for human and livestock consumption, irrigation, and river baseline flows.

• **Hydraulic fracturing** - rogue fractures induced by the coal seam fracturing process may extend into other rock units, contributing to, or causing the environmental concerns above. Chemicals used in the fracturing process, may leak (either through primary, or secondary permeability, including rouge fractures) into surrounding aquifers, and cause contamination.

• **Impact of produced water on the environment** - water removed from the coal seam during de-pressurisation, fracking, and extraction often contains high concentrations of salts, heavy metals, hydrocarbons, and radioactive elements. This water must be stored and processed correctly, as direct discharge into the environment may cause environmental degradation.

• **Air quality and fugitive emissions** - methane, carbon dioxide, and other gasses within the coal seam, may leak into the atmosphere due to poor well design, poor well emplacement, and induced interconnectivity caused by fracking. Not only is methane an effective greenhouse, but may also harm human or animal health in the region.

• **Surface impacts** - drilling for, collection of, and transportation of coal seam gas requires land clearance and disturbance. Roads have to be built to drill and access well sites, land has to be cleared for installations and storage, and pipelines have to be built for gas transport. These present necessary sources of surface footprint.
• **Seismicity** - hydraulic fracturing and pressure inversions may cause the build up and subsequent release of stress in rock units resulting in seismic events. These events may have the potential to damage property and cause harm.

• **Subsidence** - depressurised coal seams may experience compaction, causing further fracturing of overlying strata and contribute to problems outlined above.

Within the scope of this thesis, only the environmental issues that may be affected by overlying strata fracture density will be discussed in any detail. This is limited to the depletion of aquifers by the inversion of pressure gradients, and contamination of aquifers by natural and fracking chemicals.
2.2 Regional Geology

2.2.1 Sydney Basin

The Southern Coalfield lies close to the southern margin of the Sydney Basin, a structural trough, at the southern end of the much larger Sydney-Gunnedah-Bowen Basin. The Sydney Basin is bordered to the northwest by the New England Fold Belt, to the northeast by the Gunnedah Basin at the Mt Coricudgy Anticline, and to the east by the Lachlan Fold Belt (Bembrick et al. 1980) (Figure 2.9). Deposition took place predominantly between the Middle Permian, and the Middle Triassic, as the New England Fold Belt was thrust over the older and more stable Lachlan Fold Belt, creating the Hunter-Mooki Thrust and causing the subsidence of a foredeep immediately to the south west of the thrust system. The elevation of the New England Fold Belt behind this thrust system supplied large amounts of sediment to the young basin, subsiding under the weight of the thrust system (Herbert 1980a). Sediment derived from this orogeny, as well as contributions from the Lachlan Fold Belt were deposited predominantly in shallow marine and fluvial systems. These sediments now lay relatively undeformed within the confines of the basin. Reaching a maximum thickness of approximately 3000 metres towards the centre of the basin, thick units generally thin gradually towards the margins (Reynolds 1976).

In the Southern Coalfields, unconformably overlying the Palaeozoic basement is the Talerterang Group and the Shoalhaven Group, a series of predominantly marine sediments, deposited during multiple marine transgressions and regressions (Runnegar 1980). The basal unit of the Shoalhaven Group, the Pebbly Beach Formation lies beneath the Snapper Point Formation, The Wandrawandian Siltstone, The Nowra Sandstone Berry Siltstone and the volcanically interbedded Budgong Sandstone.
Overlying the Shoalhaven Group is the Illawarra Coal Measures, a series of lithic sandstones, siltstones, and economically significant as well as minor coal units. The Illawarra Coal Measures are thought to have been deposited predominantly within a deltaic distributive floodplain environment (Bowman 1980, Hutton 2009). Key to this study due to its stratigraphic position at the top of the Illawarra Coal Measures, as well as its economic importance, is the Bulli seam. This unit is present throughout the Southern Coalfield and represents the majority of the coal reserves in the measures, with a thickness generally around 3 metres. The Bulli seam is low in ash and high in...
vitrinite, resulting in its mining for use as high grade coking coal. Other significant seams within the Illawarra Coal Measures include the Balgownie, Wongawilli, Tongararra and other minor bands (Hutton 2009).

The base of the Narrabeen Group that overlies the Illawarra Coal Measures is considered to have been deposited within the same depositional system as the upper Illawarra Coal Measures (Dehghani 1994). This phase, known as the Wombarra depositional system, encompasses the fluvial Coalcliff Sandstone and floodplain Wombarra Claystone. The middle sequence, known as the Narrabeen depositional system includes the fluvial Scarborough Sandstone, the floodplain Stanwell Park Claystone, the varied fluvial depositional regimes of the Bulgo Sandstone, and the Floodplain Bald Hill Claystone. In the upper reaches of the Narrabeen Group the Newport Formation, forms the basal part of the Hawkesbury depositional system, which includes the Newport formation, and the Garie Formation (Dehghani 1994). This unit will be discussed in detail in Chapter 3.2.

The overlying Hawkesbury Sandstone is a thick quartzose sandstone unit, with minor thin mudstone lenses (Conaghan 1980). The Hawkesbury Sandstone dominates the landscape of Sydney, forming hard, high cliffs along the coastline that veer inland towards the south, forming the prominent Illawarra Escarpment. Although multiple modes of deposition have been postulated since the middle of the nineteenth century, it is now thought to have been deposited in a large braided river system, similar to the modern day Brahmaputra (Conaghan 1980, Ward & Kelly 2013). This unit is key to this study as the significant regional aquifer, and thus will be discussed in further detail in Chapter 2.3.2

The uppermost preserved unit in the Sydney Basin is the Wianamatta Group. This unit represents a single regressive sequence, as a continuing supply of sediment into the Sydney Basin resulted in a retreating shoreline. Units therefore grade upward from the marine influenced, and lacustrine to the alluvial deposits of the Bringelly Shale at the top of the Group (Herbert 1980b).
A simplified table of the units overlying and including the Illawarra Coal Measures is given below.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Characteristics</th>
<th>Hydraulic conductivity (m/day)</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wianamatta Group</td>
<td>Interbedded shales and quartz-lithic sandstone.</td>
<td>Horizontal = $1\times10^{-2}$ to $1\times10^{-1}$</td>
<td>Locally variable Unconfined, or perched porous rock</td>
</tr>
<tr>
<td></td>
<td>Maximum thickness 80m</td>
<td>Vertical = 0.05</td>
<td></td>
</tr>
<tr>
<td>Hawkesbury Sandstone</td>
<td>Interbedded quartzose sandstones, limited mudstone lenses and laminates.</td>
<td>Horizontal = $9\times10^{-4}$ to 70</td>
<td>Unconfined and semi-confined porous rock and aquifers</td>
</tr>
<tr>
<td></td>
<td>Maximum thickness 290m</td>
<td>Vertical = $6\times10^{-4}$ to 0.05</td>
<td></td>
</tr>
<tr>
<td>Narrabeen Group</td>
<td>Interbedded conglomerates, lithic sandstone, quartzose sandstone, red, green, and grey shales, siltstones, and claystones. Maximum thickness of 600m</td>
<td>Horizontal = $1\times10^{-5}$ to 1.0</td>
<td>Leaky confined porous rock and aquitards</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vertical = $2\times10^{-6}$ to $3\times10^{-2}$</td>
<td></td>
</tr>
<tr>
<td>Illawarra Coal Measures</td>
<td>Interbedded sandstone, siltstone, claystone, and coal.</td>
<td>Horizontal = $5\times10^{-5}$ to $1\times10^{-2}$</td>
<td>Leaky confined porous rock</td>
</tr>
<tr>
<td></td>
<td>Maximum thickness 520m</td>
<td>Vertical = $3\times10^{-2}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1 (Herbert & Helbey 1980, Hutton 2009, Emerson & Branagan 2011, Ward & Kelly 2013)

2.2.2 Narrabeen Group

As the barrier between the Illawarra Coal Measures, and the Hawkesbury Sandstone aquifer, the Narrabeen Group and its hydraulic characteristics are significant to the environmental implications of coal seam gas extraction. Additionally, the depositional environment of sedimentary sequences gives rise to heterogeneities that impact on groundwater flow and aquifer connectivity. For example, a quartzose sandstone may have significant porosity, where as a flood plain sequence may possess
dendritic aquifers, intersected by shale aquitards. The Narrabeen Group is composed of eight units. These units are highly variable in their physical and hydrogeological characteristics, therefore understanding their properties as discrete units, is key to understanding the hydrogeological behaviour of the overall group. All thicknesses indicated are representative of the units present at Camden NSW, unless otherwise indicated.

**Coalcliff Sandstone. (10m - Coalcliff)**

The Coalcliff Sandstone is composed of moderately sorted quartz-lithic sandstone, predominantly light grey in colour. The unit is interbedded with dark mudstones, and outcrops as shore platforms and low cliffs at Coalcliff near Stanwell Park. The unit reaches a thickness of around 10m at Coalcliff (GHD Geotechnics 2000), thinning out towards the west and is not present at Camden. The Coalcliff Sandstone represents local fluvial channels in the Wombarra depositional system responsible for the Bulli Coal Seam and the Wombarra Claystone. It is composed predominantly of downstream to lateral channel accretions, however other architectural systems are also recorded (Ward 1972, Dehghani 1994). These elements are indicative of a low to moderate sinuosity mixed-load fluvial system, with channels ranging from 1.4 to 4.5 metres deep. Primary porosity within the Coalcliff sandstone range between 0 and 2, with secondary porosity between 0 and 15.2 (Gahtani 2013)

**Wombarra Claystone (17m)**

The Wombarra Claystone is similar in composition to the top strata of the Coalcliff Sandstone, with small scale cross bedding and ironstone bands in interbedded claystones and sandstones (Ward & Kelly 2013). It is composed of interbedded green, to green-grey and chocolate claystones, with increasing sandstone units towards the south and west (GHD Geotechnics 2000). The unit reaches a thickness of 17m at Camden. This unit was deposited within sediment laden freshwater floodplain and lacustrine deposits, with dispersed splay deposits (Dehghani 1994). The Wombarra Claystone represents the upper end of the Wombarra depositional system, a result of the inability of peat deposition to keep up with the rate of subsidence, following compaction of the underlying coal seams (Dehghani 1994). Within the Wombarra
Claystone, primary porosity values range from 0 to 3.7 %, with secondary porosity between 0 and 12.7 (Gahtani 2013)

Scarborough Sandstone (127m)

The Scarborough Sandstone is a layer of interbedded volcanolithic sandstones, conglomerates, mudstone lenses. The majority of the sandstone beds range from 60 to 180cm thick (Ward 1972, GHD Geotechnics 2000). The Scarborough Sandstone represents the lowermost fluvial deposit of the Scarborough depositional system, which lies on a basin wide erosional surface on the underlying Wombarra depositional system. The mode of deposition is predominantly gravely bed forms, as longitudinal bars, and to a lesser extent, gravely dunes. Dehghani (1994), suggests that this depositional system is a response to the flexural rebound of the basin floor, following the slowing of subsidence caused by the thrustal loading that initiated the Wombarra depositional system. This rebound implicated the forward migration of conglomeritic sediment from the New England Fold Belt, as basin sediments were elevated by basal rebound. Primary porosity range from 0 to 4%, with secondary porosity values between 0 and 18% (Gahtani 2013)

Stanwell Park Claystone (80m - Sutherland)

The Stanwell Park Claystone is a thin unit of interbedded chocolate to olive green claystone and green lithic sandstones. While it reaches a thickness of up to 80m at Sutherland, outcrops near Stanwell Park are limited to a few metres (GHD Geotechnics 2000, Pells Consulting 2011). This unit represents the floodplain deposits of the Scarborough depositional system. Renewed thrust loading of the New England Fold Belt re-initiated a final stage of subsidence in the northern Sydney Basin, resulting in the deposition of these fine grained sediments in the new lowlands (Dehghani 1994). Primary porosity values range from 0 to 2.5%, with secondary porosity between 3 and 8% (Gahtani 2013).

