THE UNIVERSITY OF QUEENSLAND
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A comparison of CBM in the U.S. versus CSG in Australia: Lessons from the U.S.

Working Paper

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The information, opinions and views expressed in this report do not necessarily represent those of the University of Queensland, the UQ Centre for Coal Seam Gas or its constituent members or associated companies.

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The report has not yet been peer reviewed.

EXECUTIVE SUMMARY

Many environmental concerns have been aired about large scale Coal Seam Gas (CSG) development in Australia. Development for domestic consumption commenced around 1996 but has been in ‘full swing’ since 2008/9, projecting upwards of 25,000 wells by 2025. As of end 2014 over 7,000 CSG wells have been drilled. Uncertainties about future impacts appear to dominate the public debate.

Similar developments in the USA preceded the current Australian (Queensland dominated) development by over twenty years. Commencing in the mid 1980’s, by 1990 some 8,000 coal bed methane (CBM) wells had been drilled with over 14,000 by 2000. In the early stages, similar environmental concerns were aired in the US. This white paper seeks to compare the matured experiences of environmental concerns and any eventuated impact in the US with current experiences and concerns in Australia. In this way whether those early concerns in the US eventuated into environmental harm, might inform relative concerns and risk assessments in Australia.

There is a significant amount of academic, government and industry research covering over 30 years of CBM development in the US and Canada including major baseline studies and two major official independent reviews of environmental performance. Findings and summaries are grouped into four main areas where concerns of significant environmental impacts had been aired in the US and have been espoused by Australian stakeholders regarding CSG. Each of these is discussed in a chapter of this report:

1. Water Drawdown & Produced Water Management Related Issues.
2. Risk of Water Contamination Associated with Natural Gas Extraction from Coal
3. The Nature and Origin of Methane Contamination of Groundwater in Areas of Coal Gas Development
4. Impact of Development of Coal Gas Resources on Land Subsidence

With respect to water drawdown, volumes and management the main conclusion of the review of North American CBM operations relevant to Australia is that the volumes of produced water have been often a factor of two less than those initially predicted by modelling. Similarly the area of significant drawdown in the hydraulic head in key aquifers has been up to a factor of five less than that predicted by widely quoted model studies.

Regarding the risk of water contamination it is significant that no documented examples of water contamination associated with CBM development in North America were found which have been scientifically verified. The cases where water contamination was suspected have been reviewed by a major, congressionally mandated study by the US EPA that concluded none could be ascribed to hydraulic fracturing or any other aspect of CBM drilling or production.

Regarding methane in water, in almost all CBM producing basins in North America methane contamination of groundwater clearly predated gas development. In some cases poor practices in the early days of production have exacerbated methane issues. Methane seeps both on the land and under rivers and lakes are a natural phenomenon and whether coal gas development has increased the methane flux at existing seeps or has created new seeps is an issue that cannot be resolved with currently available data. Comparison of observed subsidence associated with North American CBM fields, suggests that predictions of deci-meters to meters of subsidence for Australian CSG fields is highly unlikely. Total subsidence of a few centimetres might be expected in most cases.

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CHAPTER ONE:
Rationale and Background for this Study

1.1 Rationale and Scope

This white paper sets out to review the literature on the environmental impact of coal seam gas development in the US, Canada, and Australia. The rationale was to attempt to inform evaluations of the likelihood of significant environmental impacts occurring in Australia in the future based on the longer and much more extensive track record of exploiting coal for natural gas in the U.S. and Canada. This paper reviews each of the main potential environmental impacts of natural gas development from coal seams: produced water disposal; perturbation of groundwater/surface water systems; chemical contamination of aquifers; methane contamination and migration in shallow groundwater; and land subsidence.

The review does not set out to examine the many complex issues surrounding 'Social Licence to Operate' – however it does aim to set out an experiential fact base, against which to frame some of those issues and to inform some Australian societal concerns. For example, the NSW Chief Scientist and Engineer in a 2013 review of the issues associated with coal seam gas (CSG) has described it as a "… *complex and multi-layered issue* …[that has]… *proven divisive chiefly because of the emotive nature of community concerns, the competing interests of the players, and a lack of publicly-available factual information*". Inevitably environmental concerns, whether evidence or science-based or otherwise, impact social acceptance.

1.1 Background

Development of natural gas resources from coal has the potential to provide a relatively low cost, clean-burning fuel for power generation and to stimulate national and regional economic development. However extraction of natural gas from coal has also resulted in a number of environmental, regulatory and public policy challenges. The potential for environmental impacts related to coal seam gas CSG in Australia has become a matter of widely reported concern for the general public, landholders and government regulators.

As an example of the varied way some concerns have been raised. Williams et al. (2012), an independent consultant writing for The Australian Council of Environmental Deans and Directors (Deans' Report), noted that "*…the potential impacts of CSG could be significantly less than the impacts and degradation already experienced as a result of agricultural and urban development over the past two centuries in Australia*". However, it is also possible to infer from their report that they perceive that the potential for environmental damage is substantial, particularly regarding possible impacts on water resources. They cite the long-term, cumulative impact of CSG development on the water resources of the Great Artesian Basin (GAB) as being of particular source of concern suggesting that "*Water extraction in this part of the Surat Basin and the GAB is reported to have lowered the head of water pressure by 100 m in some areas, and subsidence amounting to metres has been observed in some locations near wells*". Since CSG development was in its early development when that report was written, it is assumed that the 'water extraction' referred to relates to agricultural use (as reported by CSIRO in 2008 for the Condamine Alluvium). Neither this assertion nor the metres of subsidence reported as being "observed" near wells are referenced.

In Australia, critics of CSG have made many serious charges regarding the risks associated with the development of this resource. For example, writing for the National Toxic Network, a community based network organisation, clinical psychologist Dr. Somerville (2013), has asserted that "*CSG … is an unprecedented threat to our community*" and that "*entire communities are being exposed to … a witch's brew of air, water, and soil contaminants*". Similarly Jeremy Buckingham spokesman for the NSW Greens suggested that "*People across NSW have legitimate concerns about the impacts on the environment, health and safety, and the economic sustainability of their communities*" and that these concerns "*are founded on leaking gas wells, sick animals, dead trees and polluted water associated with unconventional gas in the US, Queensland and now NSW*" (Buckingham, 2011). David Shearman, Emeritus Professor of Medicine, University of Adelaide has suggested that for coal seam gas development "*The fundamental public health issue is the potential for water contamination by chemicals which could seriously affect human health decades after exposure. Health* *impacts may arise from the use of fracking chemicals or from the release of hydrocarbons and other contaminants from the coal seams.*" (Shearman, 2012)

In reference to methane emissions from CSG development in Australia Douglas Tait, Damien Maher and Isaac Santos, researchers from Southern Cross University, have suggested that "*With no independent baseline studies or long term monitoring of Australian CSG fields, the CSG industry may send shockwaves through the environment and no one will ever know*" (Tait et al., 2013).

These kinds of concerns if supported by robust evidence would have direct impact on "*social license to operate*" of companies engaged in coal seam gas development (Lacey et al., 2012; Lacey and Lamont, 2014). The then Deputy Premier of Queensland, the Hon. Jeff Seeney has suggested that there is a "*critical need*" for resource companies "*to establish a social license to operate in their local communities*" (McCarthy, 2014).

Notwithstanding these concerns, commercial CSG production has taken place in Queensland for the domestic market since 1996 albeit at a much smaller scale of development than the more extensive CSG-LNG developments which received approval in 2008/9. In terms of scale of deployment, Australia is at a similar state and rate of development of natural gas extraction from coal seams that the US saw from the mid 1980's. For this reason this paper sets out to make a comparison of the potential environmental impacts of CSG development in eastern Australia with those actual impacts observed over the last three decades from the large-scale, commercial development of coal bed methane (CBM) fields in the US and Canada.

In the US, gas has been extracted from coal seams at commercial scales since the 1970's when gas wells began to be used to degas coal seams ahead of mining (Elder and Deul, 1974) to mitigate the hazard of gas explosions. In 1980, the US Congress passed a tax credit for the development of unconventional gas and by 1990 on the order of 8,000 wells had been completed in coal seams in the US (Pashin and Hinkle, 1997). By 2000, 14,000 wells had been drilled. By way of comparison, between 2008 and 2013, approximately 4,000 CSG production wells were drilled in Queensland, though many were not put into full production.

By 2000, in the USA, the cumulative gas production from coal seams totaled 1.3 trillion cubic feet (Tcf), and was 7% of the US gas production (Nuccio, 2001). By 2009 the US was by far the largest producer of natural gas from coal in the world having produced more than 1.91 Tcf of gas (Pashin, 2011).

According to the US Energy Information Administration (2014), US CBM production peaked in 2008 at 1,966 Bcf and has been in decline since, with total US gas production from CBM for the years 2009, 2010, 2011 and 2012 at 1,914, 1,886, 1,763 and 1,655 Bcf respectively. For comparison, Queensland's CGS production for the year 2012-13 was approximately 249 Bcf (264 PJ) (Department of Natural Resources and Mines, 2014).

In Canada, CBM developed rapidly in the early to mid-2000s. In Alberta the number of CBM wells more than doubled in 2005 when over 4,000 wells were completed, including new wells and recompleting conventional wells as CBM producers. In 2006, an additional 3,000 CBM wells were completed (Alberta Energy and Utilities Board [AEUB], 2006; AEUB, 2007). In 2010, Alberta produced 319 Bcf of natural gas from CBM activity (1/10th of the States conventional gas production). The province of British Columbia has total CBM resource is estimated at as much as 84 Tcf, however development there has thus far been limited.

The 1980s and 1990s in the U.S. were a period of considerable anxiety amongst a number of stakeholder groups regarding the potential environmental impacts of developing coal bed methane. In 2002 Bryner wrote that "*The tremendous and rapid growth in coal bed methane development has posed daunting challenges for the communities in which it has occurre*d" . Fisher's (2001) paper on the environmental impact of CBM development suggested that it presents a "*substantial environmental risk*". He listed the following factors: 1) surface disturbance from the construction of roads, well pads, pipelines; 2) air pollution from traffic on access roads and compressor exhaust gases; and, 3) methane leakage. He also identified the main environmental concerns to be water-related, as follows: 1) the need to dispose of "*large volumes of produced water*"; 2) "t*he potential for the uncontrolled release of gas from the coal reservoir to shallow groundwater*"; 3) "*the potential for drawdown of shallow groundwater*"; and 4) the potential for fracturing completions to impact shallow groundwater. Since Fisher's 2001 paper was written it would seem that the documented environmental damages related to CBM development in the North America have been rather limited. A key question is of course to what extent this lack of documented environmental damage is a result of lack of study.

Since the early 2000’s there have been numerous focused studies and at least two significant, wider-ranging, official studies. The first of these was by the US Environmental Protection Agency (U.S. EPA, 2004) and the second by the U.S. National Academy of Sciences (National Research Council, 2010). The outcomes from these studies along with many other journal articles and government scientific reports form the key scientific basis for the remaining chapters of these working papers.

CHAPTER TWO:

Water Drawdown & Produced Water Management Related Issues

2.1 Introduction

Drawdown is the term given to sub-surface pore pressure reductions in confined aquifers which result from the abstraction of oil, gas or water. This Chapter reviews the literature on the produced water volumes and on the drawdown which results from those extracted volumes. It also reviews US approaches to water management that have been used to minimise the environmental impact of water production.

The production of natural gas from coal involves depressurisation of the coal seam prior to gas production and co-production of water with the gas. This results in lowering the water pressure in the seam surrounding the production well causing water to flow from the coal seam towards the well. Depending on local geological conditions and the amount of drawdown, lowering the pressure in the coal seam could also result in vertical flow from the overlying and underlying aquifers towards the coal seam being dewatered.

Natural fractures or cleats are typically several orders of magnitude more permeable than the coal matrix and dominate flow of water and gas in coal. Both coal fracture and matrix permeability also tend to be highly anisotropic, typically with significantly lower vertical permeability than horizontal permeability (e.g. Seidle, 2011). Permeability may also be stress dependent, decreasing with increasing drawdown and production. These factors and the presence of low permeability lithologies (aquitards and aquicludes) can reduce or even effectively stop the vertical component of flow. However, this geological complexity is difficult to represent in conventional (hydrogeological) numerical predictive models which are required to cover large areas of a basin and inevitably require an element of aggregation and simplification (or ‘upscaling’).

Water quality is often described in terms of its total dissolved solids (TDS) content. It may be described as ‘fresh’ if there if there are less than 500 mg/L, and ‘low salinity’ or ‘brackish’ between 500 and 30,000 mg/L. ‘Brine’ is typically associated with a TDS of over 40,000 mg/L. For context, (i) the Australian Drinking Water Guidelines (ADWG) suggest a limit of 600 mg/L as the upper threshold of taste (National Health and Medical Research Council [NHMRC] & National Resource Management Ministerial Council [NRMMC], 2011); (ii) World Health Organisation guidelines (WHO, 2011) suggest that above 1,000 mg/L TDS, drinking water palatability is “unacceptable”; and, (iii) sea water typically ranges between 36,000 and 38,000 mg/L.

Produced groundwater from CSG operations typically ranges from low salinity, to brackish in character. Production of significant quantities of such groundwater may have a deleterious impact on local surface and groundwater unless it is effectively managed. Water is becoming an increasingly valuable resource in many areas for the world. Cyclical droughts are focusing increased importance to regional water management in several areas where large volumes of water are being produced associated with unconventional gas development. With appropriate treatment such water could serve as a resource for the local community. At the same time, in dry climates disposal of salt (either in solid form or as brine) may be problematic.

2.2 Produced Water Volumes and Management - General

Depressurisation (including production of in-seam water) of the coal seam enables desorption of methane from the coal (Khavri-Khorasani and Michelsen, 1999). In comparison to other gas plays, producing natural gas from coal results, on average, with the largest volume of produced water per unit of gas production. However, some coal basins are associated with minimal water production and require no initial dewatering as methane is saturated under the ambient conditions in the well. The chemistry and volumes of produced water vary considerably between coal basins and in some cases within individual gas fields. The relationship between rates of water production and gas production can change dramatically over the area of a producing field and the production lifetime of the well.

The nature of water produced with gas production from coal seams depends on a number of factors including: the depositional environment and the coal type; the permeability of the coal; and the permeability of the formations above and below (Jackson and Myers, 2002). Some coal seams contain little producible water.

Farmers have an understandable concern for the potential impacts of the dewatering of underlying coal beds and subsequent its disposal. Farmers, particularly in water stressed areas may have an understandable objection to groundwater potentially usable for agricultural purposes being discharged into streams or evaporated or otherwise disposed of.

In general, produced water can be disposed of by: evaporation ponds (increasingly discouraged or banned by regulators); reinjected into a subsurface aquifer; recycled after water treatment (such as reverse osmosis to reduce salinity); used after minimal processing if the salinity is low; or discharged into streams or rivers. Discharge of untreated groundwater (in any jurisdiction) into streams would require careful study as freshwater ecosystems are sensitive to salinity and temperature (depending on the tolerance of specific species), both of which can be perturbed by produced water disposal. The potential for environmental damages from disposal of this water is controlled largely by the salinity of the produced water. Produced water from coal seam gas wells in addition to salts may also contain traces of other naturally occurring hydrocarbons depending on the character of the coals or other hydrocarbon source rocks in the basin.

Depending on local environmental sensitivities (including soil types), volumes and rates of untreated produced water spilt, or from usage for suppression of dust on unimproved roads, may result in cumulative soil degradation.

In many jurisdictions, use of untreated water for environmental discharge is simply not allowed or is strictly regulated. For example, in Queensland disposal of coal seam water to streams is only possible where there are no other feasible beneficial use options and the disposal will not adversely affect environmental values of the water course (DEHP, 2012).

2.2.1 Produced Water Quality, Volumes and Management in US CBM Fields

Farmers and well owners in States in the west of the U.S. have specific concerns about the potential impact on water quality and quantity by development of CBM. Chronic water shortages in these States make these issues even more critical.

In some US (and Canadian) basins produced water has been by far the biggest environmental concern. In others produced water is negligible. In the US produced water is either reinjected, released into surface waters, sent to evaporation ponds without further treatment or in some cases is desalinated and used in agriculture. The method of disposal used depends on both the quality of the produced water, and its location relative to proposed beneficial use (such as irrigation). The economics of disposal depend on the cost of necessary water treatment and the cost of the infrastructure required for water management (transport, storage, and injection). The impact of disposal of produced water with a range of chemical characteristics, with a wide range of treatment technologies and discharge strategies are becoming better understood in the US after several decades of experience and study.

The volumes of water involved in several US CBM fields are substantial, although the water quality varies substantially between the fields. It has been suggested by DeBruin et al., (2000), based on predictive, numerical modelling, that on the order of 2,000 GL of associated water will be produced from CBM extraction in the Powder River Basin (PRB) within Wyoming over the lifetime of the gas fields. However, monitoring actual water production shows a distinctly different story. Water production from PRB's CBM wells has been considerably less than that predicted by the Federal Bureau of Land Management (US BLM) in modelling for their EIS's (Wheaton. et al., 2007).

The quality of produced water, particularly the concentration of total dissolved solids (TDS), largely determines the preferred water management option for CBM developers. The PRB (~1,000 mg/L TDS), Greater Green River (~1,500 mg/L), and Raton (~500 to 6,000 mg/L) CBM basins have relatively high quality produced water (ALL Consulting & Montana Board of Oil & Gas Conservation, 2004) and consequently have a variety of viable disposal options (such as injection, irrigation, discharge to surface waters, evaporation, infiltration or surface recharge, and livestock watering).

Data on the distribution of naturally occurring radioactive material (radionucleotides) associated with produced water in the US, presented by Colorado School of Mines researchers, Dahm et al. (2011) suggested that radioactivity of such water associated with CBM is not in general an environmental or health concern.

In Canada, the majority of CBM has been from the Horseshoe Canyon formation in Alberta. This coal seam has little associated water and only minimal water production is associated with the development of the gas resource (e.g. Bastian et al, 2005).

2.2.2 Produced Water Quality, Volumes Management in Australian CSG Fields

In Queensland, where the vast majority of Australian CSG development is taking place, the Department of Environment and Heritage Protection (DEHP) has a Coal Seam Gas Water Management Policy (2012) the aim of which is "*to encourage the beneficial use of CSG water in a way that protects the environment and maximises its productive use as a valuable resource*" (DEHP, 2012). It sets water management priorities and criteria ranging from (1) beneficial uses – including for example, aquifer recharge, irrigation, livestock watering and environmental releases for local environmental values; to (2) treating and disposing of residual portions of CSG water to watercourses under strict conditions. Disposal to evaporation dams is being phased out as an approved method. The policy similarly sets salt management priorities and supports strategies ranging from a preferred search for beneficial, commercialisable uses to disposal options in solid or brine forms.

In 2010, the Australian Government's National Water Commission (NWC) stated that "*Current projections indicate the Australian CSG industry could extract in the order of 7,500 gigalitres of co-produced water from groundwater systems over the next 25 years, equivalent to ~300 gigalitres per year. In comparison, the current total extraction from the Great Artesian Basin is approximately 540 gigalitres per year*" (NWC, 2010a). However, when this water is produced (pumped out of the ground), it is largely above the Australian Drinking Water Guideline (NHMRC & NRMMC, 2011) threshold TDS limits and relatively little is *used* in operations. More recently non-government organisation (NGO) commentators Public Health Association of Australia and Doctors for the Environment Australia (DfEA, 2013) have suggested that the Australian CSG development uses "*enormous quantities of water*", "*removing a potential source of water for future generations whose lives will be particularly threatened by a lack of water*" (PHAA, 2012).

Prediction of produced water (and salt) volumes is an active area for research with regularly updated modelling by the Queensland government's Office of Ground Water Impact Assessments (OGIA). The most up to date, public date forecasts (Queensland Water

Commission, 2012) have reduced CSG water extraction estimates to an average of 95 GL/year and reports industry estimates to be approximately 75 GL/year (some 21% lower).

Perhaps the most important characteristic of the produced water associated with CSG, other than volume, is the salt content. In the Surat Basin, state government regulators have estimated that the salinity of produced water will be generally above ADWG taste thresholds and TDS will range from 500 mg/L to more than 10,000 mg/L (DERM, 2010).

The annual production of salts with produced water CSG from Great Artesian Basin aquifers has been estimated to be of the order of 750,000 tonnes (Senate Standing Committee on Rural Affairs and Transport, 2011). Estimates are uncertain and the pace of development and updates is high. As an illustration, in 2013, researchers at the University of Queensland (Keir et al, 2103) in a report prepared for the Queensland Department of Natural Resources and Mines (DNRM) reported an estimated 21% reduction in P50[1] forecast of cumulative salt production compared to a report completed the previous year. Predictions of cumulative salt production are of course highly dependent on predictions of water production.

In their Deans' Report, Williams et al. (2012) noted that, "*The disposal of brines and residual solids and slurries from the water treatment process…*" is a very active topic for research and development by the CSG industry and academia. Researchers at the University of Wollongong, Nghiem et al. (2011), have reviewed the possible beneficial uses of produced water from CSG development in Australia the role of Reverse Osmosis (RO) membranes in its treatment. This paper is however 3 years old and while not evident in peer reviewed journals, government and industry personal communications indicate active research and trialling of additional water management (e.g. aquifer recharge and deep injection) and salt management (e.g. crystallisation) options.

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[1] The P50 estimate is the average estimate over a large number of probabilistic evaluations i.e. 50% of estimates are above the P50 and 50% of estimates are less than the P50.

2.3 Perturbation of Groundwater/Surface water System by Coal Gas Development

Large scale dewatering of specific aquifers as a consequence of production of methane from some coal seams may result in long term impacts on the hydrology at a basin wide scale. In the US, researchers from the University of Southern California, Jamshidi and Jessen (2012), suggest that methane bearing coal seams in their geological settings "are often in some communication with an aquifer". They note that as a consequence "*it is likely that gas production from coal seams will result in encroachment of water from the associated aquifer*". It is typically assumed that drawdown (decrease in hydraulic head) of aquifers in or close to coal seams being dewatered for producing natural gas from coal seams is an inherent aspect of CSG production, at least when gas development requires dewatering. Drawdown of coal seam can potentially impact the hydraulic head of aquifers even beyond the boundary of the gas producing well field. As gas production can extend for two decades or more the long-term cumulative impact on regional aquifers is a concern worthy of careful attention. Other specific concerns include situations where natural gas production from coal seams can impact shallow alluvial aquifers where they directly overlie the coal seams. This is most significant where coal seams feed streams via alluvium.

2.3.1 Aquifer response to CBM development in the US

Drawdown in overlying aquifers can be a direct response to dewatering of some coal seams in the US. However, not all coal seams require dewatering (for example the Appalachian gas fields are methane saturated without dewatering and produce minimal water). The sum total of dewatering and other water management strategies can result in reduced recharge for particular aquifers and in at least one case in Colorado stream flow is being monitored to assess whether base flow into streams will be impacted by reduced aquifer flow (S.S. Papadopulos & Associates, Inc., 2006). The key question i.e. whether CBM activities are likely to impact the water levels in domestic, municipal, or agricultural water wells, is highly dependent on local geology.

A recent National Academy of Sciences review of water issues associated with CBM development in the US concluded that CBM development in the San Juan, Raton, Uinta, and

Piceance basins, "*is unlikely to cause lowering of the water table of shallow alluvial aquifers because of lack of hydraulic connectivity between the deep coals and shallow aquifers*" (National Research Council, 2010). In each of these basins there is several thousands of feet separation between the coal developed for CBM and the shallow ground water aquifer. They further note that gas-bearing seams of coal in these basins are over and underlain by low-permeability lithologies and thus have low to minimal hydrologic interaction in shallower sections of the basin. Such relatively high levels of vertical confinement may not be generally analogous to the Queensland Surat Basin, though may be more like other Australian CSG plays such as the Permian Bowen or Sydney Basins.

In contrast to the aforementioned Basins, depths to methane-bearing coal beds in the Powder River Basin (PRB) are relatively shallow some act as source of water for residences and farming (Wheaton et al., 2005). As noted by the National Research Council (2010), the water in the coal seams being exploited for methane in the San Juan and Raton basins, and some portions of the PRB, is "fossil water" i.e. it has effectively been sealed in coal seams for a long period of time and is non-renewable. This reflects the hydraulic isolation of these formations, which clearly limits the environmental impact on overlying aquifers of depressurising them. Such water would almost certainly never be used for other purposes.

Case Study One: Potential Impacts of Dewatering of the Fruitland Formation in the northern San Juan Basin

The Fruitland CBM field covers greater than 3000 square miles of the San Juan Basin in New Mexico. This is a very productive CBM basin with well over 11 Tcf (21 PJ) of gas produced from over five thousand wells. There has been a long standing concern that dewatering of the Fruitland formation for CBM development may reduce base flow to streams and result in reduced flows in rivers to drain the basin underlain by the Fruitland Formation in the northern San Juan Basin (Cox et al., 2001). However, Riese et al. (2005) have used a range of isotopic data to conclude that regional flow patterns related to dewatering of the Fruitland Coal were incompatible with the geochemical data. They noted that "*Our analysis calls into question hydrologic assumptions regarding the flow of water in coal bed aquifers and finds that a re-examination of coal bed aquifers in other basins is also warranted.*" They also show the prevailing hydrologic modelling to have been incorrect due to more complex, discontinuous intra-coal seam architecture than initially recognised and concluded that "*reservoir performance predictions require that an array of wells has already been drilled across the producing area*." (Reise et al., 2005)

The prevailing hydrological modelling of the time was based on the widely used USGS, MODFLOW software and in at least in one key instance (Applied Hydrology Associates, 2000) treated the Fruitland Formation as a single hydraulic unit on a ½ mile (~800m) grid spacing over the whole basin.

Case Study Two: The Powder River Basin

While no two sedimentary basins are the same, the PRB *may* be a closer "analogue" in some respects to the Queensland, Surat experience than other US or Canadian basins.

A key issue in the PRB is that coal seam aquifers locally play an important and direct role in recharging streams. This is because a number of coal seams outcrop as "clinker" within the watersheds of significant streams. The clinkers act as springs directly recharging shallow alluvium and providing stream base flow. During dry periods this phenomena may be responsible for a significant portion of the stream flow.

Meredith et al. (2009), in their monitoring report for the 2008 water year on the Montana portion of the PRB predicted the 20-foot drawdown contour in the Dietz and Canyon coal beds (two key CBM reservoirs) would eventually increase to 4 miles (6.4 km) beyond the boundary of the big production fields.

Myers (2009) developed a large scale, nine-layered (including 4 coal seam layers) hydrologic regional model of the PRB using MODFLOW (grid spacing 800m). This predicts that the aquifer drawdown and consequent impacts last longer than the period of CBM related pumping. Myer suggests that the time required for substantial aquifer recovery will span over half a century after the cessation of dewatering for CBM production when "*…the flux to the reservoir has recovered to the pre-development levels".* However, importantly, Myer also notes that *"This flux decrease reflects the conceptualisation of a hydraulic connection…"*. In other words, it is recognised that the predicted, modelled time-frame for recovery is sensitive to the geological concepts which can be incorporated into large, regional models. In themselves, these are limited by computing power considerations and inherent limitations of the software and modelling approach which includes many simplifications and assumptions.

In apparent contrast to Myers' earlier MODFLOW predictions, National Research Council (2010) note that little change has actually occurred in water levels of groundwater monitoring wells in Montana since 2004, the areal extent of water drawdown in the coal beds is predicted to increase in the future as CBM production increases.

The National Research Council (2010) noted although these two coal seams are present regionally, that they are "*not necessarily the same as shallow alluvial coal bed aquifers that may supply substantial domestic and livestock water or contribute to significant base flow of perennial water resource*s". Wheaton and Meredith (2009) also noted that in the core area, where pumping was highest, heads in the Anderson seam had recovered 65 per cent in 10 years. The National Research Council (2010) concluded that there was insufficient information to understand why the head was recovering at this pace.

What does seem clear is that Myers' large scale, regional groundwater simulation model may not be an accurate predictor to the evolution of these aquifers, perhaps systematically over-estimating water production and/or the extent of drawdown effects. Both the PRB and San Juan case examples indicated that the limitations imposed by the modelling approach taken are significant and the simplifications and aggregations made about geological heterogeneity and the simplification flow regime in the coal may in some cases result in water production being overestimated.

2.3.2 Aquifer response to CSG development in the Australia

The most important areas of activity for CSG in Australia are in areas in Queensland (Surat and Bowen Basins) with lesser developments in New South Wales. The Surat and younger strata in the southern Bowen Basin lie within aquifers that are part of the Great Artesian

Basin (e.g. Habermehl, 2006). This huge complex of aquifers has an aerial extent of about 22% of the Australian land area. It is a water-source for a large number of towns, and pastoral users. Legitimate concerns have been aired that CSG developments in the Surat Basin may impact water availability or water quality (by cross-contamination or by disposal produced water or the residues from water treatment).

In both NSW (non-GAB) and QLD (GAB) groundwater depletion issues have preceded the development of CSG presumably related to some combination of over pumping and reduced recharge related to drought conditions. In a 2011 Australian Senate inquiry, a Queensland farmer in a proposed CSG development area testified that, "*About 20 years* [sic early 1990's] *ago bore owners within the entire management area were cut back to 70 per cent of their nominal entitlement and in the last few years during the height of the drought bores within subarea 3 were cut back to 50 per cent*" (Senate Standing Committee on Rural Affairs and Transport, 2011).

Case Study: Surat Basin Queensland

The Surat Basin coals being exploited for CSG are within the Walloon Subgroup, which is comprised of coal inter-bedded with siltstone and sandstones (e.g. Scott, 2007). The target zones for CSG are typically thin and discontinuous seams of high-volatility bituminous coal. The Surat Basin is being developed utilising mostly vertical wells that access the entire coal rich portion of the stratigraphy. Water production typically precedes gas production and is followed by two-phase flow of gas and water. The relative amounts of water and gas and the time-frame required to get to maximum gas flow are inherently highly variable because of geological heterogeneity.

The overall water balance for the Surat Basin is poorly constrained as much of 35% of non-CSG water wells are unmetered. Kellet et al. (2003) have estimated that the total recharge into the GAB is 323 GL/year and current groundwater use in this area of the GAB is 549 GL/year (National Water Commission, 2006). The character, mechanisms, magnitude and spatial distribution of recharge of the great artesian basin are not well known. Uncertainties in the effective vertical hydraulic transmissivity between aquifers will likely result in a considerable in range of aquifer drawdowns and extracted volumes *predicted* by large scale flow modelling.