Bulgo Sandstone (240m)
The Bulgo Sandstone is the largest unit of the Narrabeen Group. The base of the Bulgo Sandstone consists of coarse-grained pebbly sandstones and conglomerates. This basal unit is overlaid by grey to green volcano-lithic sandstones. The top of the Bulgo Sandstone consists of finer grained sandstones and shales. Many of these sandstones are grey to brown, with red laminae occurring closer to the Bald Hill Claystone (Ward 1972, GHD Geotechnics 2000). Following the thrust loading of the northern part of the Sydney Basin that resulted in the Stanwell Park Claystone, another stage of flexural rebound, similar to that responsible for the Scarborough Sandstone was initiated (Dehghani 1994). The Bulgo depositional complex as it is known, included three depositional settings. The first being the coarse-grained fluvial deposits at the base of the unit, followed by the finer braid plain and mixed load deposits, and capped by the gradational floodplain deposits that represent a waning sediment supply to the basin, limited relief and slowing activity of the slowing New England Fold Belt (Dehghani 1994). Primary porosity in the Bulgo Sandstone ranges from 0 to 3.7 percent, with secondary porosity contributing more significant values, ranging from 4.2 to 14% (Gahtani 2013).

The Bald Hill Claystone (41m)

The Bald Hill Claystone consists of interbedded red-brown massive claystone, composed predominantly of kaolinite and hematite. Woody fragments are present in paleosols within the unit much like the overlying Garie Formation (Ward 1972). Dehghani (1994) suggested that the Bald Hill Claystone was deposited in a stable floodplain environment. This is supported by the presence of paleosol horizons, indicative of subaerial exposure. The high kaolinite content is a function of either highly weathered source material or formed in situ, from the weathering of bedrock in an environment in which tectonic activity has slowed. No primary porosity has been observed within the Bald Hill Claystone, however secondary porosity values are given as 1.5% (Gahtani 2013).

The Garie Formation (6m)

The Garie Formation is a layer of lightly coloured kaolinitic claystone. It is
mineralologically similar to the underlying Bald Hill Claystone, except for siderite (Fe$^{2+}$) being replaced by hematite (Fe$^{3+}$)(Ward 1972). The unit contains fossilized plant remains, including in-situ root structures. This unit represents volcanic activity in the New England Fold Belt, as it is composed of ash fall materials including accretionary lapilli, thinning from north to northeast, southward (Dehghani 1994).

Newport Formation (34m)
Underlying the Hawkesbury Sandstone is the Newport Formation, consisting of massive, and regularly laminated fine to medium-grained sandstone, with interbedded shales (Ward 1972). This unit begins to form a prominent cliff line north of Garie Beach. The Newport Formation represents the lowest part of the Hawkesbury depositional sequence, which also includes the underlying Garie Formation. Quartzose tongues from the northwardly progressing Hawkesbury depositional system are thought to have penetrated the lagoonal environments of the Newport Formation depositing sediment transported from the Lachlan Fold Belt (Dehghani 1994). As the system slowly moved north the deposition of the Hawkesbury Sandstone fluvial system became predominant. Primary and secondary porosity values within the Newport are around 0.5 and 2 % respectively however no significant porosity exists in shale lenses (Gahtani 2013).

The average porosity for sandstone units within the Narrabeen Group is 0.7 %, however did not occur in siltstones. Average secondary porosity values are given as 4.7 % (Gahtani 2013). Shale and siltstone beds are dominant within the Bald Hill, Stanwell Park and Wombarra Claystones. The low porosity of these units, as well as the Newport Formation, due to the presence of siderite, kaolinite, ankerite, and mixed layer illite/smectite, and other factors such as grainsize and sorting suggest that these units are effective hydrogeological seals. The depositional history of these units is important to note, as it alludes to the composition, and in turn mechanical and hydrogeological characteristics of each rock type. Finer grained and more weathered units will tend to have lower porosity. A rock unit deposited predominantly within a bedload fluvial system will have larger grain sizes, and potentially larger primary porosity values. Source material will have an impact on the type of cementation and
secondary porosity creating processes that can take place. These influences are relevant to a better understanding of the units of interest.
2.3 Groundwater

2.3.1 Introduction

Groundwater is water that accumulates in the pores and fractures of subsurface rock units. These water-bearing units are termed aquifers and can be grouped based on their properties. Aquifers where the upper surface exists at atmospheric pressure, such as the water table, are termed unconfined aquifers. Confined aquifers are characterised by a confining layer, in which the water within the aquifer is confined at higher than atmospheric pressure. This pressure is exerted by the combination of low porosity units above the aquifer, and overlying units applying overburden pressure, and as such, tend to exist at greater depths than unconfined aquifers (Singhal & Gupta 1999, O'Kane 2013).

Groundwater is replenished by the slow infiltration of meteoric water through porous rock units. This recharge often occurs at outcrops of porous or highly fractured rock units. Water then moves through the subsurface, flowing along hydraulic gradients to areas of lesser hydraulic pressure (Geoscience Australia 2013b). This groundwater is eventually discharged into rivers and out of rock seeps, or used by plants during evapotranspiration. The time scales in which these movements take place vary considerably based on the local, and regional geological conditions. Water found deeper within rock units is likely to be older than shallower water, except in circumstances of preferential subsurface flow paths (Figure 2.10).

Groundwater is of great importance in NSW, especially to regional communities that rely on its access for stock, irrigation and drinking water. However it is also essential for baseline flow in some rivers, groundwater springs and Groundwater dependant ecosystems (GDEs) (Madden 2010, O'Kane 2013). Australia wide, the demand for groundwater increased 90% from 1983 to 1996, and is expected to rise in the future, as climate change alters weather patterns, and impacts the reliability of surface water to meet ever growing demand (Geoscience Australia 2013b). In recent years, a greater understanding of the relationship between groundwater, and surface water, has lead to its conceptualization as a dynamic and heavily interconnected system (Council of
Australain Governments 2010, O'Kane 2013). This has understandably resulted in concerns about the potential impacts of CSG extraction within drinking catchments, and where the community uses groundwater.

![Figure 2.10 Simplified groundwater recharge model (United States Geological Survey 2014)](image)

2.3.2 Conceptual regional groundwater model

Other than Quaternary alluvial aquifers, The Hawkesbury Sandstone is the most significant and primarily used aquifer in the Southern Coalfield, with some wells able to yield up to 2 L/s (Sydney Catchment Authority 2006, Parsons Brinckerhoff 2011). Groundwater flow is heterogeneous and variable within the unit, and generally associated with zones of higher primary porosity, often caused by reduced proportions of accessory minerals such as siderite and clays (Gentz 2006) and the effects of secondary porosity (Parsons Brinckerhoff 2011). Shale lenses within the unit, although volumetrically insignificant, play an important role in the character of flow. These thin lenses form scattered impermeable zones that restrict vertical movement, and may be the nucleus for perched aquifers (Gentz 2006). The sandstone units of the Narrabeen Group are only considered minor aquifers. This is related to lower primary and secondary porosity, as well as poorer water quality (Parsons Brinckerhoff 2011). However, units such as the Scarborough Sandstone do provide baseline flows to some
rivers in the Woronora catchment (Madden 2010). The Narrabeen Group also contain the Bald Hill, Stanwell Park, and Wombarra Claystones, that are considered effective aquitards (Parsons Brinckerhoff 2011, Gahtani 2013). These units are considered to play a major role in reducing connectivity between the potential aquifers of the Narrabeen Group, and surrounding units (Parsons Brinckerhoff 2011). The effectiveness of these units in limiting connectivity between the Illawarra Coal Measures and the Hawkesbury Sandstone, may be more reliable when their cumulative effects are considered, as there is evidence to suggest doubt as to the Wombarra Claystones ability to restrict vertical leakage between the coal measures and the Scarborough Sandstone (Madden 2010).

2.3.3 Groundwater and Coal Mining

Traditional coal mining methods have the potential to alter subsurface hydrogeological systems, where retrieving coal comes into contact with, or changes the local conditions of water bearing units. This disturbance can be caused by both surface and underground mining methods, and with both partial and full extraction of a coal seam (Reynolds 1976, Judell 1984).

Partial extraction methods such as board and pillar mining, involve removing long, tabular blocks of coal, leaving pillars to support the weight of the overburden units. Full extraction, such as long wall mining, involve supporting the roof with hydraulic jacks, while large swathes of coal are removed. Following coal extraction, the jacks are removed, allowing the roof to collapse behind the advancing mine works (Reynolds 1976). Any removal of coal will change hydrogeological conditions within the unit. Free space, once occupied by the coal, will act as a pressure sink, allowing fluids to migrate into these areas through hydrogeologically connected strata. Removal of coal, either by partial or total extraction, will also result in subsidence of overlying strata. Following partial extraction, the matrix of the pillars left behind to support the roof will compress under the weight of overburden pressure. Overlying strata will generally compensate this stress, via bed separation, fracturing, and the lowering of surface topography (subsidence). Where total extraction is employed, the undermined roof of the coal seam will break and fall into the space below, occupying
more space as non-tessellating blocks rather than singular cohesive units. The space in which they occupied will then be free for the process to be repeated, propagating a wave of fracturing and subsidence above the mined coal seam (figure 2.11) (Reynolds 1976, Department of Environment and Climate Change 2007, McNalley & Evans 2007). The magnitude of surface subsidence is dependent on local geological conditions, and is commonly quantified as the proportion of subsidence, to mined seam thickness. In NSW, maximum values tend around 60-65% of seam thickness (Pineda & Sheng 2013). The fracturing associated with subsidence creates conduits of fluid flow, potentially allowing hydrogeological connections and flows that were originally restricted by now fractured impermeable units. This phenomenon, coupled with the pressure sink created by the removal of coal has the potential to dramatically alter local hydrogeological regimes (Reynolds 1976, Judell 1984).

![Conceptualised coal mining subsidence following long wall extraction](image)

*Figure 2.11 Conceptualised coal mining subsidence following long wall extraction*(School of Surveying and Spacial Information Systems 2014)

This process poses a number of environmental threats, including the draining of aquifers, disconnection of surface waters dependant on groundwater supply, and
changing the chemistry of ground and surface water (Department of Environment and Climate Change 2007). Water can be drained through subsidence induced fractures, into space once occupied by coal, reducing the volume of water available to humans and the environment in the affected, and hydrogeologically connected aquifers. This may result in an inadequate supply of water used for human consumption, irrigation and drinking water for livestock. Many aquifers are responsible for supplying creeks and rivers with baseline flows. As these ecosystems are often disconnected, widely dispersed, and limited, they may support Groundwater Dependant Ecosystems (GDEs) that can be home to many threatened and endangered species of flora and fauna (Department of Environment and Climate Change 2007). These GDEs can potentially be cut off from their water supply, resulting in the destruction of their habitat. Fracture induced connection of groundwater with previously unencountered strata, especially units high in heavy metals, organic matter and sulphur, such as the coal seam, can cause changes in the chemistry of groundwater. Material in a closed system, now connected with surface water, may leach salts, minerals, radioactive material and other pollutants into ground and surface waters, changing the salinity, pH, toxicity and making them unsuitable for use by humans, and potentially devastating on the environment. Incidence of surface water drainage, groundwater dependant upland swamp scalding, and domination by iron oxidising bacteria have been documented as a result of mining subsidence on the Woronora plateau (Department of Environment and Climate Change 2007) (Figures 2.12 & 2.13).