In 2008, a CSIRO report for the Australian Government (Barnett and Muller, 2008) concluded that (pre-CSG) levels of extraction from key alluvial aquifers overlying the Walloon coals was “*not-sustainable*” and that over-extraction would impact river flow. The report also mentioned ongoing changes in water use (and in re-capping of bores) which led to significant water level perturbations across a large area of the region i.e. there were non-static, already perturbed, pre-CSG conditions against which any impact would have to be judged. This has significant implications for criticisms levelled about lack of base-line data. A base-line is commonly thought of as static state at some point in time. Clearly, in the Surat Basin there was a significant pre-existing and poorly constrained dynamic. It is not self-evident that the concept of a conventional static baseline measurement was ever achievable.

Between 2008 and 2009, within their Environmental Impact Statement (EIS) submissions, the three major CSG-LNG project proponents included the results of extensive hydrogeological modelling. Many analyses and commentaries have been undertaken since then. Some key ones which show the evolution of the public, scientific conversation are documented below. It should be noted, especially given the pace of development, that there is significant lag time between continuously improved, state-of-the art knowledge at work in the gas companies and the regulator and when that knowledge enters the public domain through reports. The lag is even greater for independently peer reviewed journal articles.

In 2010, Moran and Vink (University of Queensland) suggested that the impact of “*large scale dewatering and changes to capillary pull of the coal seams is completely unknown*” (pp.53). They also suggested that the existence of high flow pathways associated with existing faults and fractures must be accounted for in the groundwater flow simulation models. Another important issue not accounted for in most if not all flow simulation models at that time was the discontinuous and highly heterogeneous nature of the coal seams, the importance of which to prediction was becoming increasingly evident from US, CBM experience.

In 2010 GHD, a water modelling consultancy noted that of the then available groundwater models (typically MODFLOW-type, large scale, regional models) of the Surat Basin none were yet capable of making a robust assessment of the cumulative effects of the anticipated development of CSG (GHD, 2010).

Also in 2010, in a written response under the Federal EPBC Act after referral of three of the major CSG-LNG projects, the Water Group (WG), a water conservation consultancy, cited an average annual CSG extraction from the Surat Basin of 61 GL/yr. From their own analyses, WG (2010) suggested cumulative produced water could be as low as 307 GL, as high as 45,000 GL and "*…most likely in the order of 14,035 to 27,411GL*" (pp. 10). WG (2010) also concluded that because of the "*sheer variability*" that can be calculated, then "*on balance of probability, it is likely that more groundwater will be produced than predicted by the proponents…*" (pp. 28). These figures and relative likelihood are unsubstantiated. WG (2010) further consider that co-produced water volumes could be greater still if work done on vertical communication between aquifers in the Surat Basin by Hodgkinson et al. (2010) were correct and perhaps this influenced their assessment. However, Hodgkinson et al. (2010) only pointed to evidence of such communication in a geological time-frame (*pers. comm.*) and did not comment on CSG production time-frame dynamics.

By 2011, the Queensland Gas Company (QGC) had developed a more detailed, 3-D interpretation of the Walloon Coal Measures based on drill stem data, that suggested that (in common with US, PRB and San Juan realisations) individual the coal seams are highly discontinuous and disconnected being separated by low permeability shales (University of Southern Queensland, 2011). Given this realisation and higher resolution modelling, it is likely that predicted aquifer drawdowns would be more localised than would be portrayed in contemporary, large scale groundwater simulation results with less (or un-)representative levels of vertical and lateral heterogeneity. In 2011, using data provided by industry, RPS Aquaterra together with the University of Southern Queensland (USQ, 2011) attempted to estimate the combined effect of individual evaluations of CSG projects by summing the drawdowns of the individual modelling results. In so doing, Aquaterra recognised that because the individual impacts had significant spatial overlap, that this approach would result in overestimating drawdowns. Their (likely overestimated) results suggest that by 2060 at least two of the key aquifers would have drawdowns of hydraulic head of greater than five metres, extending over the majority of the CSG tenements.

By 2012, Klohn Crippen Berger (KCB, 2012), a consultancy working for the Queensland Government, had developed a tool for estimating CSG related water production. They made a comparison with previous estimates and concluded that their approach (based on their interpretation of EIS data) gave a result of approximately 4,500 GL for the ultimate, cumulative water production (by 2060) approximately 87 GL/year on average. This cumulative total is consistent with the earlier estimates by Aquaterra (USQ, 2011), based on access to industry data. The earlier University of Queensland estimate (Vink et al., 2008) was also consistent out to 2025.

By July, 2012, the Queensland Office of Groundwater Impact Assessment (OGIA, formerly the Queensland Water Commission) had completed an assessment of groundwater impacts of CSG based on a coarse grid (1-5km), regional simulation with relatively gross layering (one formation represented by a single layer of model elements). Many geological sources of vertical permeability spatial variation and heterogeneity could not be included in the model in detail. However, to offset this uncertainty, and to ensure a high level of prudence in predictions, 200 model simulations were performed with conservative 95th percentile maximum predicted draw down used to derive ‘impact’. This modelling resulted in a prediction that of 21,000 private water bores in the modelled area, an estimated 528 would be impacted in the long term beyond a 5m reduced-head trigger level. Of these, the majority, 76% (401), draw water from the coal measures themselves rather than from overlying aquifers (QWC, 2012).

Thus, the most recent comprehensive, public independent estimate based on all government and industry data at the time (QWC, 2012), which included development work by GHD, suggests an annual average CSG extraction of 95ML/year, while reporting industry estimates at 75ML/yr.

The modelling approaches and limitations taken have a great deal in common with approaches taken in the PRB and San Juan Basin. It is as yet too early to determine, using data, whether any systematic estimating error is present but given, conservative and prudent handling of uncertainties and similarities in software and underlying methodology between Surat Basin and PRB cases, over estimation of impacts must be considered a real possibility.

Following an adaptive learning process, OGIA is developing an ever more detailed and ever better calibrated multi-layered groundwater model for the Surat Cumulative Management Area and, as importantly, is implementing a process to regularly update and improve its models based on new data as it becomes available. This learning process coupled with conservative treatment of uncertainties, probably serves to minimise the risks of greater than expected water extraction impacts. However, while prudent from a risk management perspective, it could also inadvertently anchor concerns into inherently high-side, less likely estimates of impact.

2.4 Mitigating the Impact of Water Production

The lessons from around two decades of mitigating the impacts of produced water associated with CBM development in the US have been assembled in the report for the US Department of Energy by the ALL Consulting group (ALL, 2003). Management of produced water can be split into two issues: water disposal or beneficial use; and salt disposal or beneficial use. If produced water has suitable quality (or can be mixed with treated water to achieve a suitable water quality) then beneficial uses include; water for cattle; aquaculture; crop irrigation; tree plantations; and augmenting town water supplies.

If the produced water is of high quality (low in salts and other contaminants) it can also be used as artificial recharge of shallow aquifers or discharged into surface water, at relatively low cost. Typically produced water is too high in salt and other contaminants and must be either disposed of by injection into deep formations or treated to improve its quality.

Veil (2002) has suggested that "[CBM operators] *are likely to select the least-cost options that are authorized by state permitting authorities*". This is clearly not always the case as operators in drought prone areas where water is a highly valued commodity for the communities have found it in their best interest to pursue desalination by RO. In principal, though, the impact of CBM development on aquifers can be mitigated by: (1) strategically reinjecting produced water to minimise impacts on key aquifers; (2) creating artificial recharge basins assuming produced-water with appropriate quality is available (Wang et al., 2007), designed to mitigate aquifer drawdown and in some cases minimise base flow deficiencies in key streams.

Fisher (2001) also identified two key environmental issues associated with US, CBM development to be: 1) the need to dispose of "large volumes of produced water"; and 2) "the potential for drawdown of shallow groundwater". There are a limited number of studies available that have monitored the long term impacts of CBM development on aquifers. Perhaps the most interesting monitoring study has been of the ongoing impact of CBM production on aquifers in the Montana portion of the PRB carried out by the Montana Bureau of Mines and Geology (Wheaton J. et al., 2007; Wheaton and Meredith, 2009; Meredith and Kuzara, 2013). Amongst other things, this project has established that the amount of produced water has been significantly less than originally projected in the project EIS. Meredith and Kuzara (2013) presented information on actual versus predicted per well water production for CBM production wells in the Montana part of the PRB. The EIS predictions were based on a maximum water production per well at initiation of pumping of approximately 14 gals (53 L) per min. The observed maximum water production typically occurred after 5 months at an average of approximately 7 gals (26 L) per min - or ca. 50% of the EIS predictions of maximum rate. For the first 72 months, figures in that report (*ibid*) indicate that cumulative actual water production was only around 64% of the predicted EIS production and was between the 10th and 20th percentile of the EIA estimate. Meredith and Kuzara (2013) noted that "*Since most water is produced early, the EIS somewhat over predicted total water production*". After 72 months the projected average from the EIS becomes lower than the observed average. However, the authors note (*ibid*) that this is at least in part because an increasing number of production well are shut down.

Perhaps not surprisingly, monitoring in the Montana portion of the PRB also has revealed that observed drawdowns "…were less than those predicted in modelling" (National Research Council, 2010: p.123). Similarly, after pumping stopped the National Research Council (2010) noted that "…75 percent recovery of the water levels in one of these coalbed aquifers occurred within five years when pumping was discontinued. In the centre of the area monitored, where pumping was most aggressive, groundwater levels in the affected coalbed for which data were available have recovered 87 percent in 10 years". Head recoveries predicted by the outputs of groundwater simulations to take decades (Myers, 2009) had actually largely occurred in less than a decade.

While no two basins are geologically identical, predictive methods used for groundwater impacts in the PRB were computationally similar (software, boundary assumption types, model scale, model layers, grid cells sizes ...) to those used in the initial stages of the Surat CSG impact assessments.

Prior to 2010, in Queensland produced water was typically contained in evaporation ponds varying in area between one and a hundred hectares. From 2010 on, evaporation ponds have been discontinued in Queensland as an approved permanent strategy for disposal of produced water from CSG development. This seems to have been in response to concerns over risk of leakage of saline water into aquifers and rivers and also local concerns at apparent wastage of potentially valuable water in an area prone to drought. In 2010, Moran and Vink, noted that the Queensland State Government favoured management of produced water from CSG through aquifer reinjection. This has several advantages over other strategies including mitigation of head loss in deep aquifers and possible associated subsidence issues.

As evidence that the regulatory regime is evolving and adapting, in the Queensland State Government's 2012 Coal Seam Gas Water Management Policy (DEHP, 2012), the preference was more widely stated as being "beneficial use". This includes potential reinjection as just one option amongst several such as irrigation, livestock watering, dust suppression and so on. Virtually all such beneficial use options require water treatment and operators have installed significant processing capacity throughout the fields.

For example, in the Surat Basin, development of water treatment infrastructure includes the development of QGC's Kenya Water Treatment Plant 35km south-west of Chinchilla, Queensland (The Chronicle, 2013). The initial plant has a capacity of 92 mega litres of a day, and includes a 33-megawatt gas-fired power plant to supply power to the Reverse Osmosis (RO) system. A 20km pipeline will transport the treated water to landholders and Chinchilla Weir.

One problem that has been reported as a concern for local landowners in Queensland is the time frame for depressurisation versus that for aquifer recovery. Depressurisation is dominantly early in the project whereas it may take many decades after CSG production ceases for aquifers to recover. Recognising these issues some companies are considering injecting produced water (that has been treated using reverse osmosis (RO) technologies and some form of chemistry-matching) into brackish or low salinity water aquifers. For example in the Surat Basin the Hutton and Precipice Sandstone have been identified as potential target aquifer for banking relatively fresh water for future use (APLNG, 2012).

Some managed aquifer recharge projects seek to replenish the depleted aquifers used for town or agricultural uses. For example, Santos carried out a three-month trial injection of treated CSG water into the Gubberamunda aquifer. That aquifer had been in use for industrial urban and stock water for around 100 years and while still in use pressure was declining (URS, 2011). Similarly, Origin Energy has designed and permitted a 8.1 ML per day injection well as part of their Spring Gulley Project targeting the Precipice formation and have proposed an additional 30 ML/d aquifer injection project (Moser, 2013).

Waste salt from CSG fields in Queensland has been stored in brine ponds and salt pits (Williams et al., 2012). Companies are investigating the industrial demand for purified salts though this does not look likely to be a commercially viable option. In theory, salt could be sold for industrial or commercial purposes. However, in Australia, salt is largely produced by sea water evaporation and from natural deposits. CSG-related sodium chloride would represent just 10% of Australia’s production but processing or purification and transport costs from remote inland fields to coastal markets currently make it non-commercial. Consequently, at the present time it looks most likely that salt will be sent to special landfills licensed for disposal, though there may be an element of injection of brine concentrates deep water injection as common in the US. Williams et al. (2012) note that two brine injection wells are already operational.

2.5 Summary – Water Drawdown and Management

The main finding of the review of North American CBM operations relevant to Australia is that the volumes of produced water have been often a factor of two less than those initially predicted by modelling. Similarly the area of significant drawdown in the hydraulic head in key aquifers has been up to a factor of five less than that predicted by widely quoted model studies.

Water drawdown forecasts are at the heart of addressing concerns about groundwater impacts caused by CBM/CSG. The most commonly employed numerical (hydrogeological) modelling methods, mostly based on MODFLOW, are inherently limited in their ability to represent the degree of geological heterogeneity inherent in coal seams which dominates assessment of vertical and lateral spread of pressure depletion in the sub-surface. These modelling limitations, possibly together with inherent and justifiable prudence of regulators (who *demand* conservative assessments) and industry (who *must* build sufficient water handling capacity to assure commercial gas production) may result in systematic overestimation of draw-down effects.

CHAPTER THREE:
Risk of Water Contamination Associated with Natural Gas Extraction from Coal

3.1 Introduction

This chapter outlines the potential pathways for contamination of groundwater by CBM/CSG development and reviews information on the chemistry of produced water and fracturing fluids that represent the potential sources of contamination. It examines the (potential) hazards[2] associated with development of natural gas from coal seams based on information on the chemistry of produced water and fracturing fluids from both the US and Australia.

Concerns that development of coal seams for gas production will result in environmental damage are widespread in Australia. Decades ago similar concerns were widely voiced in the US. As a result in 1998, the Ground Water Protection Council (GWPC), a non—profit organisation of US state regulatory agencies, carried out a survey of those agencies seeking information on any incidents in which coal bed methane (CBM) development had led to contamination of water wells. Twenty five states responded - thirteen of which had CBM wells and all had no reports of such contamination (GWPC, 1998). By 2000, a review of coal bed methane by the USGS suggested the main environmental impact concerns were: produced water; methane emissions; and methane migration (Nuccio, 2000). However Nuccio’s fact sheet included little information to quantify these concerns.

Evolving events in the US resulted in groundwater contamination becoming a key concern. Two court cases brought by the Legal Environmental Assistance Foundation (LEAF) against the U.S. Environmental Protection Agency (EPA), decided in 2001 by the U.S. Eleventh

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[2] ‘Hazard’ is defined in the Oxford Dictionary as a “potential source of danger” and in this sense reference to “potential hazard” is unnecessary. However, it is not an uncommon term found in literature as indeed is “possible risk”.

Circuit Court of Appeal decisions (informally known as LEAF 1 and 2) forced the EPA to conduct a comprehensive investigation of the possible impacts of CBM development on underground supplies of drinking water (USDW). Their concerns were twofold: 1) that there was "*intentional direct injection of fracturing fluids into a USDW* [Underground Sources of Drinking Water]"; and 2) that hydraulic fracturing of relatively shallow coal seams may result in "*communication between the target coal bed formation and adjacent USDWs*" (EPA, 2004).

Subsequently the EPA conducted a comprehensive investigation of potential contamination incidents based on input from NGOs, the general public and state agencies (EPA, 2004). This study, like the earlier GWPC study did not identify any incidents where the scientific evidence confirmed that CBM development had contaminated drinking water supplies.

The court case LEAF v. EPA was based on a private home's water well in Alabama whose owner believed had been contaminated by hydraulic fracturing of a nearby CBM well. Sampling and chemical analysis of this well by both the state regulatory agency and independently by the EPA resulted in both agencies concluding that this was not the case (EPA, 2004). Historical data on water quality going back to the 1950's suggested to investigators that water wells in the area had "*bad taste*", "*bad odours*" and "*oily films or sheens*," decades before CBM development started (EPA, 2004).

Since the EPA (2004) report, environmental concerns in the US have focused on:

1) Potential problems salt contamination of ground and surface water with the storage, transport or disposal of produced water from coal gas fields.
2) Leakage of hydraulic fracturing fluids either by surface spills during transportation or storage.
3) Leakage of methane and/or saline produced water into fresh water aquifers resulting from inadequate cementing of the drill hole casing.
4) Leakage of fracturing fluids, into fresh water aquifers during or subsequent to the fracturing

Discussing contemporary concerns in Queensland, Cham and Stone (2013) have suggested that although the CSG industry "*typically sees hydraulic fracturing as a low-risk method for accessing the coal seam … gas reserves*" that some stakeholders believe it to be an "*unacceptable risk*". In a recent paper, from the University of Queensland School of Population Health, masters student Navi et al. (2014) examined the "*potential hazards*" in Queensland from water associated with coal seam gas development. Navi et al. (2014) suggested that the hazardous substances associated with CSG water in Queensland are "f*luoride, boron, lead and benzene*" and that "*the likelihood and risk of unplanned CSG water release is an unknown in Queensland*". Perhaps a more relevant question would have been, "*What is the likelihood of having an unplanned release of produced water that results in significant damage to the environment or to human health?*"

Disposal of water produced from oil and gas operations has been an environmental concern since the early days of the industry. Produced waters from coal seams can naturally contain high levels of total dissolved solids (mostly salts) as well as trace hydrocarbons, trace metals and other trace contaminants such as boron, bromine, fluorine, and radium all of which may be above, perhaps not surprisingly, UN drinking water standards. Sodium is typically the dominant cation in produced water from coal seams. Sodium competes with the essential nutrients potassium, calcium, and magnesium for uptake by plant roots. As a result discharge of untreated produced water into streams (which is not permitted in Queensland) could stunt plant growth and harm soils. In an analysis of a large data base of produced water from the CBM fields in the Western US, Dahm et al. (2011) found that sodium as both bicarbonate, and chloride ions made up more than 95% of the total.

Except where TDS and trace elements in produced water are sufficiently low to allow safe discharge into surface water or beneficial use for agriculture or other purposes, such water must be either be treated to improve water quality or disposed in an approved manner (currently in Australia all produced CSG water is treated). In dry climates there is a considerable pressure from stakeholders to treat the produced water. The most cost effective technology to treat saline waters to enable beneficial use and/or safe discharge into ground or surface waters, are based on membranes. Reverse osmosis (RO) membranes are currently the most common method of treatment of produced water. The energy cost of the RO process depends primarily on the salinity of the water being treated. Costs become prohibitive for most purposes as the salinity increases beyond that of seawater. RO techniques use electric power to run pumps to drive the osmotic process. Large collections of RO facilities may require their own electric power supply to run the pumps etc. RO membranes produce water very low in contaminants and in addition a waste stream of hyper-saline brines that must be safely disposed of for example, in a licensed land-fill or even disposal in the ocean. Such brines might also be injected into deep disposal wells in appropriate formations, which is the option generally preferred in the US. However, thismay not be permitted in Australia where injected brine may also need to be treated to be compatible with the target aquifer. Accidents and spills involving storage, transportation and disposal of such hyper-saline brines may prove to be the highest risk to the environment associated with CSG development in the future.

Evidence for contamination of groundwater from leakage or spills of hydraulic fracturing fluid have not been found despite over three decades of fracturing of CBM reservoirs (EPA, 2004; National Research Council, 2010; Vengosh et al., 2014). Nor is there any evidence of groundwater contamination by fracturing fluids arising from the fracturing process itself.

Gross et al (2013) note indications, that surface spills, albeit a "*minimal*" number, may be a contamination route "*… and should be a focus of programs to protect groundwater*"; though these are from shale gas operations where volumes are considerably larger. The Royal Society and The Royal Academy of Engineering's 2012 review of hydraulic fracturing, citing Groat and Grimshaw, 2012, similarly reported that "*Surface spills of fracturing fluid may pose a greater contamination risk than hydraulic fracturing itself*" (pp. 19). Such a conclusion would suggest that industry and regulator prime focus should be on the training of operational staff, operational quality control and OH&S procedures. These matters of industrial good practice, have not been amongst concerns aired publically to date.

3.2. Water Quality Hazards Associated with US CBM Fields

The most likely source of contamination of groundwater from the development of natural gas from coal seams might be considered to be produced water, simply because of relatively the large volumes being stored, transported and treated. Produced water in US CBM fields varies considerably between basins in the average TDS concentrations. The PRB has the lowest with an average TDS of 850 mg/L (and a range from 370 to 1,940) based on the work of Rice et al., (2000). In contrast the San Juan Basin ranges from 10,400 to 23,500 mg/L in TDS whereas the Raton Basin varies between 1,000 and 4,600 mg/L (Benko and Drewes, 2008)

Concerns have been expressed too, about possible contamination with fracturing chemicals. The fracturing chemicals used in CBM development in the US include a wide range of formulations and fracturing technologies such as cross-linked gels, nitrogen foam, carbon dioxide foam, and slick-water formulations (EPA, 2004). Bactericides are typically hazardous by nature (EPA, 2004) though there persistence is unclear. Available data suggests that companies using hydraulic fracturing in US CBM fields have used a variety of approved, licensed biocides.

While BTEX organics have been removed from fracturing and other drilling and completion fluids for over a decade. Concerns remain about contamination by ‘organics’. There are naturally occurring sources of these compounds in the sub-surface. Therefore, one key water quality measure to evaluating the risks associated with produced CBM water is the concentration of Benzene (a known and high profile carcinogen). Information presented by Dahm et al. (2011) Benzene levels in the Raton Basin showed an average of 4.7 ppb, ranging from below detection limit (BDL) to 220 ppb; and, for the San Juan Basin averaging 150 ppb and ranging from BDL to 500 ppb.

The concentrations of other organics of concern in produced water from CBM wells in the PRB appear to be lower than the level of any health concerns. Orem et al. (2007) conducted a focused study of the organic compounds in the produced water from two wells in the PRB. They found a wide range of compounds including: “*PAHs, phenols, biphenyls, aromatic amines, O-, S- and N-containing heterocyclic compounds, aliphatic hydrocarbons, and aliphatic organic acids*”. They concluded that the phthalates were likely “*from plastics used in sample processing*” and/or well construction. Concentrations of all the organic compounds they detected were “*low*” ranging from 18 ug/L to 100’s of ng/L. They noted that the “*low concentrations of individual compounds (most <1 ug/L) … precludes any acute* *human health or environmental effects*". Orem et al. (2007) studied the chemistry of two wells over the first two years of production and found that that levels of organic compounds in produced water decreased over that time perhaps because pumping exhausted the "*water associated with the coal (high organic compound content)*". They concluded the initial produced water would have the highest level of organic compounds.

Other recent US research has also shown some interesting trends on a decadal time scale in which certain chemical parameters in produced water in the PRB, have either increased or decreased over time (Reddy et al., 2014). For example from 1999 to 2009 the average pH of produced water in PRB disposal ponds in their study increased from 7.9 to approximately 9.2.

Kaszuba and Buys (1993) observe that spills of produced water (typically of minor volume) are common occurrences in the CBM fields of New Mexico and Colorado. They also document in their paper that such spills can be remediated effectively at relatively low cost.

3.3 Hazards Associated with Contaminated Water in Surat and Bowen CSG Fields

The report by the NSW Standing Committee suggested that a significant question is "*whether coal seam gas activities could contaminate or deplete water resources"*, and that *"the scientific evidence on this question is contested*" (LCGPSC, 2012, pp. xiv). Notwithstanding, pre-existing and concurrent aquifer usage, ideally, analysis of this issue should begin with an evaluation of the baseline quality and its spatial and temporal variability of the aquifers in question (prior to gas production activity). In the US, CBM development proceeded with little if any prior baseline monitoring of groundwater chemistry.

3.3.1 Naturally Occurring Hydrocarbon Systems

For additional context, it is important to recognise a background or baseline of natural hydrocarbon generation and migration processes. Queensland's Bowen (Permian and Triassic) and Surat (Jurassic) Basins reservoirs, in addition to CSG fields, there are conventional oil and gas producing fields (e.g. Boreham et al, 1999). These are sourced predominantly (Late) Permian formations and predominantly, but not exclusively comprise land-plant organic matter. These source rocks are largely gas-prone coals though there is some marine mudstones contribution. Thermogenic (burial related) generation and subsequent migration of hydrocarbons (oil and then gas) commenced in the Triassic and continued to the mid-late Cretaceous. While methane is the main focus on this study, it is important to note that this “conventional”, naturally occurring hydrocarbon system has produced not only methane but also many aromatics and higher hydrocarbon fractions (e.g. to $C15^+$, Al-Arouri et al, 1998) which have migrated through the geological system. Non-hydrocarbon gases such as CO and CO_2 have also been sourced in some cases (Boreham et al, 1998). Traces (shows) of higher-end hydrocarbons can commonly be found in GAB aquifers outside conventional accumulations along migration routes and in some cases in formations above the cap-rock of those accumulations (Garnett et al, 2013).

In contrast to these older source rocks, the Middle Jurassic Walloon Coal Measures, the source of most Australian CBM/CSG have long been recognised as “oil-prone” coals (Khorasani, 1987). Such source rocks should be expected to produce higher end hydrocarbons not just methane. Likewise, in all basins with hydrocarbon generating systems, methane is likely to be found dissolved in aquifers.

3.3.2 Anthropogenic Water Quality Hazards & Concerns

Important post-script. *This section was first written in the context of 2015, looking back on estimates, proposals and suggestions from 2010 onwards. There have been significant changes in actual use of chemicals since these early views. For example, THPS (tetrakis phosphonium sulfate) is not on a 2019 list of potential components supplied by APPEA, APLNG or Santos.*

The first water quality issue of concern to many stakeholders in Australia is the possible impact of hydraulic fracturing chemicals on groundwater quality. This concern seems not to be grounded in any assessment of likelihood based on historic frequency of contamination events caused by hydraulic fracturing.

Around 2014, the understanding was that in the then 'current' phase of Surat Basin CSG projects, hydraulic fracturing would have limited use with perhaps a majority of the wells not undergoing fracture stimulation (URS, 2010; Coffey Environments Australia, 2012).

Components of fracturing additives **initially and preliminarily suggested** or being used for hydraulic fracturing in the Surat Basin (Golder, 2010; URS, 2010; Shaw, 2010) includes: Company "A", THPS (tetrakis phosphonium sulfate), potassium carbonate, teramethyl ammonium chloride, a proprietary compound, sodium persulfate, ethylene glycol, methanol, oxyalkylated alcohols, boric oxide, methanol, gas oils (petroleum), quartz, oxy-1,2-ethanediyl, ethylene glycol monobutyl ether, sodium acetate and guar gum; Company "B", Bronopol (2-bromo2-nitro-1,3-propanediol), sodium hypochlorite, sodium hydoxide, sodium chloride, monoethanolamine borate, ferric chloride, guar gum, ethanol, sodium hydroxide, acetic acid, sodium thiosulfate, potassium chloride, terpenes and terpenoids. In each of these two fracturing fluids the highest risk chemical is highly likely to be the biocide (King, 2012), in these two formulations, Bronopol and THPS. The Queensland Department of Environment and Heritage Protection (DEHP, 2013) list four other chemicals being used in hydraulic fracturing in Queensland: 5-chloro-2-methyl-2h-isothiazolol-3-one; 2-methyl-2h-isothiazol-3-one; Sodium hypochlorite; and C.I. pigment red 5. With the possible exception of THPS (the toxicity status of which is currently under review by the EPA)[3], all the above biocides appear to be characterised by low toxicity and rapid biodegradation. This latter point determines how pervasive a chemical might be in the (mostly sub-surface) environment and seems often missed is many public commentaries about chemical use.

For example, environmental risk assessments for fracture fluids used by Santos are disclosed to the public can be found at https://www.santos.com/media/3778/glng-upstream-hydraulic-frac-risk-assessment-compendium-of-assessed-fluid-systems.pdf and https://www.santos.com/media/4483/glng_upstream_hydraulic_frac_risk_assess_appendix__c.pdf (Santos, 2016)[4].

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[3] Comment included at time of writing. *There have been significant changes in actual use of chemicals since these early views. For example, THPS (tetrakis phosphonium sulfate) is not on a 2019 list of potential components supplied by APPEA, APLNG or Santos.*
[4] Link updated 7 January 2020

A key question regarding fracturing fluid is, after the fracturing event and water production begins, initially presumably returning some of the fracturing fluid to the surface (sometimes called “flowback”), what is the chemistry, volume and concentration of the water being produced, how does it change over time and what does this mean for any fluids remaining in the formation? Campin (2013) has presented data reflecting the evolution in water chemistry after hydraulic fracturing of a CSG well in the Surat Basin. Campin suggest that steady state conditions apparently are not reached within the 6-10 weeks in his plotted data. However, he also notes that the time between fracturing operations and flow back varies considerably due to operational reasons and that therefore, changes in flow back chemistry may result from changes in residence time.

Not unsurprisingly given major geological differences between coals and shales, the data for the Surat CSG well has a very different character to the chemical changes during the first few weeks of water production in *shale* gas wells in the US. Over the first week of CSG water production TDS increased from 4,500 mg/L approximately 7,500 and then averaged approximately 5 to 6,000 for the following four weeks. At the same time the concentration of Boron for most of the time series is essentially constant at approximately 50 to 55 mg/L and Barium starts at 10 to 11 mg/L and in general drops to 6 to 8 mg/L after two weeks. In shale gas flow back the initial water composition is similar to the injected fluid and exponentially approaches that of the in-situ brine over a period of days or weeks. The concentration of elements such as Boron and Barium in shale gas produced water are correlated with the concentration of TDS. In this CSG data there is no such strong positive correlation with TDS.

Arguably the most toxic component of the produced water, Benzene, starts on day one at 3.5 mg/L and decreases to 0.6 mg/L on day two, followed by an approximately linear decrease to approximately 0.2 mg/L by day ten and remains at this level till day 29. Benzene levels then drop to 0.075 mg/L for Day 34 to the end of the time series. Campin (2013) observes that the high initial concentration of organic constituents (such as Benzene) and subsequent decline is consistent with hydraulic fracturing resulting in the release of “*weakly absorbed fractions*”. As previously mentioned, there are naturally occurring hydrocarbons which are generated through the burial and maturation of coal over geological time periods. Ordinarily, while common in sedimentary basins containing hydrocarbon source rocks such as coal and shales, the impact on groundwater quality of this slow release natural process are generally mitigated through process of dilution, dispersion, adsorption and biodegradation.

Obviously only a limited set of elements in the produced water have been analysed. Batley and Kookana (2012) suggested that due to the complexity of carrying out a comprehensive chemical analysis of the initial flowback of CSG water after a hydraulic fracturing event that not all of the chemicals in the mixture being analysed will be detected. As a result they propose "*ecotoxicity testing*" of the effluent stream "*to gauge the collective impacts from all chemicals present in the mixture*" which could include toxic metabolites or reaction products from the interaction of fracturing chemicals with chemicals components in the subsurface.