One such event, the cracking of the Cataract riverbed followed longwall widening of the Tower colliery in 1992, downstream from the Broughtons Pass Weir. Subsidence in the region reached levels of up to 475mm, about 19% of seam thickness. Cracks in the exposed sandstone riverbed began to propagate. This resulted in the drainage of rock pools and the subsurface diversion of flow. In 1994, exacerbated by drought conditions, flow ceased altogether (McNalley & Evans 2007). Joint patterns present in the region were opened up by subsidence, and apertures up to 20mm wide were recorded. Stream water losses of up to 4ML/day were recorded in some areas. Methane emissions around areas of dead bankside vegetation were observed and vegetation death was said to be linked to the generation of anoxic conditions, as methane migrating through the soil was oxidised (New South Wales Department of
Between 1999 and October 2002, no flow events occurred on over 20 occasions. Water that returned downstream was heavily deoxygenated, and contaminated with iron (Department of Environment and Climate Change 2007) (Figure 2.12).
Figure 2.12 Iron oxidising bacteria in the lower Cataract River (Department of Environment and Climate Change 2007)

Figure 2.13 Scalding in swamp as a result of alkaline mine water discharge, upper end of Lizard Creek (Department of Environment and Climate Change 2007)
2.3.4 Groundwater and coal seam gas extraction

The most significant hydrogeological effect of coal seam gas extraction, involves the dewatering process required for production. The effect of this action is not dissimilar to the removal of coal in traditional mining methods, in that it reduces hydraulic and mechanical support of overburden units, and creates a pressure sink, in which fluid is conducted. Depressurising coal seams by removing water reduces hydrostatic pressure within the coal seam allowing gas to mobilise from the storage structures. This process results in a zone of lower hydrostatic pressure surrounding the wellbore. Water from within the seam will flow towards this area of depressurisation, down a hydrostatic pressure gradient. Interconnectivity between the coal seam aquifer and surrounding units, either through primary or secondary (including those induced via fracking) porosity may result in water being drawn into the seam from hydrogeologically connected units. This in turn may lead to draw down or depletion of beneficial aquifers. Much like the impacts of aquifer depletion resulting from traditional coal mining, drawdown from aquifers that are essential to baseline flows in rivers and creeks, may result in increased incidences of no flow, habitat fragmentation via longitudinal disconnection, and changes to stream morphology, such as those seen in the Cataract River (Department of Environment and Climate Change 2007, McNalley & Evans 2007, Jankowski & Knights 2010, Pineda & Sheng 2013). In the Southern Coalfield, this could result in the habitat destruction of endangered and vulnerable aquatic species such the Macquarie Perch. The Macquarie Perch require a water depth of at least 12cm over riffles in order to be able to feed and distribute their eggs. Any reduction in water level in these systems could potentially see the disappearance of these vulnerable organisms in the affected streams (Department of Environment and Climate Change 2007).

Put simply, aquifer drawdown that changes environmental flow regimes to streams reliant on these aquifers for baseline flows could potentially reduce the amount of water within the system, to levels unable to support its aquatic community. This alteration to natural flow regimes is listed as a "Key Threatening Process" in the Threatened Species Conservation Act (Department of Environment and Climate Change 2002).
Similar to traditional mining methods, coal seam gas extraction also results in a measure of subsidence. Removal of water and gas from a coal seam, results in a decrease in pore fluid pressure, causing an increase in effective stress on the coal matrix (Pineda & Sheng 2013). The effective stress is the difference between the total stress and the pore pressure. Therefore as pore pressure is reduced, effective stress is increased. If the matrix of the coal is unable to support this increase in stress, it will experience compression. This causes an decrease in primary porosity of the coal matrix, resulting in subsidence of overlying units (Harpalani & Chen 1992) (Figure 2.14).

![Figure 2.14 Theoretical diagram for coal compaction following fracking, and extraction (Pineda & Sheng 2013)](image)

The magnitude of subsidence following coal seam gas extraction is highly variable, and is a function of the hydro-mechanical properties of the coal seam, the volume of gas extracted, the method of extraction, area over which extraction takes place, and the local geological setting of the coal deposit (Pineda & Sheng 2013). Due to the smaller volumes of material extracted, subsidence caused by coal seam gas extraction will not rival the amount of subsidence caused by traditional mining methods. Proportional values of around 60% of seam thickness will unlikely be approached by coal seam gas extraction induced subsidence. The maximum expected subsidence value in Australia is predicted to be 280mm (IESC 2014). While there are no
observed incidences of subsidence caused by coal seam gas extraction in Australia, in the US, subsidence of up to 83mm over three years has been observed (IESC 2014). In the Southern Coalfields, Mine Subsidence Engineering Consultants (2007) concluded that potential for subsidence due to coal seam gas extraction is negligible. Where subsidence does occur, much like traditional coal mining, fractures are likely to accommodate the associated strain. Subsidence induced fractures can potentially exacerbate the potential for drawdown discussed above. The diversion of water through subsidence fractures, or the opening of regional fracture patterns already present, may expose ground and surface water to units that may alter its chemical composition.

A study of water quality across an area of longwall mining in the Waratah Rivulet was conducted by Jankowski and Spies (2007). Across longwall panels, a significant portion of flow is diverted through subsidence fractures to subsurface routes in times of low flow. During this time, water reacting with minerals exposed in fresh fractures are characterised by the dissolution of carbonates, reductive dissolution of oxides and hydroxides, and the oxidation of metal sulphides. Water returning to the surface downstream was also enriched in Ca, HCO$_3$-, Fe, Mn, Ba, Zn, Co and Ni. Returning water also has much higher electrical conductivity and pH, and significantly lower reduction potential and dissolved oxygen compared to surface water upstream (Jankowski & Spies 2007). Chemical differences between water diverted to subsurface paths, and surface flows, can be seen clearly, as iron-oxidising bacteria act as an effective marker (Figure 2.15). Methane is being released through fractures in the riverbed, where subsidence has increased connectivity with organic units, potentially even the coal seam (Figure 2.16). Remediation techniques, such as pumping grout into the subsurface in order to seal mining induced fractures are taking place throughout the rivulet. Grout is pumped into zones identified as having a high fracture density, until the grout reaches the surface, preventing the subsurface diversion of surface water (Figure 2.17).
Figure 2.15 Iron oxidising bacteria mark water exposed to subsurface flows in the Waratah Rivulet. Water to the right of the image is fed from a surface pool approximately 20 metres upstream out of the photograph. Water to the left of the image, flowing over stained rock, flows from a horizontal fracture, assumed to be induced by subsidence. It is expected that this water flows from the same pool, through fractures, however this hypothesis could not be quantified.

Figure 2.16 Methane bubbling from a fracture in the bedrock creek bed, Waratah Rivulet. Bubble at the surface is approximately 2 cm in diameter.
Documented incidences of the aforementioned environmental issues caused by coal seam gas extraction are scarce. The independent review of coal seam gas activities in NSW (O'Kane 2013), and it's associated background papers and submissions (Anderson et al. 2013), fail to identify any relevant examples of the environmental issues discussed above beyond anecdotal, well construction and water storage incidents. However, coal seam gas extraction has the potential to cause the same hydrogeological effects that have resulted in environmental degradation caused by longwall mining. This is especially the case if conditions are unfavourable, and best practice is not adhered to. In a case so sensitive, it always does well to remember that absence of evidence is not always evidence of absence.
2.3.5 Limitations to flow

The drainage of the Hawkesbury Sandstone through the Narrabeen Group, and into the Illawarra Coal Measures to equilibrate an overburden induced pressure gradient following gas extraction, is ultimately limited by the volume of gas and produced water extracted from the seam. As gas is stored at near liquid state within the coal seam (O’Kane 2013), equations regarding its volume will be made at methane boiling point.

If fracture induced connections between the coal seam and aquifers were existent, once the volume of water conducted from surrounding aquifers, met the volume of products removed via extraction, the overburden induced pressure sink would be equilibrated and influx would cease. This volume of gas and produced water removed from the seam, will therefore dictate the potential for aquifer drainage. Gas production does affect the porosity and permeability of coal seams (Harpalani & Chen 1992), meaning space available for influx following gas extraction would be reduced, however this process is complex, and quantifying the effect requires extensive knowledge of the properties of the coal seam, and is thus beyond the scope of this thesis.

Gas volumes.

Data obtained from coal exploration reports in the Camden region, give an average of 11.53 cubic metres of gas per tonne of coal in the Bulli seam, at standard temperature and pressure (Department of Mineral Resources 1999). While this measure is indiscriminate of gas type, subsequent tests reveal the gas is composed of 83.2% methane, with small amounts of ethane and carbon dioxide. Methane will therefore be used for volume calculations. Given the specific volume of methane at STP (1.5227 m$^3$/kg), and the specific weight of methane at boiling point (422.36 kg/m$^3$), It can be concluded that there is 18L of liquid gas per tonne of coal in the Bulli seam.

Water volumes
Moisture in the Bulli Coal seam is given as a loss of 0.8\% mass of coal, when dried in air between 100 and 105°C. This equates to approximately 8L water per tonne of coal at STP (Department of Mineral Resources 1999).

\textit{Coal density}

The relative density of the Bulli seam in comparison to water is given as 1.45 t/m$^3$ (Department of Mineral Resources 1999). With the thickness of the Bulli seam in this locality given as 2.62m, a block of coal with a top down area of 1 by 1 metre, and a thickness of 2.62m, will weigh 3.8 tonnes. This volume of coal will contain 68.4 L of liquid gas, and 30.4 L of water, with an influx potential of 98.8 L/m$^2$. This value represents the maximum influx potential per square metre of coal within the Bulli seam.

2.3.6 Hydraulic Gradient

In order to determine the potential for water to be conducted into the depressurised Bulli Coal seam, the pressure difference between the aquifer, in this case the Hawkesbury Sandstone, and the coal seam must first be quantified. This difference is known as the hydraulic gradient.

The hydraulic gradient, is the hydraulic pressure difference across a certain distance, and is given by $\frac{\Delta P}{\Delta X}$. In the case of this study the gradient of focus is the pressure difference across the Narrabeen Group, following the depletion of water, and gas from the Bulli Coal seam. This creates an area of close to atmospheric pressure immediately surrounding the well head in the coal seam (AGL 2014a). Although within metres of the wellhead, the hydraulic pore pressure will begin to rise. This phenomenon is difficult to quantify. For the purposes of this study, in modelling the potential impacts of this effect, it will be assumed that a large area within the coal seam will exist at atmospheric pressure following coal seam degassing and dewatering. This will allow the hydraulic gradient to represent worst-case scenario conditions.
Hydraulic data, including well depths, water level and unit height above sea level, have been synthesized from AGL groundwater monitoring reports for the 2014 financial year (AGL 2014b), and coal exploration reports from the Camden region (Department of Mineral Resources 1999). A summary of the hydraulic conditions for the given scenario can be seen in Figure 2.18

This figure illustrates the hydrogeological conditions that will be assumed in order to model worst-case scenario conditions following coal seam gas extraction. A hydraulic gradient of 1.393 will be assumed across the Narrabeen group. This will simulate the maximum potential flow vertically above the well bore, where the coal seam is hydrogeologically connected with the aquifer.
2.4 Fractures

2.4.1 Introduction
Fractures, including joints and faults, are planes in which stress exerted on a rock unit has resulted in a loss of cohesion, forming a discontinuity. These are generally linear planes that manifest as boundaries separating blocks of consolidated rock matrix, and represent the planes of weakness within the unit (Singhal & Gupta 1999). Fracturing is a brittle deformation process. The characteristics of individual fractures are usually determined by their mode of genesis and associated stresses. Fractures rarely form individually, but are usually part of a larger fracture set. The dislocation of a block of rock mass laterally, tangential, or vertical in respect to another along a fracture plane, is referred to as a fault. Joints are defined as discontinuities with only opening displacements (Pollard & Aydin 1988).

2.4.2 Genesis of fractures
Stresses associated with fracture genesis will dictate the types of fractures or fracture sets formed. Many complex processes can result in the formation of fractures. These include but are not limited to, tectonic stresses and resulting deformation, contraction, dilation, unloading, loading, weathering, hydrostatic pressure etc. (Singhal & Gupta 1999). Fractures can be classified into two broad groups, systematic, and non-systematic. Non-systematic fractures are irregular, and often curved. They meet, but do not cross other fractures. They are mostly dilatational of origin, and exist in weathered areas. Non-systematic fractures are often caused by unloading of overburden, and are therefore not indicative of fracture patterns at depth (Singhal & Gupta 1999). Systematic fractures are planar and regular in distribution, they develop due to regional stresses, and exist in parallel sets (Singhal & Gupta 1999). Three groups of systematic fractures are generally recognized (Pollard & Aydin 1988, Singhal & Gupta 1999, Indraratna & Ranjith 2001).
• Sheer fractures, which generally develop on angles of 20-45 degrees to the normal stress. Sheer fractures exhibit lateral movement along the plane of discontinuity (faults).

• Dilational fractures, originate predominantly via tensile forces, and commonly develop perpendicular to the bedding plane and normal stress direction. They can also be formed via hydraulic stress, cooling contraction, and desiccation. Because the mode of displacement is normal to the fracture plane, this type tends to possess larger apertures (inter-block space).

• Hybrid fractures, which exhibit features of both

It is worth noting that bedding planes in sedimentary rocks can also behave as discontinuities, as variations in material properties effect the homogeneity of a block matrix, and often proxy as planes of weakness (Indraratna & Ranjith 2001).