Volk et al. (2011) have reviewed the scientific evidence for BTEX (benzene, toluene, ethylbenzene, and xylenes) contamination associated with CSG development in Australia and notes that produced water may contain a variety of organic compounds including BTEX and PAHs. They note that Sydney Gas in 2005 reported BTEX values in a gas exploration well, near Wyong, NSW and similarly AGL reported trace BTEX levels in gas exploration wells in the Hunter Valley. In both cases the BTEX values were below the laboratory limit of reporting. In November 2010, Arrow Energy reportedly found traces of benzene (1 to 3 ppb) in produced water from wells in the northern Bowen Basin (SMH, 2011) and similar results have been reported from the Surat Basin by APLNG (APLNG, 2015). For comparison purposes, while the reported produced water is clearly not "drinking water", the Australian Drinking Water Guidelines (NHMRC, 2011) set the limit for benzene at 1 ppb while the World health Organisation limit is 10 ppb (WHO, 2011).

In contrast to shale gas development in the US, hydraulic fracturing is relatively rare in Australian CSG developments. Estimates are that 8% of the ca. 4500 CSG wells drilled in Australia between 2000 and 2012 have been fractured (e.g. SBS, 2013). The chemicals used in hydraulic fracturing in Australia must be disclosed and controlled (see for example APLNG, 2013) and are essentially BTEX free.

By far the largest volume of fluids associated with CSG development in Australia for most projects is produced water. Shaw (2010) reported the results of sampling of produced water from seven CSG wells from the Surat Basin by Queensland government regulators. In these analyses the electrical conductivity (a proxy for TDS) varied from 1,305 to 1,707 (µS/cm), the Sodium concentration varied from 337 to 472 (mg/L), the Chloride concentration varied from 30 to 71 (mg/L), and the Boron concentration varied from 0.5 to 0.76 mg/L (ADWG 4 mg/L). In a larger data set in Shaw's Table 10 extracted from Surat basin project EIS documents, TDS values were typically in the range 2,000 to 8,000 mg/L. In this same data set, Arsenic levels vary from 0.001 to 0.01 mg/L (ADWG <0.01 mg/L) and total organic carbon varied between 6 to 36 mg/L.

3.4 Preliminary Risk Assessment of Water Related Hazards Associated with CSG Development

There are several scenarios that could result in contamination of ground and/or surface water as a result of coal gas development:

1) Spills of leaks of produced water from holding impoundments, tanks, pipelines or tanker trucks.
2) Cross contamination of formation water resulting from well integrity problems with coal seam gas production wells
3) Spills or leaks of fracturing fluids at the well site or being transported to the well site.
4) Contamination of aquifers by fracturing fluids from a hypothetical fracture event that penetrated the aquifer by mistake.

Assuming that the various processes involved in points (1) through (4) above are appropriately regulated to ensure environmentally safe operations then contamination of drinking water (or stock water) would only occur from accidental releases. A recent review (Navi et al., 2014) of potential hazards and exposure pathways for contaminants in water from CSG development in Queensland identified 14 distinct exposure pathways. Campin (2013) has reviewed the possible impacts of hydraulic fracturing and CSG development on the water quality of aquifers and notes that fracture half lengths of around 200 m for CSG wells "*provides a scenario for potential risk of damage to well casings or to aquifer integrity*". Both Campin (2013) and Navi et al. (2014) outline potential hazards related to produced-water and fracturing fluids. To evaluate the actual risks related to these hazards both the likelihood of exposure events and the consequence of such events must be estimated.

As noted by Campin (2013), King (2012) has estimated the likelihood of a range of types of incidents associated with hydraulic fracturing of shale gas and tight reservoirs in the US that are directly relevant to the potential exposure pathways. King and King (2013) distinguish "*barrier failure*", as a breakdown of one element of the system of barriers in place in a well versus "*integrity failure*" as multiple breakdowns of barriers that together result in fluids from the reservoir under production leaking into protected aquifers. The analysis below is in part based on the analysis of failure frequencies presented in King (2012) and King and King (2013).

3.4.1 Above Ground Accident Scenarios

(1) Spill of produced water caused by tank truck accident

To estimate the likelihood of accidental spill from tanker truck transporting saline produced water, US truck accident data suggested 0.26 accidents per million miles driven, with 3.4% of wrecks resulting in spills (King, 2012: p60). King assumed all the water from a shale gas production well was trucked (based on an estimated 915 truck trips loaded, 25 miles each), which results in an estimate of 2 x10^{-5} spills per well. For a CSG well it is assumes that an average of 10 truck trips per well is appropriate as most produced water transport will be by pipeline. On this basis we would estimate a likelihood of 2 x 10^{-7} spills per well.

Note that the analyses are US-based and largely shale-gas related, an application requiring significantly larger quantity of water than CSG. In Australia, trucking of water is also minimised and limited to the appraisal phase and early production prior to wells being connected to (pipeline) gathering systems and routed to treatment plants.

(2) Spill of concentrated fracturing fluid due to a truck accident or other accidental release

King (2012) considered the spill of 2 m^3 (2,000 L) tank of concentrated fracturing fluid, such as biocide. He estimated that assuming one truck load per fracture job, results in a likelihood of 2.2×10^{-8} per fractured well.

(3) Produced water spill from a pipeline

To estimate the likelihood of spills of produced water from pipelines two approaches were used. First, records from state regulators in the Wyoming section of the PRB, allow calculation of the spill rates of pipelines transporting produced water as 3.2×10^{-3} m^3 spilled per m^3 of water transported. Second, the same data set was used to estimate the likelihood of a produced water spill larger than 60 m^3 (60,000 L) from a pipeline as 1.84×10^{-6} per m^3.yr of produced water transported.

3.4.2 Below Ground Accident Scenarios

(4) Fracture fluids leaking into shallow aquifer due to rupture of surface casing

The likelihood of a fracture job rupturing the surface casing and allowing fracture fluids to escape into fresh water aquifer has been estimated by author (Duncan I) as 6×10^{-6} per fracture job and by King (2012) as 1×10^{-5} per fracture job. It should be emphasised that this estimates are based on historical data extended back some forty years and that wells constructed to contemporary standards would be expected to have an order of magnitude or more lower likelihood.

(5) Hydraulic fracturing enables contamination of shallow aquifer

In this scenario described by King (2012) a shallow fracture job in well less than 610 meters intersects a shallow leaky fault or high permeability pathway allowing frac fluids and reservoir formation water to leak into a shallow aquifer. King estimates the likelihood of this happening as 5.0×10^{-6} per fracture job.

(6) Failure of well integrity resulting in leakage of produced fluids to aquifer

King and King (2013) have estimated that the frequency of breakdown of well integrity for modern well construction as 4.0 to 5.0 x 10^{-5} based on the data from state regulatory agencies presented in Kell (2011).

Report author (Duncan I), a researcher at the Texas Bureau of Economic Geology, has argued that for each of the six spill/leakage scenarios outlined above that the risk to the environment is very small and the risk to human health and safety is negligible. This conclusion is certainly consistent with the record of the environmental impact of CBM development in the US.

3.4 Summary, Discussion and Conclusions

This Chapter set out to examine the implication of the chemistry of fluids associated with CSG (and CBM) development for assessing the possible environmental and health risks. The likelihood and consequences of surface spills of produced water from CSG are such that the overall risk seems low. Navi et al. (2014) have noted that a surface spill of CSG water occurred in 2011 south of Narrabri, NSW resulting in the discharge of 10,000 litres (NSW-DTI 2011). They also noted that in 2012, an accidental release of drilling fluids occurred “into the Condamine River” (ABC-News 2012). Investigation of any environmental consequences of such spills would be useful but based on available information they are likely not consequential.

Navi et al. (2014) have asserted that “*the role of fracking in generating new pathways for gas and CSG water migration has not yet been evaluated in Queensland*”. There is no reason to believe that Queensland has special circumstances that would make leakage pathways significantly different to the rage of geology and environmental settings found in the US. The implication of several statements in Navi et al. (2014) appear to be that hydraulic fracturing associated with CSG in Queensland poses a significant threat to the environment. This inference is inconsistent with the conclusions of both the EPA study of hydraulic fracturing associated with CBM (EPA, 2004) and the US National Academy of Sciences (National Research Council, 2010). Based on the nearly 40 year record of development of unconventional gas development from coal in the US it is clear that the risks of groundwater contamination are very small. Both the EPA and the US National Academy of Sciences reports (EPA, 2004; National Research Council, 2010) concluded that no case of possible groundwater contamination linked to CBM had been substantiated by detailed investigation. The National Academy study concluded that "*adverse effects from hydraulic fracturing [associated with CBM development in the US] have not been documented*", though they noted that "*the issue is of concern to the public*" (National Research Council, 2010). Similarly Woodman and Silver (2013) concluded on the basis of an extensive literature search that "*aquifer contamination from hydraulic fracturing have a very small amount of available evidence*". Though the "*small amount of available evidence*" they presented came from reports on shale gas rather than CSG or CBM. Campin (2013) suggests that "*pre-emptive [baseline] water quality sampling*" can confirm the "*absence of harm as a result of hydraulic fracturing*". This is something that regulators appear to be implementing in both Queensland and NSW and is the obvious prerequisite to a robust program to monitor for any future contamination from CSG development.

Use of holding ponds has been widespread in the US. Although leaks from such impoundments have been documented there is a dearth of documentation of any measurable contamination of soils or groundwater from such leakage. National Research Council (2010) in their review of CBM water management in the US, describe the results of a long-term, extensive study in the PRB of Wyoming that has been assessing the impact on local groundwater quality of produced water being stored in impoundments. In this study 170 monitoring wells were drilled to attempt to detect leakage from 144 impoundments. Results suggest that in that 72% of the wells there was no apparent impact on water quality. Some 18% of wells appeared to increase in salinity and sulphate concentrations at some point in their history, whereas in 6% of the monitoring wells the water quality improved. A recent comprehensive review of water contamination associated with development of unconventional gas reservoirs found no examples of such contamination (Vengosh et al., 2014). Similarly, while spills from produced water pipelines have been documented in the US and Australia, no long term contamination has yet been documented. The situation is similar for hydraulic fracturing fluids. No chemical from CBM hydraulic fracturing fluids has been documented to have contaminated fresh water aquifers in the US, Canada, or Australia (Vengosh et al., 2014).

Apart from possible contamination from leakage of hydraulic fracturing fluid, there are legitimate concerns that toxic chemicals naturally present in coal may contaminate groundwater aquifers. However evidence of such contamination is rare and almost always equivocal. Volk et al. (2011) concluded that water soluble organics such as phenols and BTEX have been found in Australian basins, however they note that in general their "*origin … is unclear*". They note that some of the detected compounds "*clearly have no natural origin from coal*" whereas other compounds "*such as BTEX and PAH*" may "*be derived from coal*". They specifically note that "*reports on BTEX and other organics associated with CSG are sparse… despite the aromatic nature of coals*" (Volk et al., 2011).The experience from the US and Canadian CBM fields has been that the occurrences of BETX contamination in water wells, when subjected to scientific investigation, were found to be related to causes other than natural gas development (EPA, 2004).

Concerns have also been raised that extraction of natural gas from coal seams may result in cross-contamination between aquifers. This could occur either by inadequate cementing of production wells creating new vertical pathways for fluid flow between aquifers or by pressure perturbations created by gas extraction or dewatering causing lower quality water to intrude into fresh water aquifers. These possibilities do not seem to be substantiated by any evidence.

Robust, documented evidence of CBM or CSG development resulting in chemical contamination of freshwater aquifers appears to be lacking. This may be because dewatering of coal seams creates a low pressure zone such that fluid flow tends to be directed into the coal seam. As a result contaminants are not likely to flow into surrounding aquifers. A possible exception to this might be if the coal is hydraulically fractured. During this process water and chemical additives are injected at fairly high pressures to fracture the coal. Ideally, immediately following this event dewatering begins and flow of fluids towards the well is established, though for operational reasons immediate flow-back might not be possible. While such a mechanism might be considered a reasonable hypothesis, no evidence of fracturing additives has been found in freshwater aquifers in association with hydraulic fracturing of CBM wells in the US (National Research Council, 2010).

CHAPTER FOUR:

The Nature and Origin of Methane Contamination of Groundwater in Areas of Coal Gas Development

4.1 Introduction

Methane is the main component of natural gas found in coal, typically on the order of 98% by volume. Methane contamination of groundwater resulting in flaming taps has become a symbol of the dangers of hydraulic fracturing and the development of unconventional gas reservoirs. Such images make exciting movie footage. However the suggestion that this methane is directly or indirectly associated with the development of unconventional gas reservoirs is controversial (for example, see discussions at

1. https://www.propublica.org/article/scientific-study-links-flammable-drinking-water-to-fracking
2. https://stateimpact.npr.org/pennsylvania/2011/12/19/flaming-taps-methane-migration-and-the-fracking-debate/
3. https://www.energyindepth.org/extinguishing-the-flaming-faucet-exploding-the-myth/).
4. https://www.forbes.com/sites/greatspeculations/2011/03/07/dont-be-swayed-by-faucets-on-fire-and-other-anti-fracking-propaganda/#2bad7ae6165f

Methane from the subsurface could enter homes either from exsolution of dissolved methane from water taps or showers where well water is being used for domestic purposes or from seepage from beneath the house. The latter is only likely in houses with basements (common in the US). Methane is colourless and has no odour or taste. It is not toxic, but rather is believed to act as a simple asphyxiant. Dilution of air by approximately 60% methane will result in death from anoxia (insufficient oxygen). By far the main hazard from methane is from fire or explosions. Methane-air mixtures are flammable over a narrow range of concentrations, approximately 5% (50,000 ppm) to 15% (150,000 ppm) of methane by volume (Harder et al., 1965; Duncan 2015). In confined spaces, methane and air can form explosive mixtures. However, outdoors the buoyancy of methane (being lighter than air) typically prevents build-up of a sufficient volume of gas-air mixture to form an explosion. As a result confined spaces, such as coal mines, are the most common sites for methane explosions (Allister and Hamilton, 1983). Duncan (2015) concluded that although methane can result in death from hypoxia (lack of oxygen) at levels in the air of over 60%, this is unlikely to occur except under exceptional circumstances. There is no evidence that low to moderate levels of exposure to methane in air has any toxic effect on humans.

In the subsurface, methane occurs either as a free gas phase or dissolved in water as an aqueous phase. Methane escaping from the ground to the atmosphere is termed seepage. Macro-seeps, readily detected by field examination, come in a variety of forms including burping mud-holes, fissures (sometimes with eternal flames), areas of vegetation die-off, and sections of rivers with ongoing bubbling (Kvenvolden and Rogers, 2005; Etiope, 2009). Lower-intensity methane seepage (micro-seepage) may not be detected by visual inspection but can be quantified by using technologies that measure methane flux. Etiope et al. (2008) suggest that macro-seeps are typically surrounded by large areas of micro-seepage. Etiope et al. (2008) also suggest that together these areas of seepage are the surface expression of leakage from a large methane-bearing natural fracture system.