2.4.3 Hydrogeology of fractures

Fluid flow along fractures is a somewhat complex concept. Put simply, fluid may flow through space disconnected from the remaining matrix of a rock unit. However, different types of fractures may posses varied levels of hydraulic conductivity due to the mode in which the fracture was created. For example, dilatational fractures may conduct large amounts of fluid, because two unit blocks have been pulled apart, allowing a large aperture to form. Sheering faults may cause what was once considered pore-space to be forced closed through frictional sorting and micro-fractures, hence reducing hydraulic conductivity. Concretion of fractures by dissolution of minerals may result in the fracture becoming more impermeable than the surrounding matrix, acting as a barrier to flow. Faults with large displacements may also affect large-scale flow by altering connections between hydrogeological units. Describing flow through singular discontinuities is difficult, as flow is dependent on permeability, which in turn is a function of
• Stress (sheer and normal stresses, and their direction in relation to the orientation of the feature)

• Pressure (overburden, hydrostatic)

• Geometry (surface roughness, variable aperture)

(Indraratna & Ranjith 2001)

Flow through singular joints is only one consideration in fluid flow through fractured media. In most cases, the interconnectedness of fracture sets is the limiting factor in secondary permeability (Indraratna & Ranjith 2001). Multiple sets of discontinuities often exist within a particular rock unit, often in relation to multiple episodes and origins of stress. This can create a complex interconnecting web of fractures that increase the secondary permeability of that unit. The interconnectivity of fracture sets is important in dictating the hydraulic continuity (Singhal & Gupta 1999). For this, fracture orientation, size, and spacing are paramount.

2.4.4 Fracture flow equations

Flow through fractures in which the walls are not significantly permeable enough to warrant factoring in their effects, are most commonly described using the parallel plate model (Neuzil & Tracy 1981, Singhal & Gupta 1999, Indraratna & Ranjith 2001). Derived from a number of equations governing Darcy flow, the volumetric flow rate through a single fracture \( Q_f \), bound by impermeable parallel plates can be expressed as

\[
Q_f = \left( \frac{Y}{12\mu} \right) \times L \times b^3 \times J
\]
Where -

\[ \gamma = \text{Specific weight of water} = 9.789 \text{ @ 20}^\circ\text{c} \]
\[ \mu = \text{Dynamic Viscosity} = 0.001002 \text{ @ 20}^\circ\text{c} \]
\[ L = \text{Length normal to fluid flow} \]
\[ b = \text{Aperture} \]
\[ J = \text{Hydraulic Gradient} = \frac{DP}{DX} \]

In order to calculate the flow over areas easily conceptualised, the flow for a single fracture \( (Q_f) \) is multiplied by the fracture density per square metre, and the desired area of calculation.

This equation is known as the Cubic Law, and is valid for fractures with smooth walls, experiencing laminar flow (Witherspoon et al. 1979, Singhal & Gupta 1999). In nature however, it is often not appropriate to assume these conditions, especially in crystalline rocks where asperities on fracture walls can be very large, changing the fracture geometry, resulting in turbulent flow (Neuzil & Tracy 1981). The Cubic Law is most valid in dealing with fractures with small apertures, and smooth walls, like those within shale bedding planes and joints in claystones (Singhal & Gupta 1999). As wall roughness, contact points between the fracture walls, normal stress, and aperture size increase, the validity of the Cubic Law is questioned, as all these factors would lead to a change in velocity, and type of flow, resulting in a decrease in the volume of water transmitted (Witherspoon et al. 1979, Neuzil & Tracy 1981, Singhal & Gupta 1999, Indraratna & Ranjith 2001). Other equations exist in an attempt to factor these effects into flow calculations, however the parameters needed to complete these calculations are hard to measure outside of the laboratory (Singhal & Gupta 1999). Use of the Cubic Law in measuring hydraulic conductivity is useful in this analysis, in order to constrain the potential flow in the worst-case scenario, with open, smooth joints in the claystone units, undermining the hydrogeological seal they are assumed to be. When fracture walls are significantly permeable enough to be accounted for within flow equations, the dual porosity model is most commonly used.
This equation factors in the rate of water loss or gain from the surrounding matrix blocks. It is assumed that this model is not appropriate for flow within many of Narrabeen Group units, due to their low porosity. Quantifying dual porosity effects for units such as the Bulgo and the Scarborough Sandstone, with higher porosity values, would require much more detailed knowledge about the petrology of the rock units of the Narrabeen Group, and is therefore beyond the scope of this thesis.

2.4.5 Regional fracture patterns

Jointing patterns and their relation to regional stress fields in the Sydney Basin have been studied by extensive field analysis (Fergusson & Memarian 2003) and by aerial photography and Landsat imaging (Bowman 1974, Mauger et al. 1984). However these studies have been limited to mapping and structural analysis, with little attention given to the hydraulic implications of the fractures.

Two main joint groups are identified within the southern Sydney Basin. Group 1 regional joints, forming sets in the N-NNE, NE and SE directions, and the less significant, and later formed Group 2, propagating sets in the NNE, E and SSE directions (Memarian 1994, Fergusson & Memarian 2003). Group 1 joint sets are vertical, long, straight, segmented and post depositionally filled with siderite and calcite (Memarian 1994). These joints are thought to have formed during extensional rifting of the Tasman Sea in the Late Cretaceous. Group 2 joint sets are less frequent, and often abut Group 1 joint sets. The recracking of Group 1 joints, and the formation of Group 2 joints is associated with NNE compression, tentatively related to the collision of the Indo-Australian and Pacific Plates (Memarian 1994). Although it is not possible to calculate real values of tectonic stresses, the jointing patterns infer the least principle stress ($Q_3$) was always horizontal (Fergusson & Memarian 2003). This is important to note, as fracture plane conductivity is inversely related to normal stress at depth, implying that smaller $Q_3$ would result in larger apertures (Singhal & Gupta 1999).

Similar work conducted on a larger scale using Landsat and aerial photographs, predominantly in the Western Coalfield recognised surface patterns of fracture
orientation. An orthogonal pattern of SSE and ENE trending fractures was found to extend across the Sydney Basin. A prominent NNE lineament trend is also present in the Grose Sandstone (Shepherd & Huntington 1981). In the Western Coalfield surface fracture patterns have been shown to be similar to those within the underlying coal seam (Shepherd et al. 1981), suggesting vertical consistency.

2.4.6 Fracture concretion

Work on joints conducted in the Illawarra Coal Measures and lower Narrabeen Group (Memarian 1994), demonstrated crystals of calcite over fracture walls, indicating that the fractures are open at depth (Lorenz & Finley 1991). These calcite filled joints show no evidence of sheering. Many fracture walls are stained with siderite and ankerite, as determined by XRD analysis. Where both calcite and siderite are present, siderite lines the joint wall, indicative of preliminary precipitation, followed by calcite infilling (Memarian 1994). The filling of fracture planes with minerals serves to reduce the porosity of the plane.

2.4.7 Fracturing in claystones

As the most likely aquitards within the Narrabeen Group, fracture flow in the claystone members may very well be the limiting factor in the overall hydraulic conductivity of the group, as the primary vertical hydraulic conductivity of these units is low (between $2 \times 10^{-5}$ and $6 \times 10^{-5}$ m/day) (Ward & Kelly 2013). Recently, work in relation to the ability of claystones as aquitards, has been carried out in the context of determining areas suitable for nuclear waste disposal (Horsemann et al. 1999, Arnedo et al. 2013, Zhang 2013, Gerard et al. 2014). This research is a good analogue for concerns surrounding coal seam gas extraction, as the breakdown of nuclear disposal components can form significant quantities of gas (predominantly hydrogen) that may be transported as a gaseous phase, or dissolved on pore water (Horsemann et al. 1999, Gerard et al. 2014). This draws similarities with concerns surrounding the ability of methane, released via the fracking process to leech into aquifers. The characteristic rheological deformation and swelling capability of claystones results in a recovery process following the propagation of fractures, caused by wetting induced swelling,
weakening, and slaking, that can gradationally seal fracture planes within claystones (Zhang 2013). Bedding planes can also influence mechanical and hydraulic properties of the claystones, influencing water and gas forced normal to these planes to move along complex paths, increasing the surface area of fracture contact, and the potential for swelling and slaking processes (Arnedo et al. 2013).

The claystone units in the Narrabeen Group vary in mineralogical composition, and therefore their fracture recovery characteristics will vary as a result. The Bald Hill Claystone is composed of around 75% kaolinite, with siderite making up the majority of the remainder (Loughnan 1963, Ward 1972). Potential for swelling recovery is limited, but mechanical compaction and rheological deformation are likely. The Stanwell Park Claystone is predominantly composed of kaolinite, illite, montmorillonite, mixed-layer clays and chlorite with some smectite (Deen 1999, Pells Consulting 2011). This unit has caused engineering problems in structures such as tunnels and outfall pipes, as smectite and montmorillonite swell in contact with water, undermining the integrity of engineered structures. This however makes the unit an effective aquitard, as a combination of mechanical action, and swelling constituents, will result in the closure of fracture planes. The Wombarra Claystone is composed predominantly of quartz, with kaolinite subordinate to interlayered clay minerals (Loughnan 1963). This means that the units potential for swelling and rheological deformation are limited.
3.1 Constraining fracture density

In order to assess fracture patterns, clean, accessible outcrops of the Narrabeen Group needed to be identified. This was realised in the form of shore platforms. Fieldwork was conducted along an approximately 15 km stretch of coastline, in the Royal National Park, NSW, between May and June 2014 (Figure 3.1). The uppermost unit of the Narrabeen Group, the Newport Formation, forms a prominent cliff line approximately 1km north of Garie Beach. Due to the syn-depositional synclinal nature of the Sydney Basin (Herbert & Helbey 1980), underlying units crop out at sea level progressively southward from Garie Beach. The lowermost unit, the Coalcliff Sandstone, crops out at sea level at Coalecliff, underneath the Sea Cliff Bridge (Figure 3.2).
Fieldwork took place over a series of weeks, walking the length of the shoreline in the study area. Study sites took the form of shore rock platforms and cliff faces. Systematic joint sets were identified by measuring strike angles and representative areas were sampled. At each site, sets were measured for joint interval along scan lines using a tape measure. Spacing was corrected for angle of incidence if scan lines were not normal to joint strike. Where possible, three-dimensional exposures of joints were measured for joint dip.

3.2 Constraining joint aperture and associated characteristics

Core sample DM Cook DDH 73 (Department of Mineral Resources 1999), was identified as a suitable core sample to inspect in order to attain constraints of fracture aperture and concretion. It was taken from the Camden Region, and was used by AGL geologists in conducting pre-studies in relation to the Camden Gas Project. This core, held at the NSW Core Library at Londonderry, was inspected in late May 2014. The core was inspected by hand in order to identify fractures. Fracture aperture was obtained using a hand microscope with scale markings, and values were recorded. Rugosity was measured by taking images through the same microscope, in order to
gauge the scale of asperities on the fracture plane. These images were later analysed digitally identifying plane length of fracture relief over straight-line distance. While it was beyond the scope of this thesis to attain quantitative data on fracture-fills, images were taken in order to inform qualitative analysis.

3.3 Calculating hydraulic conductivity

Hydraulic conductivity was calculated using the Cubic Law (Chapter 2.4.4). Mean aperture values for each unit were calculated, and joint spacing values were analysed. Lower, middle and upper quartiles were extracted for computation within the Cubic Law calculation. Flow was calculated over a 25 m$^2$ area, in order to be easily conceptualized.
4.1 General characteristics and qualitative analysis

Due to the coastal location of the study site, representative sample areas took the form of jointed tidal platforms of varied sizes (Figure 4.1). The step-like nature of these features can be attributed to different mechanical and weathering properties of the interbedded sandstone and mudstone units that make up the majority of the Narrabeen Group. This results in the exposure of the tops of unit beds, displaying a horizontal cross-section of the bed. Joints were by far the dominant fracture mode in all units, except for the Bald Hill Claystone. Joint intensity appeared highest in finer grained and thinner beds, with much larger spacing in coarse-grained beds of larger thickness (Figure 4.5).