Methane in groundwater or in seeps may have a number of different sources. Methane may be biogenic (formed at shallow depths by microbial action on organic material) or thermogenic (formed at higher temperatures, generally through the geological process of burial, by the breakdown of more complex organic molecules to methane). Biogenic methane can be produced by several metabolic pathways (methane from methanol/methyl-utilising processes and methane from reduction of CO2 utilising acetate fermentation) each with a distinctive imprint on the carbon and hydrogen isotopic character if the resultant methane (Strąpoć et al., 2011). Biogenic methane is widely distributed in groundwater, being formed in a range of anaerobic environments, including landfills, swamps, peat deposits, as well as lacustrine and aeolian sediments (Barker and Fritz, 1981; Grossman et al., 1989). Biogenic methane can also be formed in coal and in shale. In many basins, coal gas has either biogenic (Flores et al., 2008), or thermogenic (Strąpoć et al., 2007), or most commonly, mixed biogenic/ thermogenic origins (Faiz and Hendry, 2006; Golding et al., 2013).

Identification of the source of methane in water wells is typically based on the “isotopic finger printing” approach. In this approach, the stable isotopic ratios of carbon and hydrogen are measured for methane in the groundwater as well as for possible sources of methane (such as conventional gas wells, coal gas wells, pipeline gas, landfill gas). Schoell (1980), in an influential paper, presented a graph that drew fields for various types of biogenic and thermogenic methane. Unfortunately, as such gases are transported in the subsurface, either as a free gas phase or in the dissolved form, their isotopic signature is likely to be altered. The isotopic signature of methane can be modified by a number of processes including mixing, microbial modification, and/or isotopic exchange with rock components.

Coal seams can themselves be sources of thermogenic methane, they can also be traps for upward migrating thermogenic methane from other underlying petroleum source rocks and they can also be the sites for biogenic methane production. As mentioned in the previous chapter, hydrocarbons other than methane as well as non-hydrocarbon gasses are naturally occurring in some parts of some aquifers.

Bowen Basin CSG field stable isotope measurements of methane reflect both biogenic and thermogenic origins (Kinnon et al., 2010). Similar results have been obtained for the Surat Basin CSG fields (Golding et al., 2013). The fine pores in coal are strong absorbers of methane (Moore, 2012) and to some extent coal seams trap upwardly transported methane and other short chain alkanes. When the pores in a coal seam become saturated in methane, methane will migrate upwards, in part being trapped by small stringers of coal. In addition, in places it will bypass the larger coal seams by utilising naturally occurring permeable faults and networks of open fractures (Dawson et al., 2012).

The degree to which coal seam gas development results in *increased* methane concentrations of groundwater, methane seeps, and methane ebullition in surface water bodies is likely to be (and perhaps remain) a controversial issue. The only exception perhaps, being an area where intensive and detailed baseline sampling is completed prior to initiation of drilling for gas resources. Methane seeps and methane in groundwater aquifers appear to have been endemic in most, if not all, basins that are producing significant production of natural gas from coal seams (Chafin, 1994; US BLM, 1999; US EPA, 2004; Riese et al., 2005).

The nature and mechanics of methane migration in the subsurface are critical to understanding how, when, and where methane contamination occurs in groundwater. Unfortunately a number of key studies have made assertions about such contamination but have essentially ignored issues related to the mechanisms of methane transport and the nature of leakage pathways. This paper examines the nature and controls on methane migration in the subsurface. It also assesses the nature of leakage pathways. Old, abandoned oil/gas wells, auger test bores for coal, or water boreholes that penetrate through the main coal seams, are an obvious set of such pathways. However these features are not present in all areas. A second set of plausible pathways are faults or fracture zones that penetrate the same stratigraphic layers and form planar zones of high permeability. A third pathway is where coal seams shallow out, and become subject to near surface processes. Each type of pathway can result in significant quantities of methane becoming dissolved in groundwater and/or free gas collecting in porous rocks and in fractures.

Public concerns have been raised in Australia regarding whether the development of coal seam gas (CSG) results in contamination of groundwater. A major problem, from a scientific view point, is the lack of a comprehensive baseline study to characterise the chemistry of the groundwater prior to initiation of CSG activities as well as pre-existing depressurisation trends from agricultural activities. If CSG development has been initiated, then the results of baseline sampling may be considered controversial.

This chapter first examines the strategies and issues with baselines testing by reviewing baseline studies in the US and Canada. It then examines the evidence in the US that significant methane levels existed in groundwater prior to the initiation of CBM extraction. Finally, evidence for the existence of widespread natural methane contamination of groundwater in Australia prior to CSG development is examined. It further reviews the available information on possible contamination incidents (such as the methane bubbling into the Condamine River in the Surat Basin of Queensland), and examines the evidence that methane migration may have increased following CSG development.

4.2 Baseline Testing: Methane Background Levels in Areas of Coal Gas Development

Finding methane in groundwater is quite common. For example Gorody (2012) notes that over half of the water wells in the U.S. appear to have measurable amounts of dissolved methane. One of the most systematic baseline assessments of the concentrations and isotopic geochemistry of methane in groundwater is being made by the groundwater observation well network (GOWN) in Alberta (Ing et al., 2015). An important part of the baseline project was to characterise the chemistry and isotopic character of the natural gas and produced water from the underlying CBM reservoirs (Cheung et al., 2010).

Since 2008, 408 samples of groundwater have been collected from the GOWN network (Ing et al., 2014). Interestingly, 158 (39%) of monitoring wells had a free gas phase. The composition of the gas samples varied from negligible amounts of methane to almost pure methane gas. Of the samples with a free gas phase, approximately 80% (126) contained ethane (with concentrations 0.05ppm to 3,000ppm by volume). Only five samples had propane levels exceeding 1 ppm by volume. Based on stable isotope analyses of carbon and oxygen, Ing et al. (2014) concluded that the free gas sampled in their study was largely biogenic methane.

Another ongoing baseline survey in Alberta specifically targets future CBM developments. Since 2006 Alberta has required baseline sampling of areas of CBM development. Between January 2004 and May 2006, Griffiths (2007) reports Alberta regulators investigated 125 water well quality complaints in the Central Region and found that none were due to CBM activities. In the Southern Region, 230 complaints were investigated during the same time period, and 23 of these were set aside for further investigation because of a possible connection to CBM development. By mid-2007, 5 (2%) of these complaints (most regarding free methane gas in the well water) had not been resolved. An independent study by the Alberta Research Council (ARC 2008) concluded that the "*energy development projects in the areas most likely have not adversely affected the complainant water wells*" (ARC 2008).

In the US baseline studies have not been as systematic or as comprehensive as in Alberta. Only very recently have some states mandated baseline testing for natural gas development, and results from such studies of areas of coal gas production have not yet been published. Between 1995 and 2003, the US Geological Survey (Naftz et al., 1997; Stolp et al., 2006), made a baseline study of methane gas concentration in soils and ground water near Price, Utah, where CBM pilot projects tapping coal seams 1,000 and 4,485 feet (300 to 1,370 m) beneath the surface, began in 1985. By November 2003, 772 coal-bed methane wells were operational in this field. The monitoring program was focused on producing CBM wells and nearby residential areas. Twenty monitoring sites were established for annual sampling rimming the CBM field (Stolp et al., 2006). A total of 420 shallow (2- to 4-ft depth) soil-gas and ground-water samples were collected from 174 soil and 15 ground-water sites. The average methane concentration from1995 to 2003 was 2,740 ppm though the median was less than 10 ppm.

Based on the spatial and temporal variation in methane concentrations Stolp et al. (2006) concluded that there is no "*obvious, widespread, or consistent migration of methane gas to the near-surface environment [associated with CBM development]*". At 15 of the 75 sites where temporal data were available, the annual measurements of measured methane concentrations in soil-gas showed no consistent increasing or decreasing trends. At sites with measurements over 10,000 ppm had been found earlier, the most recent measurements averaged 23 ppm methane. These initial high concentrations might be associated with disturbances to the geohydrologic conditions that occur during drilling of coal-bed gas wells or with well maintenance problems. Stolp et al. (2006) observed that the maximum methane concentrations were typically found immediately after a well was drilled and that these values "*generally decrease and remain low over time*".

The Colorado Oil and Gas Conservation Commission (COGCC) completed a baseline study between 2000 and 2003 in the Raton Basin to "… *document existing conditions, to collect data that can be used to address future complaints, and to identify and monitor areas of concern*". The baseline study included: a search for methane seeps that covered 2,749 linear miles, documenting sixty seven individual seeps; sampling 100 water wells and 50 gas wells; and locating 1,141 coal exploration bore holes (COGCC, 2003).

The US Geological Survey also conducted an extensive baseline study of dissolved methane in groundwater in New York state between 1999—2011 in an area of potential future shale gas development (Kappel and Nystrom, 2012). Their study showed that, although no drilling for unconventional gas had taken place near any of the sample locations, nearly 10% had significant levels of dissolved methane. Kappel and Nystrom (2012) noted that although 90% of the wells studied had methane levels at or below 10 mg/L (considered a safe level), in nearly ten per cent of the samples, the methane content exceeded 10 mg/L. In five samples, the levels of methane measured were over 28 mg/L or two per cent. Reportedly, in a similar study in Quebec, researchers' analysed 130 water samples collected from residential and municipal wells in a 14,000 square km area of between Montreal Leclercville and Trois-Rivieres (see Science World Report (Griffin, 2013)). It was found that although no shale gas drilling had taken place in this region, 14% of the wells had methane concentrations of more than 7 mg/L. Based on the carbon isotope values of the methane, nearly half of these had some imprint of a thermogenic source.

In Australia, the proponents of large scale Coal Seam Gas (CSG) have embarked on large scale baseline water quality projects with ongoing monitoring planned and underway. Some earlier baseline data collected for other purposes in available. For example, between 1995 and 2004 the NSW Division of Resources and Energy collected geochemical data on 300 samples from water bores found in the Great Artesian Basin within the state (NSW-DII, 2010). This study showed that more than 90% of the wells emitted methane, around 60% and 30% emitted ethane and propane, respectively, and around 85% carbon dioxide. The methane emitted ranged from 3 ppm to more than 600,000 ppm, with the concentration varying according to local geology and the shallowness of the coal. The emissions could have come from natural fractures or the intersection of the bores through coal seams and natural gas sands and/or through biogenic activity.

4.3 Leakage Mechanisms and Potential Leakage Pathways

For leakage of natural gas to occur, Watson and Bachu (2009) noted that there must be a source for the leak as well as a driving force, such as buoyancy forces or a differential hydraulic head. The pathways and mechanisms by which methane can be transported to the surface of the earth have been of great interest to the oil and gas industry for nearly a century, as methane and light hydrocarbons halos were commonly found as a naturally occurring phenomenon above oil or gas reservoirs. Methane can migrate vertically either by buoyant rise of gas bubbles (Webb, 2006; Etiope and Martinelli 2002); by two phase flow of methane and water; and by dissolved methane driven by a vertical (advective) component of groundwater flow.

Leakage from wells by two phase flow has been studied in the context of leakage from CO_2 sequestration projects Nordbotten et al. (2005). These authors modelled the leakage of CO_2 as a uniform leak of supercritical fluid escaping radially from a well bore beneath a sealing shale layer. The resultant CO_2 saturated plume accumulates with its widest extent immediately beneath the shale layer. In the case of a leaking coal gas well, the leak would be of produced water and bubbles of methane gas, rather than the pure CO_2 leak modelled by Nordbotten et al. (2005). If the leakage rates are low and the aquifer contains extensive vertical fractures, it would be expected that bubble flow in fractures will dominate and the bubbles of leaking methane may well become separated from the leaking produced water. The discussion that follows, in part, attempts to examine the factors controlling such a transition.

Buoyancy will be the dominant driving force for natural gas transport in most cases where contamination from gas development is detected. Transport of dissolved methane by aquifer flow will be a slow process at “*typical groundwater flow rates*” it may require “*decades*” for contaminants to be observed in shallow aquifers (Vengosh et al., 2014).

The vertical migration of bubbles of methane will be driven by the density difference between methane and water. A buoyantly rising methane bubble will be acted on by three main forces related to: buoyancy; surface tension; and inertia. For a bubble of methane in water, the buoyancy force (F_b) is given by:

$$F_b = (\rho_w - \rho_m)\, g \sin \theta$$

where ρ_w is the density of water (or brine), ρ_m is the density of methane, g is the gravitational acceleration, and θ represents the orientation of a line emanating from the centroid of the bubble.

Bubbles can aggregate into a more elongate form commonly termed a slug. Slug flow has been found to be a significant form of two phase flow associated with both pipes and open fractures (Moissis and Griffith, 1962; Chung and Kawaji, 2004). The buoyancy force for a slug of gas in a fracture is given by:

$F_b = (\rho_w - \rho_g)\ gh$; where h is the height of the slug.

The buoyancy force acting on bubbles is also opposed by inertial forces. One inertial force identified by Corapcioglu et al. (2004) is related to the motion of a bubble, accelerating relative to the surrounding fluid, creating flow field and associated kinetic energy. They note that such a bubble in motion will behave as if it has an additional mass equal to a ratio of the fluid mass that is displaced by the bubble. An additional inertial force is created by drag of the water surrounding the bubble (Corapcioglu et al., 2004). As noted by Wang and Clarens (2012), these inertial forces are associated with the viscous resistance to shear in the water phase, which have "*an appreciable but poorly understood impact*" on the upward transport of gas bubbles.

In addition the buoyancy of methane is opposed by the capillary forces associated with constriction of the bubble by narrow pore throats or impingements within open fractures. The macro-scale capillary pressure (P_c), can be approximated (Porter et al., 2006) as:

$P_c = P_m – P_w$ where P_m is fluid pressure of methane (the non-wetting phase), and P_w is that for water (the wetting phase).

This approach fails to account for pore-scale properties such as the interfacial area between the two fluids, the Gibbs free energy of the interfacial phase (related to the interfacial tension), and the geometry of the pore space. The effects of interfacial tension on the mechanics of a gas bubble in a fluid were first investigated by Thomas Young and published in a qualitative way in 1805 (Young, 1805).

Young's equation was derived formally by Pierre Laplace (1806) in his treatise *Traité de Mécanique Céleste* in 1806. It relates the contact angle ϑ, defined as the angle between the tangent to the liquid–fluid interface and the tangent to the solid interface at the contact line between the three phases; it also involves the values of water–methane gas interfacial tension, γ_{wm}, solid–water surface tension, γ_{sw}, and solid–gas surface tension, γ_{sm}:

$$\gamma_{wm} \cos \vartheta = \gamma_{sm} - \gamma_{sl}.$$

A more useful relationship, known as the Young–Laplace equation, is a nonlinear partial differential equation that describes the capillary pressure difference sustained across a static interface between a fluid and a gas, as a result of the surface energy of the interface (as represented by the surface tension). Considering a hemisphere of methane (for example, a half bubble of methane pushed out of a pore space into an open fracture), then the force due to surface tension is equal to $2\pi r\gamma$, where $2\pi r$ is the length of the circumference of the hemisphere. The force created by the differential pressure is $(P_m - P_w)$ times the projected area of the hemisphere, i.e., $(P_m - P_w)\ \pi r^2$ and at equilibrium: $(P_m - P_w)\ \pi r^2 = 2\pi r\ \gamma$ which expressed as:

$$P_m - P_w = 2\gamma / r$$

where $P_m - P_w$ are the internal and external pressures of the spherical surface and r is its radius.

In coarser grained sediments bubble flow may be little impeded by capillary effects (Amos and Mayer, 2006). In finer grain sized lithologies, bubbles have to pass through narrow pore throats with higher capillary entry pressures. As a result methane bubbles will accumulate under capillary barriers created by layers of finer grained material.

In many formations, upwards transport of methane will be dominated by vertical or steeply dipping fracture systems. The capillary-entry-pressures for methane of fractures with apertures in the range 5 to 10 um are low. As a result, bubbles can freely enter fractures and from that point their travel will be dominated by the orientation of the fracture and the buoyancy drive of the bubble. Kostakis et al (1999) suggested that the key factors facilitating upward bubble movement in fractures are: (1) the aperture of fractures compared to the average bubble diameter; (2) the dip of fractures, with vertical fractures maximising bubble velocity; and (3) the local water velocity and pressure field in the fracture. The lower the local water velocity and pressure in a fracture element, the more bubble flow is facilitated.

It has been suggested by Brown (2000) that migration of natural gas in a fracture will occur in a continuous gas-phase migration. He suggests that this flow will be initiated before gas bubble migration begins. Brown noted that the capillary pressure needed for a continuous gas phase to enter a fracture is less than that needed to form a bubble that could enter the same fracture. However, there have been few studies of the factors controlling bubble versus continuous gas streams entering a fracture. These factors are doubtlessly more complex than just the strength capillary barriers. It’s unlikely that a single fracture extends from the source of migrating gas to the surface, transport will be via a network of fractures. Bubbles in fractures that are less than vertical will migrate along the upper wall, creating drag and slowing the bubbles ascent. Brown (2000) suggests that in contrast to the impact of lower dip on bubbles, continuous gas-phase flow will have only minor impedance.

The solubility of methane in water is strongly pressure dependent (Duan and Mao, 2006) with the maximum dissolved methane concentration increasing from about 32 mg/L near the surface to 1,000 mg/L at a hydrostatic pressure equivalent to 600 metres of water. If groundwater flows towards the surface, it will become supersaturated in methane as the pressure decreases, and may exsolve a gas phase in the form of bubbles. Based on experimental data, Van Kesteren and Van Kessel (2002) suggest that the nucleation of gas bubbles occurs at small degrees of methane supersaturation. However, Claypool (1996) suggests that finer grained sediments can become supersaturated with respect to a gas phase as capillary effects inhibit the formation of bubbles.

Osborn et al. (2011) have reported levels of dissolved methane in water wells that represent a considerable degree of supersaturation at one atmosphere of pressure. There appears to be inadequate information available to understand the factors controlling bubble nucleation in groundwater oversaturated with methane.

Bubbles of methane caught by capillary forces in pore spaces dissolve to provide methane in solution, which is transported by flow of groundwater through the pores. The rate of dissolution is not well understood, but is critical to understanding the role and fate of methane bubbles in aquifers. In aquifers, the surface of methane bubbles will be contaminated by naturally occurring surfactants (such as humic acids lipids, and fatty acids) that are widespread in the near surface environment. As noted by Fyrillas and Szeri (1996), most molecules with both hydrophobic and hydrophilic domains will preferentially accumulate at the water-methane interface. Natural surfactants are produced by a variety of microbes (Cerniglia, 1984) and are also common amongst the molecules in dissolved organic carbon or DOC. Even a monolayer of surfactants at the water gas interface will likely have a dramatic effect on dissolution rates. It should be noted that surfactants will also have a significant impact on the surface tension of the bubbles. Several studies (Leifer and Patro, 2002) have noted that surfactants lower dissolution rates of gas bubbles, although experimental data relevant to methane bubbles in water that quantify this effect appear to be lacking. It is certain that if methane accumulates in large slugs with small volume to surface area ratios, the effective rate of dissolution of methane will be small.

There are two sets of empirical evidence that suggests methane bubbles in shallow groundwater dissolve little on timescale of weeks, years, and possibly decades. The data presented by Cheung and Mayer (2009) shows that a high level of methane in the free gas phase is not necessarily associated with high levels of dissolved methane in the associated groundwater. This suggests that methane in solution in groundwater is often not in thermodynamic equilibrium with the co-existing free gas phase and presumably that the dissolution rate of methane in bubbles is very slow.

Jackson et al. (2013) suggested that the sources of stray methane “*could include the production zone*”. However they concluded that the shallower overlying formations in the “*intermediate zone*” between producing reservoir and shallow groundwater “*appear to be a more common source*”. If a pathway with a significant methane flux breaches the surface, the loci of methane leaking to the atmosphere may be referred to as a “seep”. In addition to being fed by the natural vertical methane flux, the strength of such seeps also reflect natural and man induced methane from depressurisation of coal seams and/or stringers. Such depressurisation can be caused by pumping water bore for agriculture, natural drop in the water table caused by drought, and/or as an unintended consequence of coal seam gas production.

4.3.1 High Permeability Faults or Fracture Zones

Upward buoyant transport of methane can occur via high permeability pathways associated with faults and/or fracture zones. ALL (2004) in their primer on Coal Bed Methane, suggested that methane can "*migrate through more widespread fracture sets related to faults and tectonic jointing,*" and also that such "*faults can persist over several miles … and can enhance the migration pathways for the methane*". The field evidence for fracture zones and faults controlling methane migration is mixed in the sense that not all faults or fractures zones are conduits for methane. For example in his study of the San Juan Basin, Fruitland Formation, Chafin (1994) attempted to correlate mapped fractures and faults mapped at the surface with water wells that contained detectable amounts of methane. Chafin could not find a positive correlation and concluded that "*fractures are [not] substantial migration pathways between deep, gas-bearing formations and the near-surface environmen*t".

4.3.2 Gas Wells as Leakage Pathways

Watson and Bachu (2009) and King and King (2013), amongst others, have reviewed the leakage pathways for natural gas associated with wellbore leaks associated with gas wells. To have a leak from a gas production wellbore requires multiple failures in the integrity of the multiple casing pipes and cements sheaths in the annular spacing between them (King and King, 2013). The nature and factors controlling leakage through impaired wellbore casings or cement sheaths has been reviewed by Dusseault et al. (2000). The observations from regulatory agencies in the US are that leakage of gas from inside the production casing to fresh water aquifers is a rare phenomenon. For example King and King (2013: p.340) have estimatedthe overall frequency of leakage for wells oil and gas or injection wells "in service at this time" ranges from 0.005% to 0.03% (with higher frequencies possible older wells). Similarly, Dusseault and Jackson, R. E. (2013) have suggested that leakage of natural gas into fresh water aquifers as a result of hydraulic fracturing is also very rare. Their conclusions are applicable to shale gas and tight gas sands. Regarding the likelihood of natural gas contaminating fresh water aquifers as a result of coal gas development, two major studies in the US by the EPA (US EPA, 2004) and the National Academy of Sciences (National Research Council, 2010) have concluded that no such incidences have been documented.

4.3.3 Abandoned Oil/Gas Wells, Coal Test Wells as leakage Pathways

The regulations regarding well bore integrity and plugging abandoned wells have evolved considerably over the last century. Gorody (2001) noted that for deep oil and gas well construction prior to the 1950s in the San Juan Basin, the production-casing annulus was not cemented to protect the formations that in the 1980s became targets for CBM. As result, in some cases, free gas released by the CBM dewatering process migrated vertically up the open annulus of old wells. As a result a few incidents occurred where methane in both free gas and dissolved form contaminated shallow, freshwater aquifers (Beckstrom and Boyer, 1991). Further Beckstrom and Boyer (1993) concluded that accumulation of natural gas in the annulus of several legacy conventional-gas wells resulted in gas pressure being measured in the gauges of these wells. Chafin (1994) describes abandoned gas wells in the San Juan basin (drilled in the 1930s), that by the 1990’s were discharging natural gas into a shallow aquifer. This resulted in concentrations of dissolved methane as high as 39 mg/L being found in the aquifer.

4.4 Methane in Groundwater Associated with CBM

4.4.1 US and Canada: Methane in Ground Water

In many areas in the US it is well known (Chafin, 1994; US EPA, 2004; Riese et al., 2005) that methane in water wells has predated gas drilling for CBM. Subsurface migration of methane is a concern for all development of natural gas from coal seams. Methane in minor coal stringers or seams above the production zone may be released by dewatering. Buoyant methane bubbles can migrate through fractures into overlying aquifers even if the water is flowing towards the coal seam. Such buoyant methane bubbles can potentially dissolve in groundwater resulting in methane contamination. Methane bubble rising up through a water-well can ultimately convert the water from aerobic to anaerobic which in turn can promote sulphate-reducing microbes that convert sulphate ions into H_2S with significant negative impact on water quality.

In the US, the interpretation of methane in groundwater is controversial largely because of the lack of extensive, quantitative baseline data prior to gas production from coal seams. The U.S. Department of the Interior, BLM (1999), provided a history of gas seeps and methane contamination of drinking water wells in the San Juan Basin. US EPA (2004) note that even before oil and gas drilling operations began in the area, methane gas was being produced from shallow water wells in the San Juan Basin. Historic records from settlers in the 19th century include observations of gas bubbles in the Animas River. Subsequent discovery of shallow methane gas in the same area suggested to Chafin (1994) that the observed bubbles were likely methane. Chafin also notes that gas seeps (characterised by areas lacking grass up to three meters across) were observed in Animas River Valley farms near Cedar Hill. One study reported that 34 per cent of the 205 domestic water wells tested in the county showed measurable concentrations of methane (US BLM, 1999). Unfortunately little, if any, information is available on pre-CBM methane levels in groundwater in the area and the origin of the contamination is unclear (US BLM, 1999).

It has been suggested by the BLM that development of CBM resources in the Northern San Juan Basin resulted in increased methane emissions, based on monitoring the strength of natural methane seeps in the outcrop area of the Fruitland Formation (US BLM 2000; US BLM/USFS, 2006). Similarly Questa Engineering (2000) has asserted that "*gas seepage from the basin as of early 2000 is estimated to have increased by at least 3 MMcfd* [million cubic feet per day, 85,000 m^3/d], *and possibly as much as 10 MMcfd* [283,000 m^3/d] over *predevelopment levels*." However these conclusions are not supported by robust quantifiable data. The available information is insufficient to estimate the magnitude of the methane emissions from the Fruitland Formation, and no baseline measurements of emissions prior to initiation of CBM activities are available.

Early in the development of the Fruitland coal, 11 CBM wells were drilled within 2 miles of the Pine River Ranches Subdivision (near the rim of the San Juan Basin). The Fruitland Formation coals are within 35 feet (ca. 11m) of the surface in the area of the subdivision. Soon after the development of the wells occurred, complaints of wells being contaminated with methane were investigated by government agencies. Eventually, 2 of the 4 residences near the CBM wells were found to contain dangerous levels of methane in crawl spaces under the houses (US BLM, 1999). A series of tests were conducted on nearby CBM wells to identify the source of the seeps (Cox et al., 1995). On the basis of the results of these well tests and subsequent computer simulations the hydrology around the wells, Cox et al. (1995) concluded that methane seepage developed from gas being released near one of the CBM wells. Their evidence suggested that the gas was being released from a shallow coal above the Fruitland and that dewatering of this coal was a side effect of the CBM development. To solve the problem, a remediation plan with targeted injection of water into the seep area was developed.

Fisher (2001) describes a "*recent infamous instance of CBM seepage*" that impacted the Rawhide Village subdivision, located about ten miles north of Gillette, Wyoming. In 1987, the mining company AMAX removed overburden and then began dewatering the Ft. Union Coal in preparation for expanding their strip mine immediately adjacent to the Rawhide Subdivision. Shortly after initiation of the AMAX project, residents of the subdivision became aware of a gas seepage problem. On the basis of field investigation and laboratory analyses Jones et al. (1987) concluded that the subdivision had potentially explosive concentrations of methane seeping into the homes. The entire subdivision was subsequently evacuated by state regulators and ultimately AMAX Coal Company bought out the home owners. Fisher's use of the term CBM-seepage maybe misleading in that the problem was not related to CBM well development in any way. Had CBM wells been developed, the methane release by dewatering would likely have been captured and produced.

In Alabama, development of CBM in the Black Warrior Basin is from depths of 150 to 1000 meters. Researchers from the Geological Survey and University of Alabama, Pashin et al. (2004) noted that stakeholders have had concerns that the CBM development may contaminate shallow freshwater aquifers. Pashin (2007) observed that the high quality Cretaceous aquifers showed no evidence of contamination from coal bed gas operations. Some cross-communication has been documented for gas production among closely spaced coal beds, however marine shales largely confine water flow to the coal seams (Pashin et al., 2004). Analysis of fracture systems and production patterns along faults suggests that many faults and fracture zones are sealed because of cementation with calcite. Pashin (2007) also summarised hydrologic testing results that suggested the coal bed reservoirs are hydrologically isolated. As a result of this, Pashin (2007) concluded that the "*environmental risks posed to shallow groundwater*" from CBM development are "*minimal*".

After reviewing the results of 304 investigations, by state regulators, of complaints of water well contamination in Alberta, consultants Worley Parsons writing for the Alberta Government (Armstrong et al. 2009) concluded that "*there is no scientific evidence of CBG exploration activity causing coal bed gas to migrate to domestic water wells*". Armstrong et al. (2009) further suggest that "*forensic sampling*" data from Alberta and "*several basins within the USA*" has identified "*almost no gas migration issues relating to [coal bed methane] development*". They suggest that the most common cause of gas impacts was related to "*inadequate sealing of historical exploration boreholes and test holes*". Armstrong et al. (2009) suggest that the potential for methane leakage from legacy wells "*needs further assessment… using geochemical and stable isotopic gas analyses*." A report prepared for the Canadian NGO, Pembina Institute by Griffiths and Severson-Baker (2003) notes that "*CBM reservoirs in Alberta are 'tight', there have been very few cases where natural methane leakage has occurred*". They do suggest, however, that pressure reduction by CBM development creates "*the potential for gas from coal seams to enter groundwater aquifers through the annuli of old wells or wells with leaky casing*".

4.4.2 Queensland, Australia: Methane in Ground Water

Anecdotal information suggests that methane in ground waters and methane seeps appear to have been historically associated with coal seams in a number of Australian basins.

Describing a water well drilling incident on 16 October, 1900, Roberts (1992), describes a gas "*blow-out*" in No.2 water bore in a Jurassic reservoir at Hospital Hill near Roma, Queensland. The well reportedly flowed for 10 days. Non-commercial gas was again encountered in the area in 1927and 1934 (Wolfensohn and Marshall, 1964), though while obviously a gas-prone area, only in the 1960s was gas commercialised from conventional gas *accumulations.* All of these gas occurrences were within GAB aquifers.

Elsewhere, Gray (1967) documented reports outbursts of methane outbursts in water bores drilled in the Chinchilla area since the early 1900's. Gray documented water bores in the region historically contaminated with methane gas based on old government drilling log records from the GAB. Anecdotal accounts gathered by Gray indicate widespread incidences methane migration via water bores and natural features.

The Queensland Gasfields Commission (GFC, 2013) compiled historical records of possible methane seeps in the state. Soil gas surveys from the 1980s and early 1990s recorded anomalous concentrations of methane in a number of basins including the Surat, Eromanga, Cooper, and Bowen.

The seeps that have received the most attention recently, are those found to be bubbling in the Condamine River at six separate locations (DNRM, 2012). Local residents have asserted the current bubbling is more vigorous than it was prior to CSG development. The seeps have been sampled 50mm above the bubbles giving methane concentration up to 85ppm (DNRM, 2012). Measurements 100mm above the bubbles are reported as "*zero*" – presumably background. Water samples from the river at the seep site give values for dissolved methane of up to 500 µg/l at the seep site. Dissolved methane concentrations are back to upstream levels (<10 µg/l) approximately 50 meters downstream methane levels. Although the isotopic composition of the methane bubbling up from the river is consistent with microbial altered or mixed CSG gas sourced from the Walloons. The study by state regulators did not establish the cause of seepage. Given the reported separation distance to contemporaneous CSG developments, there is no compelling evidence that CSG development activities have increased the rate of ebullition of methane in the river. Four CSG wells are located within a five kilometre radius of the location of the Condamine gas seep; the closest being 1.4 kilometre, however, reports that these wells are not part of a producing field. The closest CSG production well is reported to be 10km from the

Condamine River site and the closest well that was hydraulically fractured is reported to be 40km away.