Joints that cross many sandy units, and small mudstone lenses, were often arrested by a mudstone lense greater than ten centimetres thick (Figure 4.2). Smaller joint sets in thin sandy units were often unable to propagate into mudstone layers larger than one or two centimetres (Figure 4.5). Almost all fractures observed were vertical or sub vertical (Figure 4.6), leaving only scattered, meso scale normal faults with any dip. In all units, joints crossed at least one bedding plane, resulting in large connected networks of joints and beds. In the Bald Hill Claystone, no joints were observed in situ. However it appeared that small normal faults, between 2-50 cm vertical displacement, replaced joints in accommodating extensional stress in this unit (Figure 4.4). The joints in sandstone layers in the upper reaches of the Bulgo Sandstone had limited continuity into the claystone layers of the Bald Hill Claystone. Even large joints that crossed three to four metres of vertical bedding could only penetrate around fifty centimetres into sandier loams at the base of finer grained units (Figure 4.3).
Figure 4.1 Outcrop within the upper Bulgo Sandstone, with finer grained unit displaying well developed 010, 070 and 110 joint sets. Coarser set displaying only 010 and 070 degree joint sets.

Figure 4.2 Thin mudstone lense, arresting joint that crosses many vertical sand beds
Figure 4.3 Joint in upper Bulgo Sandstone arrested by basal Bald Hill Claystone

Figure 4.4 Normal faulting in Bald Hill Claystone
Figure 4.5 Representation of joints in sandstone and mudstone beds of Bulgo Sandstone. Horizontal field of view at bottom of image approx. 2 metres. Height of exposure approx. 4 metres.

Figure 4.6 Vertical fractures within the Scarborough Sandstone
4.2 Fracture orientation

Three main joint sets appeared consistently throughout the study area. The most prominent of these being the 070° strike, observed at almost every representative outcrop, in both upper and lower Narrabeen Group units (Figures 4.1 & 4.7). Commonly intersecting this was the 010-020° strikes. This set was far more pronounced in the lower Narrabeen Group. The intersections between these main sets showed limited to no lateral sheer along fracture planes (Figure 4.1). Less significant, yet still prevalent was the 100-110° strike set. This set appeared throughout the study area, over a range of units.

![Diagram showing fracture orientations](image)

Figure 4.7 Weighted strike directions of entire Narrabeen Group fracture sets within the study area (Top). Upper Narrabeen (upper Bulgo and above) Fractures (Bottom left), and Lower Narrabeen Group fractures (Bottom right).
4.3 Joint density

Mean fracture density per set ranged from 0.33 to 1.66 fractures per linear metre, with an average of 0.92. No clear pattern was identified, and differences in density do not appear to be explained by theories surrounding their genesis (Chapter 2.4.5 & figure 4.8). As these are ranges over all Narrabeen Group units, the variation observed in cumulative set joint density per unit (figure 4.9) are expected to be a function of the varied mechanical properties of each rock unit.

![Figure 4.8 Density of measured fracture sets within the study area.]

Within each Narrabeen Group unit, Mean cumulative set joint density was fairly consistent, ranging from roughly 0.4 to 1.4 fractures per linear metre (Figure 4.9). Each value represents the average density per linear metre of all sets combined within a specific unit. The highest joint density was exhibited in the upper Bulgo Sandstone, with the lowest values in the significantly coarser Scarborough Sandstone. No systematic fractures were observed in the Garie Formation, Bald Hill Claystone, Stanwell Park Claystone, or the Wombarra Claystone in the field. Density values given for the Bald Hill Claystone and the Newport Formation were extracted from Pells Consulting (2011), as these were unobserved, or unattainable.
4.4 Fracture characteristics

Fractures were not observed in all units present in the core. No fractures were observed in the Garie Formation or the Stanwell Park Claystone. Fractures were observed in core from the Bald Hill Claystone and the Wombarra Claystone, although not observed in the study area. Mean aperture values for all units with observable fractures are given in Table 4.1.
<table>
<thead>
<tr>
<th>Narrabeen Group Unit</th>
<th>Mean Aperture (Millimetres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newport Formation</td>
<td>0.24</td>
</tr>
<tr>
<td>Bald Hill Claystone</td>
<td>0.16</td>
</tr>
<tr>
<td>Bulgo Sandstone</td>
<td>0.12</td>
</tr>
<tr>
<td>Scarborough Sandstone</td>
<td>0.13</td>
</tr>
<tr>
<td>Wombarra Claystone</td>
<td>0.2</td>
</tr>
<tr>
<td>Coalcliff Sandstone</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 4.1 Mean aperture values within Narrabeen Group fractures

Newport Formation
Fractures in the Newport Formation displayed a small thrust offset of 0.5 - 0.6 mm (Figure 4.10). Fractures appeared almost completely filled with minerals, making them identifiable by a red, iron-stained plane (Figure 4.11). In many places grooves formed along the fracture plane in the core, indicating softer infilling minerals.

Bald Hill Claystone
Fractures within the Bald Hill Claystone were extremely similar in texture to the matrix of the rock, and may have been indistinguishable if it were not for iron oxide staining along the fracture plains (Figure 4.12). No offset was visible along the fracture plane (Figure 4.13).

Bulgo Sandstone
Fracture texture within the Bulgo Sandstone was markedly different from the matrix of the rock, consisting of finer grained minerals, and heavily stained by iron oxides (Figure 4.14). A mosaic of iron staining along the fracture plane is indicative of
contact points between the fracture walls, suggesting a limited effectiveness of apertures along the fracture (Figure 4.15).

**Scarborough Sandstone**
Fractures within the Scarborough Sandstone appeared to take more convoluted paths through the rock matrix, due to the coarser grain size of the unit (Figure 4.16). Crystals of gypsum and calcite precipitated along the fracture plane, indicate significant void space for the precipitation of large (in comparison to average fracture aperture) crystals. However it is expected that crystals of gypsum precipitated during storage of the core, as it is unlikely that conditions at depth are conducive to the precipitation of gypsum (Figure 4.17).

**Wombarra Claystone**
Much like the Bald Hill Claystone, the texture of fracture-fill minerals was similar to that of the rock matrix, leaving fractures to be identified by iron oxide staining (Figure 4.18). Continuity of iron staining along open fracture walls indicates limited distribution of contact points and void spaces.

**Coalcliff Sandstone**
The large grain size of much of the Coalcliff Sandstone meant that fractures were easily identifiable, as softer infill minerals formed prominent groves along fracture planes. Iron oxide staining was present at a lesser extent than many other units (Figure 4.19).
Figure 4.10 Fracture plane in the Newport Formation. Field of view = 1.6 mm

Figure 4.11 Thrust offset in Newport Group fracture Horizontal field of view = 3 mm
Figure 4.12 Fracture plane in Bald Hill Claystone. Field of view = 3 mm

Figure 4.13 Closely spaced fractures in Bald Hill Claystone, no offset visible.
Figure 4.14 Fracture within Bulgo Sandstone. Field of view = 1.5 mm

Figure 4.15 Core of Bulgo Sandstone broken along fracture. Iron staining mosaic visible along fracture plane. Core radii approx. = 10 cm
Figure 4.16 Fracture within Scarborough Sandstone. Field of view = 1.5 mm

Figure 4.17 Gypsum precipitates in fracture plane of Scarborough Sandstone. Crystal approx. 0.5 mm across
Figure 4.18 Fracture plane within Wombarra Claystone. Field of view = 3 mm

Figure 4.19 Fracture plane within Coalcliff Sandstone. Field of view = 1.5 mm
4.5 Rugosity

Mean rugosity values could not be obtained for all units, as only those with open plane samples could be accurately measured. The smoothest fracture plane was unsurprisingly observed in the Stanwell Park Claystone, with the largest rugosity value observed in the Bulgo Sandstone (Table 4.2).

<table>
<thead>
<tr>
<th>Narrabeen Group Unit</th>
<th>Mean Rugosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulgo Sandstone</td>
<td>1.09</td>
</tr>
<tr>
<td>Stanwell Park Claystone</td>
<td>1.03</td>
</tr>
<tr>
<td>Scarborough Sandstone</td>
<td>1.06</td>
</tr>
<tr>
<td>Coalcliff Sandstone</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Table 4.2 Mean rugosity values within the Narrabeen Group

4.6 Hydraulic conductivity

Hydraulic conductivity was calculated using the Cubic Law, by computing the conductivity of a metre long fracture, with an aperture value for that unit. This value was then multiplied by the density per linear metre of a joint set. This is equal the conductivity per square metre, where all fractures within each set are straight and parallel to one another. This value was then combined with the conductivity per square metre of each other set at a specific site, and multiplied by 25. The resulting figure represents the hydraulic conductivity of a 25 square metre area of a particular site, with one or more joint sets present. Different equations were conducted using the upper and lower density per linear metre quartiles, and these values were then averaged over each unit.

The largest measured potential for flow over a 25m² area, under the modelled conditions was 38.9 L per day (figure 4.20). This value represents the upper joint
density quartile within the Newport Group. The mean conductivity value within the Newport Formation is significantly lower, at 21.9 L per day, almost half the aforementioned maximum. This maximum value is more alarming in comparison to the difference between the mean and lower quartile of the Newport Formation, with the lower quartile being 15.3 L per day. The robustness of these values will be discussed in Chapter 5.6.

As density values for the Bald Hill Claystone where extracted from the literature, only one value was computed. This represents the flow for a single set with a density of 1 metre, and the observed aperture. Over a 25m² area, the Bald Hill Claystone may conduct 10.03 L per day.

Being the Largest unit in the group, with well exposed shore platforms, conductivity values for the Bulgo Sandstone are likely to be the most robust. Most sites exhibited two joint sets, some with three, and only one with a singular set present. The mean density for the upper Bulgo delivered a value of 12.75 L per day, with a mean value of 5.15 L per day for the lower Bulgo. This difference in conductivity may be due to the absence of the 110° set in the lower Bulgo, leaving only two contributing joint sets per site. The 110° set is present in the underlying Scarborough Sandstone.

The mean conductivity value for the Scarborough Sandstone is 3.6 L per day. The lower quartile of the Scarborough Sandstone, 2.27 L per day, is the lowest recorded conductivity value in the Narrabeen Group. This makes this value the observed limiting value, and the Scarborough Sandstone the limiting unit.

The most clustered unit of the Group is the Coalcliff Sandstone, with a mean conductivity of 5.2 L per day, and an interquartile range of 2.4.

Mean joint hydraulic conductivity across the Narrabeen Group is 10.63 L per day (figure 4.20).
Figure 4.20 Hydraulic conductivity of a 25m$^2$ metre area of Narrabeen Group units

Hydraulic conductivity ($K = \text{L/day}$) of a 25m$^2$ metre area of Narrabeen Group units
Chapter 5
Discussion

5.1 Fracture orientations

Limited examples of shear, both in the field, and in core, were observed within Narrabeen Group fractures, suggesting extensional stresses were responsible for their genesis (Indraratna & Ranjith 2001). The assertion by Memarian (1994) that this extensional regime was caused by the rifting of the Tasman Sea between the Permian and the present, seems a plausible explanation for the source of this stress. Suggestions of an extensional regime are supported by a lack of lateral displacement along fracture planes.

Fractures within the Narrabeen Group across the study area demonstrated orientations that appear consistent with those described in the literature. Group 1 regional joint sets as described by Fergusson and Memarian (2003) in the NNE, NE, and SE directions, are demonstrated by measured strike orientations of the 010-020°, 070°, and 110° strikes respectively. While some joints were observed in the SSE direction, their persistence was too limited to confidently identify them as recognized group 2 joint sets. The consistency of measured strike directions and the literature continues with Shepherd and Huntington (1981), who recognized fractures across the Sydney Basin, specifically in the Western Coalfield, trending ENE (i.e. measured 070°), and a prominent NNE (010-020°) trend in the Grose Sandstone. The Grose Sandstone represents the upper portion of the Narrabeen Group in the western margin of the Sydney Basin. The fractures observed in the lower portions of the Narrabeen Group in the study area, with a greater proportion of 010-020° fractures, suggest that the extensional event responsible for this strike set may not have been temporally defined, or may have not been directly translated across the basin. Alternatively, extensional strain may have been imposed during the sedimentation of the upper Narrabeen Group in the study area, where the Grose Sandstone farther Northwest, closer to the zone of active erosion, was already consolidated enough to be deformed. Further inquiry is necessary to quantify these assertions.
The continuity of fracture orientation across the Sydney Basin further supports the theory of extensional genesis, imposed by the rifting of the Tasman Sea. While this does not mean that fracture density will be consistent across the basin, it does grant some validity to using outcrops of the Narrabeen Group on the eastern margins of the basin, for analogues of fracture characteristics at Camden or Darkes Forest, where outcrops are scarce. Further support comes from measured fracture densities across the Narrabeen Group. With the lowest recorded fracture density being 0.08 and the highest being 6.66, the average fracture density remains relatively constant across the group, ranging between 0.4 and 1.4 fractures per square metre, per set (Figure 4.9). This consistency over a lateral distance of 11 kilometres, and an approximate vertical distance of 450m over the thickness of the group lends further support to basin wide tectonic stresses as the mode of genesis for these fractures, and similarly, fracture densities being consistent basin wide as well.

Confirmation of these assertions could be gained by review of Televiewer log data, taken from boreholes in the Camden region. While the data is publically available on the NSW DIGs database, the software required to view the data is expensive. Sponsorship of further research from a company such as AGL who use Tele-viewer information in assessing their projects would be ideal, in that the results would have the potential to gather further information on the fracture characteristics of regions in which coal seam gas is being extracted. Gorges cut by the Nepean River in the Camden area do not extend deep enough to expose any Narrabeen group units. However, jointing density in the overlying Hawkesbury Sandstone within these gorges could be compared with joint density on the rock platforms of Hawkesbury Sandstone immediately north of the study area, to assess the similarity of joint densities between the two regions. While the Hawkesbury Sandstone may not have experienced the same tectonic stresses as the Narrabeen Group, it may shed light on how broad tectonic stresses are translated across the basin. This would perhaps serve as an analogue for a lack of supporting evidence of basin wide fracture density continuity.
5.2 Field observations

As seen in Figures 4.2, 4.3, and 4.5, thin mudstone and shale lenses within sandier units act to arrest jointing present in sandstone units. The clear absence of jointing in these smaller finer grained beds, suggests the possibility that fractures were not observed in outcrops of claystone units, simply because they were scarce, if existent at all. Smaller beds of mudstone were much more exposed than large claystone units, as large fine-grained units formed gentler slopes than the sandstones, collecting weathered material and talus deposits. The small scale of finer beds in sandy units were buffered form this by the mechanical properties of over, and underlying sandy beds. This made these features easily observable analogues for larger fine-grained units that were unsuitable for inspection. These scattered fine-grained beds in the sandier units of the Narrabeen Group, may act as scattered aquitards, limiting vertical flow, forcing water to move in convoluted paths like mortar in brickwork. This will act to decrease the overall conductivity of these units.

The extensional stresses responsible for the genesis of jointing in sandstone beds is perhaps being accommodated by rheological deformation within these finer grained units and beds. Meso-scale normal faults observed within the Bald Hill Claystone are potentially existent within the Stanwell Park and Wombarra Claystone, accommodating these extensional stresses by scattered, large, lateral offsets via normal faulting, rather than small, cumulative mediation via jointing. This will be discussed further in chapter 5.7

With all joints in sandy units crossing at least one, but commonly two or three beds, connectivity of joint networks was significant. The connectivity of joint networks is a key factor in the hydraulic conductivity of rock units (Indraratna & Ranjith 2001). In the case of Narrabeen Group units, connectivity is definitely not a factor limiting flow, with multiple joint sets and bedding planes forming an evenly distributed, and significant web of fractures.
5.3 Hydraulic conductivity

The impacts of fracture hydraulic conductivity, depend on the potential of annual groundwater recharge to buffer the amount of water conducted (Pells Consulting 2012). If fractures are able to conduct more water than that supplied by recharge, then there is potential for environmental degradation. Values for ground water recharge are very difficult to estimate with confidence. This will be discussed in chapter 5.9. For ease of calculation, groundwater recharge values were calculated as averages per square metre, over the entire Nepean catchment, which cradles the Camden Gas Project. The Nepean catchment covers 3857.47 km$^2$ or 3 857 470 000 m$^2$. Average Rainfall over the catchment is 3741377 ML or 3 741 000 000L (New South Wales Office of Water 2010). Therefore the average rainfall per square metre per year is equal to

\[
\frac{3 741 377 \text{ ML}}{3 857 470 \text{ m}^2} = 969.9 \text{ L/m}^2/\text{year}
\]

Groundwater infiltration rates are estimated by the New South Wales Office of Water (N.O.W.), to be approximately 6% of annual rainfall (New South Wales Office of Water 2010). AGL estimates that this value is much closer to >1% (Parsons Brinckerhoff 2011, AGL 2014b). Using these values, groundwater recharge per square metre, per year, is estimated to be 9.69 L/m$^2$/year at an infiltration rate of 1%, estimated by AGL, and 58.19 L/m$^2$/year at an infiltration rate of 6%, estimated by N.O.W.

N.O.W. have also proposed a sustainable groundwater long-term average annual extraction limit (LTAAEL) of 99.568 ML or 99 568 000 000L over the Nepean catchment. This equates to 26.81 L/m$^2$/year. The mean hydraulic conductivity, for the measured limiting unit within the Narrabeen Group, the Scarborough Sandstone, is 3.67 L/25m$^2$/day. This equates to 53.582 L/m$^2$/year. Using this value, the potential for fractures within the limiting unit to conduct groundwater, is given as a percentage of available water values in table 5.1.
<table>
<thead>
<tr>
<th></th>
<th>6% Infiltration Rate (N.O.W.)</th>
<th>1% Infiltration Rate (AGL)</th>
<th>LTAAEL (N.O.W.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available Groundwater L/m²/year</td>
<td>58.19</td>
<td>9.69</td>
<td>26.81</td>
</tr>
<tr>
<td>Potential Conductivity</td>
<td>91%</td>
<td>500%</td>
<td>199%</td>
</tr>
</tbody>
</table>

Table 5.1 Potential conductivity of groundwater in respect to estimated water available

The potential of fractures in the limiting unit to conduct 199% of the estimated sustainable extraction limit is alarming, and certainly interesting. Were the Bulli Coal seam to be drained of all liquid and gas, leaving an influx potential of 98.8L/m², 368% of the LTAAEL could be conducted over two years at maximum conductivity potential before flow ceased. Were extraction and conductivity to reach potential, it would no doubt have certain detrimental effect on groundwater levels, and in turn the environment.

5.4 Realities of conductivity

Due to many assumptions made and discussed throughout this thesis, the conductivity of these fractures is highly unlikely to reach maximum potential. Tangible evidence for limited conductivity comes from real produced water volumes from the Camden Gas Project. AGL are licensed to remove 30ML (30 000 000L) of produced water per year. However, in the financial year 2012-13, only 4.7ML (4 700 000L) were removed. The Camden Gas Project draws from an area of roughly 48.279 square kilometres (48 279 000 m²). This means although they are licensed to remove 0.621 L/m²/year. They currently only remove 0.097 L/m²/year. With a potential conductivity of 53.582 L/m²/year through Narrabeen Group fractures, the Camden Gas Project is only licensed to remove 1.15% of potential conductivity, or 2.3% of the LTAAEL. The amount of water actually produced from the coal seam represents 0.181% of calculated potential fracture conductivity, or 0.36% of the LTAAEL. Even
assuming these fractures reached their conductive potential, licensing conditions would be expected to prevent that potential being realized.

5.5 Core observations and hydraulic implications

The micro-scale characteristics of fracture planes are important in assessing the accuracy and validity of using the Cubic Law to calculate hydraulic conductivity of such fractures. Many observations made from core samples suggest that calculations using the Cubic Law will result in an over estimation of hydraulic conductivity. This will be discussed further in Chapter 5.6.

All fractures observed in core samples of sandy units were filled with minerals. The extent of infilling appeared to reduce the effective aperture to insignificant representation. This however, is a function of the available scale of microscopy, as the observations to follow implicate flow. Staining of all fracture planes with red minerals scarcely observed in the rock matrix, and presumed to be siderite, ankerite (Memarian 1994) and hematite (expected to be secondary precipitation from the oxidation of siderite or volcanic fragments following core storage), suggest that fluids are able to flow from areas of mineral saturation, through fracture networks to areas of dissolution. Within core of Bulgo Sandstone, open fracture planes exposed mosaics of iron oxide staining (Figure 4.15). This blotchy pattern is indicative of the presence of contact points and voids throughout the fracture plane (Indraratna & Ranjith 2001). Crystals of gypsum, approx. 0.5mm in size observed in fracture planes within the Scarborough Sandstone (Figure 4.17) indicate the existence space available for relatively large crystals to precipitate. Calcite crystals observed by Memarian (1994) may have precipitated within these voids, decreasing the effective aperture of the fracture. Rugosity values indicate that flow paths are between 3% and 10% more convoluted than a smooth plane in claystones and sandstones respectively.

Precipitates such as these, as well as the large grain size to aperture ratio observed in sandier units such as the Scarborough and Bulgo Sandstones, suggest laminar flow will be interrupted in these sandstone units. The clogging of fracture planes with
minerals, mixtures of contact and void points, large precipitated crystals and significant rugosity values, all act to reduce hydraulic conductivity. These observations suggest that while fluid is able to flow, the Cubic Law will not yield accurate results, and values computed within this study are grossly over estimated. This was an expected outcome of the results, and serves the aim of determining the potential for fracture flow in worst-case scenario conditions, with fresh or disconnected fractures, free of these minerals.

Apertures within the claystones were difficult to identify, and thus, aperture values were taken from the width of iron oxide staining along the fracture plane (Figures 4.12 & 4.18). There are a number of potential explanations for the difficulty of identification. One being that fracture apertures were too small to be identified with the power of microscopy available, and iron oxides had leached into the matrix from the fracture plane. In this scenario, fracture apertures were very significantly overestimated. This may explain why apparent apertures of claystone fractures were larger than many of the sandstone units. Iron staining may not represent actual apertures, but the oxidation of iron into the claystone matrix. The second explanation for identification difficulties is that infill minerals are of similar composition to the matrix. This observation may be evidence of the rheological deformation, mechanical slacking, and swelling capabilities observed in the Stanwell Park Claystone (Pells Consulting 2011), and expected in the Bald Hill and Wombarra Claystones. In this case, the permeability of the fracture plane would be similar to that of the host rock matrix, and it is likely that the inability to differentiate fracture planes, from rock matrix in these claystone units is due to fractures being completely sealed by these processes. Iron oxide staining is perhaps an artefact of a short period of fluid flow, and siderite dissolution following fracturing, which was incorporated into the matrix during the sealing process, and oxidized following exposure and storage. In either case, calculated hydraulic conductivity values for these claystone units are expected to be overestimated.

In order to better identify, and quantify the hydraulic effect of these minerals, as well as attain more accurate values of aperture and rugosity, thin section petrography of
fracture planes should be an area of future research. Within the sandstone units, thin section petrography of fracture planes would assist in quantifying the effect of infill minerals on hydraulic conductivity, via decreasing the effective aperture, creating bottlenecks, filling void spaces, and precipitating minerals that contribute to rugosity. Thin section analysis of fracture planes within claystones, would assist in identifying examples of rheological sealing, attaining more accurate aperture values, and validating the use of the Cubic Law in claystone hydraulic conductivity calculations. Thin section analysis is essential in order to better understand the hydraulic characteristics of Narrabeen Group fractures that have been deliberately, but unavoidably overestimated in this study.

5.6 Validity of Cubic Law

Use of the Cubic Law for computation of hydraulic conductivity values was accepted in order to model the worst-case scenario in terms of fracture hydraulic conductivity from an environmental perspective. While some units, such as the Bald Hill Claystone and the Wombarra Claystone appear to meet the criteria of validity for the Cubic Law, others such as the Newport Formation, Bulgo Sandstone and Scarborough Sandstone do not. These units possess larger asperities and infill minerals that appear different in composition to the matrix rock. These factors would lead to preferential flow paths and turbulent flow within the fracture plane, decreasing its hydraulic conductivity. Mosaics of iron staining on fracture walls observed within the Bulgo Sandstone, suggest a large portion of the fracture plane is closed between contacts points on opposing walls. This not only limits the effective aperture of the fractures, but also causes pressure and flow changes as water is forced through voids and bottle necks. This variation in flow will act to greatly reduce the over all hydraulic conductivity. Use of the Cubic Law in these calculations leads to a gross overestimation of hydraulic conductivity, due to a number of assumed factors, such as plane properties and a lack of infilling minerals.

In order to account for these factors, a much greater knowledge of the fracture planes within the Narrabeen Group needs to be realized. Thin section analysis of fracture planes, to determine infill mineral petrography, porosity, permeability, and dual
porosity flow characteristics, will allow the integration of these factors into flow equations, leading to more accurate and robust calculations. These equations were discussed by Singhal and Gupta (1999). The advantage of the Cubic Law is that the values calculated represent the upper limits of joint hydraulic conductivity, and set limits on the potential effects of coal seam gas extraction. This represents an important starting point in a climate where very little is known about the role of fracture conductivity and groundwater surrounding coal seam gas extraction.

The significantly larger value calculated for the Newport Formation is a function of an unfavourable sampling climate, and the nature of the Cubic Law. The aperture measured within the Newport Formation was the only fracture observed. This fracture possessed a larger aperture than the mean for many other units. Most other units also exhibited aperture values of this magnitude, however their mean was buffered from these larger values (as well as smaller ones) by a larger spread of intermediately sized apertures. The Cubic Law, named so because transitivity is proportional to the cube of the aperture, acts to greatly increase conductivity values with small changes in aperture (Witherspoon et al. 1979). The combination of only observing what is assumed to be the upper end of aperture ranges within the Newport Formation, and the effect of the Cubic Law on this parameter, led to a value that was significantly larger than other Narrabeen Group units. This sampling problem could potential be mediated by identifying other examples of the Newport Formation in core and sampling a greater number of aperture ranges.

The hydraulic gradient value used to compute conductivity was calculated assuming full extraction of gas, and water from the Bulli seam, with the coal seam experiencing atmospheric pore pressure. This value was chosen in order to simulate the worst-case scenario, and maximum flow potential conditions. In reality, these conditions are unlikely to exist. At the end of a producing wells life, gas production will only be allowed to continue, until production becomes sub economic. At this point, pressures within the coal seam will still be above atmospheric pressure, due to continuing de-adsorption of gas, and the slow influx of water and gas from farther reaches of the seam. This would result in a far smaller hydraulic gradient across the Narrabeen
Group than that modelled, with increasingly smaller values moving away from the production well (AGL 2014a). In order to identify a more realistic values of hydraulic gradient, data from piezometers adjacent to production wells should be analysed to better understand pressure conditions during, and following coal seam gas production.

5.7 Competence of claystone aquitards

As the assumed barriers to vertical groundwater flow, the claystone units of the Narrabeen Group are key to the potential impacts of coal seam gas extraction on groundwater. With the primary permeability of these units low, the role of fracturing and fracture flow is integral to their competence as aquitards. In the field, fracturing of any kind was not observed within the Wombarra or Stanwell Park Claystone. Within the Bald Hill Claystone, a handful of small normal faults were observed. These faults had vertical displacements between 2 and 50 centimetres, and traces of no more than 3 metres. Usually terminating passively within a single bedding plane.

Figure 5.1 Normal fault within the Bald Hill Claystone. Vertical Displacement = 20 cm.
These faults may be the result of the same extensional stresses responsible for jointing in the sandy units of the Narrabeen Group. However, exposures were not conducive to gather the strikes of strain in the field. This data would be necessary in assessing this hypothesis.

If these claystone units were accommodating extensional stress by normal faulting rather than jointing, it would mean a smaller ratio of disconnected space per metre of extensional strain, than that caused by accommodation via jointing. Extensional strain accommodated by jointing is created by the dislocation of blocks, meaning that the net strain is equal to the sum of joint apertures. Extensional strain accommodated by normal faulting is equal to the sum of fault apertures, and the lateral slip of fault blocks, with the later accommodating a much larger proportion of strain than the former. Therefore space available for fluid to flow is significantly reduced if faulting rather than jointing accommodates strain. This results in a lower fracture density, and space available for fluid flow, for the same amount of strain. Within these claystone units, this also means that the surface area per fracture is much larger than those of joints, as the fractures take an angled route across beds. This larger surface area allows for a larger potential of swelling and rheological deformation to act on each fracture, resulting in more sealing potential for every vertical metre travelled by migrating water.

Still, these faults have the potential to act as hydraulic planes in which water is able to flow, accompanied by lateral flow along bedding planes. In order to assess these fractures as a risk to the ability of the unit to act as an aquitard, a much greater amount of information is needed. The observed scales of these fractures (traces of less than a few metres at most) are not sufficient to undermine the ability of the whole unit. However, as a connected network of faults and bedding planes, there is certainly potential for inter-aquifer connectivity. Research on the characteristics and extent of these fractures would be essential in quantifying this potential.
In core samples, no fractures were observed within the Stanwell Park Claystone. Fractures in the Wombarra and Bald Hill Claystones, exhibited properties that would limit, if not retard hydraulic conductivity. Evidence for fracture sealing processes described by Zhang (2013), suggests conductivity values may be similar to the permeability of the matrix. Whatever the reason for the difficulty in accurately measuring fracture apertures in these claystones, hydraulic conductivity values will be significantly lower than the values calculated. This would make these clay units almost certainly the limiting units within the Narrabeen Group.

With the limited distribution of fractures observed in the field, and the properties of fractures in core samples, it's no wonder why these claystone units are considered to be effective aquitards (Parsons Brinckerhoff 2011, Pells Consulting 2011, Sydney Catchment Authority 2012). Considering the properties of claystone fractures observed in core, and limited distribution in the field, as well as the inherent overestimation of hydraulic conductivity values by use of the Cubic Law, it is the author's opinion that the combination of these limiting effects would severely retard the vertical movement of groundwater through the Narrabeen Group. The incidence of groundwater drawdown from the Hawkesbury Sandstone, following even the most thorough coal seam gas extraction, would be unlikely to take place in any significant measure, given the cumulative effect of three claystone seals. The effect of these claystones would also limit the potential contamination of the Hawkesbury Sandstone, through the fracking process. However, confidence in this comes from the cumulative effect of these units. Contamination of the Coalcliff and Scarborough Sandstones with contaminants from within the coal seam or fracking chemicals is less unlikely, as concerns surrounding the ability of the Wombarra Claystone as an aquitard have already been identified (Madden 2010). These units are of negligible use as aquifers, but contamination may have unknown impacts on ecosystems existent within their exposures.

While flow of water through fractures in the Narrabeen Group may be limited by claystones, flow of dissolved chemicals, such as those used during the fracking process or present naturally within the coal seam, will have an added limitation in the
more porous units of the Narrabeen Group. Solutes moving through fractures within a porous unit will diffuse into matrix blocks of the rock, slowing their overall velocity through the unit (Singhal & Gupta 1999). Retardation by adsorption is also a process that would result in the slowing of solute transport. Quantifying this process in the field would require an extensive knowledge about the porosity, permeability, petrology and interaction characteristics of the Narrabeen Group. Further research in this area could potentially focus on the specific interactions of fracking chemicals, with units of the Narrabeen Group, using fracture hydraulic conductivity data from this study as a springboard.

5.8 Environmental impacts

With the observed fractures unlikely to allow the vertical movement of water across the Narrabeen Group in their present fashion, the potential of coal seam gas extraction to cause subsidence, and the associated fracturing needs to be assessed.

The a top down area of a representative 1 square metre of the Bulli Coal seam at Camden, will house 2.62m$^3$ of coal (Department of Mineral Resources 1999) (discussed in chapter 2.3.5). This volume of coal, following full extraction of gas and water, has an influx potential of 98.8L. This volume represents 3.77% of the overall volume of this representative block. The effects of reducing hydrostatic pressure on the compressibility of the coal matrix is a complex relationship (Harpalani & Chen 1992), and a reduction in pore pressure may result in compaction not only from the collapsing pore space, by also the alignment and compression of matrix grains. However, as this is extremely complex to quantify, it will be assumed that this value represents the space available to accommodate compaction following full extraction of gas and water. Assuming all shrinkage in the coal matrix is accommodated by vertical subsidence, and overlooking the buffering effects of depth of cover, this value translates to a 98.7mm drop in ground surface. While AGL insists that the potential subsidence cause by coal seam gas extraction in the Southern Coalfield is negligible (Mine Subsidence Engineering Consultants 2007), the effects of theoretical potential subsidence should not be overlooked.
Subsidence of approximately 10 centimetres (98.7mm), most certainly has the potential to induce brittle deformation within the sandstone and claystone units of the Narrabeen Group. The fracture patterns observed within this study may act as planes of weakness, potentially resulting the widening of existent fracture apertures, and the formation of faults on the margins of the zone of subsidence. Fractures induced by longwall mining subsidence in the Waratah Rivulet on the Hawkesbury Sandstone, loosely trend along the observed 010-020°, 070°, and 110° strikes of Narrabeen Group fractures. This was observed during recent fieldwork for unrelated research. Although interesting to note, this phenomenon was incompletely studied, and further observation is required to make any confident claims of this trend. However it is the author's opinion that subsidence fractures would be likely to open existing apertures, before propagating new fractures. The opening of these fractures and formation of faults, has the potential to undermine the ability of the claystone units of the Narrabeen Group to act as aquitards.

As the effects of subsidence reduce with increasing depth of cover (Figure 2.11) due to the bridging effects of mechanically competent units (in this geological setting, the sandstones of the Narrabeen), the most likely unit to be significantly effected is the Wombarra Claystone. This unit is already considered to be leaky (Madden 2010), and the formation of subsidence fractures may result in a significantly greater level of connectivity between the Scarborough Sandstone and the Illawarra Coal Measures. The thickest, and most competent of these claystones, the Bald Hill Claystone (Pells Consulting 2012), is over 400m above the Bulli Coal seam. The effect of subsidence on this unit is likely to be significantly less in the Wombarra or the Stanwell Park Claystone. Being less brittle than the sandstone units of the Narrabeen Group, the claystone units are expected to exhibit less subsidence-associated impacts, due to ductile flexure, and rheological deformation. However, rheological deformation is a time dependant process, and any fracture sealing mechanisms are unlikely to take immediate effect (Zhang 2013). The time between the formation of subsidence fractures, or the opening of existent apertures, and any significant rheological sealing, may be long enough to inflict significant damage to the hydrogeological environment.
of the region. The ability, and time scales of rheological remediation of subsidence fractures by Narrabeen Group claystones is a knowledge gap in which further research is necessary to properly assess the impacts of subsidence in the region.

In the Waratah Rivulet, surface water disappearing underground through longwall subsidence fractures for as little as 20 or 30 metres are significantly contaminated with iron (Figure 2.15). Even slight changes to surface flows have the potential to cause environmental damage. Fracturing in sandstone beds, particularly within the overlying Hawkesbury Sandstone are expected to have the most significant environmental effects, although this unit is farthest away from the Bulli Coal. Due to the limited use of Narrabeen Group aquifers, and the environmental significance of the Hawkesbury Sandstone, groundwater dependant ecosystems present on outcrops of this unit are likely to feel the brunt of any effects should they occur. These effects would likely include

- The diversion of surface waters to underground flows, accommodated by subsidence induced fractures

- The draining of upland swamps and sedge lands on the Illawarra plateau

- Changes in water chemistry as groundwater comes into contact with previously hydrogeologically disconnected units. This would be accommodated by the fracturing of claystone aquitard and shale lenses

At present, coal seam gas extraction in the Southern Coalfields and NSW is limited to the Camden Gas Project. In the Camden region, groundwater dependant ecosystems are limited, and dependant predominantly on groundwater from alluvial aquifers. This is due to the long history of agriculture in the region, and the associated changes in landscape, ecosystems and river morphology. Were the potential environmental implications of coal seam gas extraction to be realised in the current extraction
climate, those most significantly impacted would be those that use groundwater for irrigation, stock, and drinking water on the Cumberland plain. While these impacts are not to be downplayed, humans can more easily mediate adverse groundwater impacts than other organisms. Environmental impacts on upland regions of the Illawarra plateau, fragmented remnants of a habitat that once covered much of Sydney, have the potential to destroy organisms and ecosystems that are already threatened. With coal seam gas exploration wells being drilled on the Illawarra Plateau by Apex Energy, there is potential that coal seam gas extraction in NSW will expand to more sensitive regions, within drinking water catchments. In such cases, even slight diversions of flows underground have the potential to cause significant impacts.

These environmental impacts have yet to be observed in the area surrounding the Camden Gas Project since production began in 2001, and no significant groundwater drawdown from the Hawkesbury Sandstone has been observed to date in the region (AGL 2014b). Hopefully this is a function of the limited potential for these issues to realistically take place following coal seam gas extraction. The observations made within this thesis, combined with the long history of successful extraction by the Camden Gas Project, and the favourable geological conditions of the region suggest that the potential environmental impacts of coal seam gas extraction, potentially the same that have been caused by traditional coal mining, are unlikely to be realised. However with more sensitive ecosystems present on the Illawarra plateau covered by exploration licences, the risks of environmental degradation need to be carefully considered.

5.9 Scope of limitations

Constraining the upper limit of fracture hydraulic conductivity, implicated that values were allowed to be overestimated. This resulted in the necessary over sight of many factors that would need to be taken into account in order to attain more realistic and accurate data. These limitations were associated with sampling, results, and theory.
Sampling

The lack of outcrops of the Narrabeen Group at Camden was possibly the largest limitation of this study. This resulted in the need to find analogues, and estimate the characteristics of fractures at Camden, based on the best available information, rather than measuring them directly. The choice of study site was the only location in which outcrops existed in a form suitable for this analysis. However, this necessitated that literature be analysed in order to infer similarity of fracture characteristics between the regions. Even with identifying the best site available, the number of suitable sampling locations within the study area was limited. This limitation meant that the data used for analysis was not robust, and more study sites may be needed to stabilise average values for each unit. The quality of Narrabeen Group outcrop posed another limitation. While conditions of sandier units were conducive to accurate assessment, the physical properties of the claystone units meant that their characteristics were often masked by vegetation, weathering, and talus deposits. While no fractures were observed in exposures of the Wombarra and Stanwell Park Claystones, this may be due to the condition of the outcrop. The strikes of normal faults in the Bald Hill Claystone were unattainable, due to limited suitable exposures of these features within the weathered outcrops. The lack of this data limited any analysis of the stress regimes responsible for the genesis of normal faulting.

While background regional jointing is the focus of this thesis, it is expected that large faults, and associated joint swarms will have a significant impact on the vertical hydraulic conductivity of the Narrabeen Group. However, the study site yielded no observable examples of these large-scale features. A known fault within the Coalcliff Sandstone, the Harbour Fault, runs metres to the south of a studied shore platform at Coalcliff. However its land exposure is now masked by road and vegetation, and was thus unsuitable for examination. No significant change in joint intensity was observed surrounding the southern end of the platform. With known faults mapped in the Narrabeen Group, but unsuitable for study, the inspection of a potential analogue was attempted. The intention was to quantify the joint intensity gradient surrounding these features, in order to make predictions about the potential increase in joint density.
surrounding faults in the Narrabeen Group. A known fault with shore platform exposure in the Broughton Formation, upper Shoalhaven Group at Hill 60, Wollongong, was inspected. However, due to local geological factors, such as the influence of a large set of dikes running parallel to the fault, it was decided that the joint intensity may not accurately represent the effect of the fault only, but also the local volcanic activity. No other suitable example was identified. The effect of large-scale faults on the hydraulic conductivity of the Narrabeen Group is an important area of future research.

Unable to gain access to fresh drill core from the Camden region, core samples were supplied by the NSW Core Library at Londonderry. The core that was examined, DDH73, was the youngest core from the Camden region, which reached target depth, and was available for viewing. This hole was drilled as part of the South Creek Drilling program in 1990, by the Department of Mineral Resources. The drilling program was to assess the potential of coal seam gas deposits in the upper Illawarra Coal Measures (Department of Mineral Resources 1999). There were no other suitable core samples identified.

Limited core samples meant that observations of fractures were limited to fractures intersected by one drill hole. This posed significant issues when fractures within this sample were limited. The samples of the Newport Formation only yielded one fracture. This fracture had an aperture that was slightly larger than the range of averages observed in the other units. Apertures of this magnitude were observed within other units. However, the range of apertures observed within those units stabilized their average. With only one fracture in the Newport Formation, there were no other fractures to increase reliability of the measurement. Thus, hydraulic conductivity values for the Newport Formation are not robust, due to the limited examples of fractures within the unit.

Being almost 24 years old when inspected, significant weathering and deterioration is expected to have introduced errors into measurement of the properties of fractures.
The potential for fracture apertures to increase or decrease due to changes in moisture, pressure and elastic rebound, as well as the potential for fractures to extend, propagate, or seal via slacking processes, due to their release from confining pressure, are all able to skew results. This potential is exacerbated by the tendency of the Cubic Law to drastically increase conductivity values with small changes in aperture. The red staining observed in all fractures is expected to be hematite, weathered from siderite over long periods of oxidation during storage. Crystals of gypsum observed in fracture planes are most likely precipitated from during, as conditions at depth are not conducive to their formation. These are also factors that have the potential to skew results, introduced due to the unavailability of fresh core.

The scale of microscopy available was also a testing limitation. While suitable for the measurement of fracture apertures in the sandstone units, the uncertainty of claystone apertures discussed in chapter 5.5 could perhaps be evolved by access to higher magnification power. Similarly, information regarding the nature, petrography and effect of fracture fill minerals could be drastically improved given higher magnification, short of thin section analysis.

Results

The absence of hydraulic conductivity values for every unit of the Narrabeen Group is a function of incomplete data. Both fracture spacing, and fracture apertures are needed to compute hydraulic conductivity. Some units did not yield useful fracture density values in the field, such as the Garie Formation, Newport Formation, and the Wombarra and Stanwell Park Claystones. In some cases, these values could be extracted from the literature, as was the case for the Newport Formation and Bald Hill Claystone. Where these values could not be gathered, calculations could not be made.

Greater accuracy of results could be attained by thin section petrography of fracture planes, in order to gain a greater understanding of infill minerals, and their potential effects on hydraulic conductivity. This analysis could also shed light on the difficulty of gaining accurate aperture measurements from claystone fractures. Thin section
petrography of fracture planes would presumably also include the surrounding rock matrix. This would allow a greater understanding of the host rock, and its hydraulic properties. This information would be necessary in making any calculations in regard to dual porosity flow and solute transfer. The role of the host rock in solute movement retardation and adsorption is an important factor in the study of the way chemicals within the seam, or introduced during fracking react with fracture flow. The role of fracture flow in contamination of groundwater following coal seam gas extraction, I argue, is the next logical step in this line of research.

**Theory**

The implications of hydraulic conductivity values on the environment depend on the ability of groundwater recharge to accommodate the potential drawdown caused by coal seam gas extraction. Groundwater recharge values are usually estimated by an infiltration rate of annual rainfall. With infiltration rates in the Nepean Catchment estimated to be around 6% by the NSW Office of Water, and <1% by AGL, there is evidence to suggest that predictions of groundwater recharge rest on ambiguous science. Additionally, the role of regional meteoric groundwater infiltration may not be the sole contributor to regional groundwater influx. Subsurface flows, fed from other areas may account for a large portion of a region's groundwater. The conceptual groundwater model for the Camden Gas Project by Parsons Brinckerhoff (2011), conclude that groundwater recharge in the Camden region is dominated by lateral flow, up gradient, and up dip from the south. Particularly from alluvial deposits in weathered valleys of Hawkesbury Sandstone. Quantifying the area and volume of groundwater recharge is a complex task, which has not yet been undertaken. Therefore, assertions made within this thesis regarding the role of groundwater on the environmental effects of Narrabeen Group hydraulic conductivity, are limited by this knowledge gap, and rely on infiltration estimates for groundwater values.

Hydraulic conductivity values are estimated assuming a constant vertical hydraulic gradient of 1.393 across the Narrabeen Group. This value assumes full extraction of water and gas from the coal seam, so that the seam exists at atmospheric pressure. This value is highly unlikely to exist in reality, due to the sub-economic nature of any
well approaching this state, and the constant, but slow influx of water and gas from farther reaches of the coal seam. More realistic values of seam pressure following extraction were not available for use in this analysis. This limited the accuracy of theoretical values used to compute the hydraulic gradient. A more accurate value could be obtained by gaining access to well adjacent piezometers, abandonment logs and information on confining pressure following coal seam gas extraction.

The impacts associated with coal seam gas extraction are based on the theoretical implications of removing gas and water from a coal seam. While analogues are drawn between coal seam gas extraction and traditional coal mining, the documented impacts of traditional mining are yet to be mirrored by coal seam gas mining. This is obviously a good thing, however in respect to this thesis, it limited the ability to draw on actual examples caused directly by coal seam gas extraction, when discussing potential impacts of coal seam gas mining in the Southern Coalfield.

5.10 Conclusion and recommendations

The fracture characteristics identified, coupled with the geological setting of the Southern Coalfield, suggest that the hydrogeological impacts of fracturing within the Narrabeen Group, following extensive coal seam gas extraction will be minimal. However, knowledge gaps, such as historically deficient data in relation to the degree of subsidence following extraction in the Southern Coalfields, and the ability of Narrabeen Group claystones to buffer any fracturing caused by subsidence, suggest that further research is necessary, if we are to accurately asses the threats posed by coal seam gas extraction. This study has identified a number of parameters in this equation, and the following conclusions can be made

- Three fracture sets are persistent across the Group, the 010-020°, 070°, and 110° sets. The density, and extent of these fractures are likely to be similar across the basin. However, more research is necessary to prove this hypothesis.
• At maximum flow potential, the studied fracture sets would be able to conduct environmentally significant volumes of water, up to 199% of the 'long term average annual extraction limit' set by the NSW Office of Water.

• Many factors will limit this potential. These include
  1. The observed fracture planes were choked with minerals, significantly decreasing the secondary porosity and increasing hydraulic drag.
  2. Scattered shale and mudstone lenses throughout the Narrabeen Group will act to restrict vertical flow, and create convoluted flow paths.
  3. Fracture plane characteristics, such as significant rugosity, a matrix of contact points and voids, and large precipitates will all act to interrupt laminar flow, and decrease hydraulic conductivity, resulting in significant overestimation of conductivity by use of the Cubic Law.
  4. Fractures in claystone units exhibited evidence of rheological sealing, and inflation of aperture estimations.
  5. Licensing conditions only allow 2.3% of the 'long term average annual extraction limit' to be extracted by AGL's Camden Gas Project.
  6. Limited fractures observed in the field, characteristics of fracture planes in core, and low primary porosity of the claystone units in the Narrabeen Group suggest that they make effective aquitards.
  7. The claystone units in the Narrabeen Group appear to be accommodating extensional stress by scattered normal faults rather than jointing. This decreases the fracture density, space available for fluid to flow, and allows a larger surface area to undergo rheological deformation per fracture. This assertion is unconfirmed, and more research is needed to assess this hypothesis.

• Coal seam gas extraction has the potential to induce the same hydrogeological conditions as traditional coal mining. These hydrogeological conditions may result in the drawdown of aquifers, the reduction and disconnection of surface
water dependant on groundwater aquifers, and subsidence induced fracturing. These effects have the potential to damage ecosystems that are dependant on groundwater. However, incidences of these impacts have not been observed in the Australian setting, and in the Southern Coalfields, the potential for these impacts to take place is limited.

- The effects of even small diversions of flow underground may have significant environmental impacts, and damage may be done before claystone aquitards can seal fresh subsidence fractures.

These conclusions are vital to our understanding of coal seam gas extraction in the Southern Coalfields. In search of continued understanding of this issue, it is recommended that future research focus on

1. The micro scale characteristics of fracture planes, specifically in claystones, in order to better constrain the potential hydraulic conductivity of these units.
2. The potential and limitations of rheological deformation in sealing fracture planes in the claystones of the Narrabeen Group.
3. The potential interactions between the rock matrix of Narrabeen Group units and chemicals existent within coal units, or introduced during fracking, and their ability to leach into aquifers.
4. The degree of subsidence induced by coal seam gas extraction.
This study has placed an upper limit on the hydraulic conductivity of Narrabeen Group fractures, identified limitations to this potential, and assessed the conceivable environmental impacts of coal seam gas extraction. While there are many limitations to this study, the acclaimed statistician George Box once said, "Essentially, all models are wrong, but some are useful". The social and scientific climate surrounding coal seam gas extraction is one of distrust and caution, and so it should be. With the very real possibility that coal seam gas extraction will take place within sensitive ecosystems such as the drinking water catchments of the Illawarra plateau, research such as this may prove useful in assessing the associated risks to the best of our abilities.

Figure 5.2 Jointed outcrop in the base of the Coalcliff Sandstone
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