4.5 Discussion and Conclusions

Is methane gas transported from deeper gas producing coal reservoirs to shallow ground water aquifers? Does the concentration of dissolved methane in water wells increase when coal gas resources are developed at depth below the well? It might be thought that baseline testing would provide simple and definitive answers to such questions. That is, if pre-development testing shows that methane levels are low and post development sampling shows that methane levels are high, that the case for contamination has been proven. A review of baseline testing for methane in areas of US shale gas development has yet (2015) to be undertaken. Methane levels in water wells can vary considerably depending on factors such as: (1) the pumping history of the well immediately before sampling; (2) the variation in weather conditions, particularly recent changes in the barometric pressure; and seasonal cycle (that may represent a combination of the first two issues). In the Surat and Bowen Basins, in addition to CSG development activities, there are non-CSG related natural, biogenic and deep thermogenic sources of aquifer methane (and other hydrocarbons) as well as non-CSG development, anthropogenic activities (water abstraction) which could change methane concentrations.

As a result, to identify whether new sources of methane have been introduced into the aquifer by coal gas development is a complicated and expensive undertaking. It would require extensive baseline testing extending over a year or more (to capture variations associated with seasons) including sampling and analysis of concentration and stable isotopic measurements for both dissolved and free gas methane). It would also be important to analyse for the stable isotopic character of the other components with readily exchangeable hydrogen, and carbon isotopes such as the water, dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC).

Making an accurate assessment of the methane content of groundwater through sampling water wells is challenging. Well water which is under-saturated with respect to methane may entrain bubbles from a fracture intersecting the well. Alternatively, groundwater saturated with methane may effervesce as it is pumped to the surface. Roy and Ryan (2010) in their academic research study of degassing issues noted that degassing was apparent for shallow monitoring wells associated with natural attenuation of hydrocarbons plumes and also for greater than 50 m deep monitoring wells completed in thin coal seams. As a result, it is difficult to accurately determine the groundwater's methane concentration in-situ.

A number of studies of methane in groundwater have attempted to ascribe the origin of the methane to leaking production wells on the basis of the stable isotope measurements. For example, academic toxicology researchers from the University of Pittsburgh and others, Goldstein et al. (2014), have suggested that "*A major issue has been whether methane identified in well water comes from nearby hydraulic fracturing activities or older conventional wells (thermogenic methane) or is present due to subsurface coal bed methane, bacterial decomposition (methanogenic bacteria), or other sources*". This approach of dividing methane into "*thermogenic*" (leaked from gas wells) versus "*biogenic*" (naturally formed methane) as suggested by Goldstein et al. (2014) is over-simplistic. As noted previously, coal seam gas reservoirs can have biogenic and mixed signatures. Furthermore, as has been shown, in the transport mechanisms section above and in discussions on other sources of natural hydrocarbons in earlier chapters, thermogenic methane may be transported from source rocks, at considerable depth (on the order of thousands of metres), to shallow aquifers by natural processes. Brown (2002) noted that this process can be rapid with the methane maintaining its thermogenic isotopic character. Finding dissolved or free gas methane in aquifers with a thermogenic isotopic signature does not require the existence of a leaking gas well. The stable isotopic composition of methane can be modified by: mixing with other sources of methane; by microbially mediated oxidation of methane; and/or isotopic exchange with bi-carbonate ions or other readily available sources of carbon and hydrogen. In addition, as noted above, as methane resides in the subsurface, its isotopic signature is likely to be modified over time. Again, the imprint of a thermogenic component of methane does not require mixing with gas from a leaking production well. As a result, applications of the fingerprint approach can easily produce misleading results.

Despite the complexities of establishing baseline levels of methane in groundwater, there is a large body of data that suggests that the occurrence of methane dissolved in groundwater is endemic in aquifers overlying unconventional gas reservoirs in sedimentary basins. Records of macro-seeps of methane and bubbles in rivers are common in areas now targeted for coal or shale gas. Numerous studies of baseline chemistry of domestic and agricultural water wells in areas of coal bed gas development water wells in the US and Canada have focused at least in part on the distribution and origin of dissolved and gas phase methane. The almost unanimous consensus of these studies has been that the methane was either a pre-existing natural phenomena, or was caused by mechanisms not related to the development of the coal gas. In the Raton Basin, Riese et al. (2005) have asserted, based on their interpretation of an array of isotopic data, that methane seeps associated with the outcrop of the Fruitland Coal are a natural phenomenon that have been "*ongoing throughout recent geologic time*". On the basis of their synthesis of geologic, geochemical and isotopic data, that CBM development from the coal in deeper parts of the basin "*has not contributed to methane gas seeps at the outcrop*". These authors assert that the methane "*seeping from the outcrop is not due to industry production activities*". Referencing US BLM (2000) and US BLM (2006).

Where non-natural methane sources have been identified, the most common causes are associated with legacy wells of various sorts, including old gas well, coal-test bore holes, and old water wells. Legacy penetrations, including boreholes drilled in the past for water wells, and other applications such as coal test boreholes, geotechnical testing wells, unplugged or improperly plugged oil and gas wells, and seismic shot holes, can play a major role locally in methane contamination of groundwater. Armstrong et al. (2009) suggest that "*forensic sampling*" data in from Alberta and "*several basins within the USA*" has identified "*almost no gas migration issues relating to [coal bed methane] developmen*t". They suggest that most common cause of gas impacts was related to "*inadequate sealing of historical exploration boreholes and test holes*". The dangers associated with methane migration in water wells and bores can be mitigated at a low cost by proper water-well construction and simple degassing equipment. Armstrong et al. (2009) have suggested that owners of water wells should be educated about both well installation and maintenance, and the proper abandonment of old and unused water wells.

The conclusion that dominantly, methane seeps and methane in groundwater in areas of coal seam gas production are largely unrelated to coal gas development is a recurrent theme in studies of these phenomena. Gorody, a scientist who has decades of experience in baseline testing of groundwater in areas of CBM development concluded that historic and recent changes in water quantity, dissolved gas concentrations found in domestic water wells, and the perceived rate of methane seeps at the surface, are largely a naturally occurring phenomena (Gorody, 2001). The Alberta Research Council (ARC) in an independent review of CBM related water well complaints filed with Alberta regulators over a three year period, concluded that the "*energy development projects in the areas most likely have not adversely affected the complainant water well*s" (ARC 2008). Similarly, based on the Alberta CBM water well baseline monitoring Armstrong et al. (2009) concluded that "*there is no scientific evidence of CBG [coal bed gas] exploration activity causing coal bed gas to migrate to domestic water wells [in Alberta]*".

If coal seam gas development is not responsible for the vast majority of methane getting into water wells then what is? As outlined in this paper there is substantial evidence that areas of potential coal gas production are characterised by sporadic natural methane contamination in groundwater. Methane contamination in aquifers will include by both free gas (immobilised in capillary traps, in pores, and in fractures) as well as methane dissolved in the groundwater. Both of these sources of methane can feed macro-seeps that are common in most areas of coal gas development.

Although our understanding of the transport mechanism of methane in the subsurface is incomplete it does give some insights into current issues related to methane migration. Seepage incidents in the Surat Basin have become the subject of controversy, particularly the seepage sites on the Condamine River (DNRM, 2012). There is evidence from historic sources that sporadic methane contamination has been found associated with water boreholes in the Surat Basin. Gray's (1967) water well blow out is consistent with a model where substantial quantities of free methane gas are trapped as ‘slugs’ in a fracture network or a local free gas gap associated with a structural high presumably trapped by a capillary barrier such as very fine grained sediment.

It is interesting to put forward a hypothesis whereby the Condamine River seep/bubble site may also be connected to a methane filled fracture network. The state regulators (DNRM, 2012) found that the river water associated with bubbles of methane was highly under-saturated with respect to methane. The largest concentration measured, 0.5 mg / L, is more than an order of magnitude less than would be expected if methane saturated water was feeding the seep.

Personnel from the CSG company Origin, between 2011 and 2012, sampled and measured the methane concentration dissolved in the groundwater and as free gas in the headspace of 25 pre-existing water bores in the vicinity of the Condamine seep (Baldwin & Thomson, 2013). It is interesting to note from the data presented that the concentration of dissolved methane is anti-correlated with the presence of significant methane concentrations in the head space of these wells. Of fourteen bores that had measured concentrations of both dissolved and headspace methane five had high (17 to 40 mg/L) levels of dissolved methane and either undetectable or trace amounts of headspace methane. There were an additional three wells that had high concentrations of head space methane and low concentration of dissolved methane (2 to 4.5 mg/L) of dissolved methane. A plausible interpretation of this correlation is that the headspace methane is being transported in fractures by bubble flow. This is a testable hypothesis that should be the focus for further work. If this is indeed the mechanism then the transport of methane in the area will be dominantly vertical (as this is the only effective direction for bubble flow in fractures as noted previously). If this is the case, then the methane source for the Condamine River seeps are local and not likely be related to activities at the CSG production area reported to be some 10km distant.

The scientific understanding of the nature and controls over methane migration in the subsurface is clearly incomplete and much remains to be discovered. However because most previous studies of methane migration spatially associated with unconventional gas have not attempted to make an analysis of the *mechanisms of transport*, they have failed to establish a rational approach to better understand these issues. This paper is a small step in that direction.

CHAPTER FIVE:

Impact of Development of Coal Gas Resources on Land Subsidence

5.1 Introduction

Although no studies of measured subsidence associated with CSG development in Australia have been published in peer reviewed literature there is concern amongst some stakeholders that this phenomenon will occur and will cause substantial damage to infrastructure and the environment.

In general, subsidence is widely associated with large scale water withdrawals from certain aquifers and gas production from conventional gas reservoirs. Unconsolidated or weakly consolidated sediments have larger compressibilities and are the most susceptible to compaction induced subsidence. Globally the main area of subsidence from over pumping of aquifers is associated with unconsolidated coastal and Quaternary alluvial aquifers such as those found around the Mediterranean Sea, Shanghai, Mexico City, and in the Antelope, Santa Clara and San Joaquin Valleys in the US. Subsidence in these areas, generally in response to significant lowering of the water table due to pumping for city water supply or agricultural purposes, has resulted in a few decimeters to nearly 10 metres of subsidence (Bouwer, 1977; Corapcioglu, 1984). It should be recognised however that it is difficult for CSG stakeholders to draw meaning from such cases because they are only superficially similar: the types of unconsolidated coastal and Quaternary alluvial aquifers are generally not analogous to areas of CSG development in Australia.

Typically oil and gas production, even from shallow reservoirs, results in minimal surface subsidence. In some specific oil fields, and in a number of shallow to intermediate depth gas fields, production of hydrocarbon fluids has corresponded with significant subsidence

(Martin and Serdengecti, 1984; Nagel, 2001). As in shallow aquifers, compaction of unconsolidated, weakly consolidated, or mechanically weak reservoirs results in surface subsidence as fluids are withdrawn (Nagel, 2001).

Subsidence associated with natural gas production from coal may be expected if significant dewatering of overlying unconsolidated (or poorly consolidated) aquifers is required to facilitate gas production. The Energy Justice Network (2005), a non-government organisation (quoting US Congressional Testimony from Merschat, 2001) suggests that "*there have been incidents where enormous quantities of water have been removed from shallow aquifers, followed by as much as a 40-foot drop (or subsidence) in the surface of the land*". The Energy Justice Network further suggest, quoting the same source, that the consequences of such subsidence include rupturing of utility lines, collapse of buildings, and damage to roads.

In a 2013 report on subsidence associated with CSG development, Pineda and Sheng (2013) of the University of Newcastle, NSW, concluded both that subsidence was manageable and that it could "…*vary in magnitude, from trivial and insignificant to substantial and damaging*". Pineda and Sheng further suggested worse scenarios such as "*large*" subsidence "*affecting infrastructure and natural resources*" and even impacting "*the gas production itself*". They further suggest that, "*based on geomechanics principles*" and "*some degree of speculation*" that "*intense cracking may develop at the boundaries of the subsidenc*e" which in turn "*may cause important stability problems on neighbouring infrastructure*".

The current review set out to evaluate the degree to which potentially important concerns expressed by concerned parties such as the Energy Justice Network (2005), and academic position papers such as Pineda and Sheng (2013), are supported by the available data. This chapter first reviews previous estimates for subsidence that could be caused by future development of CSG resources in Australia. In particular it seeks to understand the basis for these estimates. The chapter then examines the results of attempts to estimate subsidence using geomechanical modelling and demonstrates that these estimates depend on both the algorithms used to model the behaviour of the coal layer during dewatering and the boundary conditions used in the modelling. Finally the chapter reviews the results of measurement of subsidence associated with mature CBM fields in the US utilising high accuracy satellite interferometry techniques. Synthesis of the available information results in a new, more realistic estimate for the level of subsidence that might be expected as a result of methane production from the main CSG fields in Australia.

5.2 Previous Estimates of Subsidence Associated with CSG Development in Australia.

Although no independently peer reviewed published measurements of subsidence associated with CSG development in Australia could be sourced there appears to be widespread anxiety regarding risks of subsidence associated with CSG development. Several reports quote measurements of subsidence associated with Australian CSG fields, however in each case no source in given for the data. In a report prepared for the Australian Council of Environmental Deans and Directors, Williams et al. (2012) wrote that “*Water extraction in this part of the Surat Basin and the GAB is reported to have lowered the head of water pressure by 100 m in some areas, and subsidence amounting to metres has been observed in some locations near wells*”. No source for where the value was “*reported*” is cited.

As part of the environmental impact assessments carried out by proponents of CSG projects in the Surat Basin, a number of consultant reports have been published that estimate future subsidence associated with full project build out. Golder and Associates (Golder, 2010b) used a simple uniaxial strain model assuming linear elasticity, together with estimates of decrease in effective stress with dewatering, to make estimates for subsidence caused by CSG development. Their estimates varied between 0.08 and 0.18 metres. A water conservation consultancy, the Water Group (WG, 2010) summarised that based on “*the original EIS*”, that QGC estimated that “*up to 30cm of land subsidence will occur*” and that “*the Santos EIS indicates a similar level of subsidence*”. The Water Group expressed skepticism of such low estimates for subsidence associated with CSG development. They suggest that pumping of water for agriculture in the past may have lowered the pressure head in parts of the Great Artesian Basin (GAB) by as much as 100 metres in some areas. They also quote unpublished information from a personal communication from GAB research scientist M. Habermehl in 2010, reporting that he believed that several metres of subsidence had occurred in many areas, in response to past pumping.

In 2010 Geoscience Australia (the Commonwealth of Australia's geological survey agency) produced a preliminary report on the nature and possible impacts of coal seam gas extraction in the Surat and Bowen Basins, Queensland. With respect to subsidence they estimate the likely magnitude of subsidence to be in "*the order of centimetres to tens of centimetre*s" and that – based on subsidence assessments for CSG activities in similar geological environments elsewhere - "*the risk of impacts to surface water and shallow groundwater systems [from subsidence] is very low*" (Geoscience Australia & Habermehl, 2010).

The NSW Chief Scientist's report states that "*Estimates by CSG proponents of subsidence across CSG areas range between 0.06 m and 0.2 m over 2 km lateral distance*". The report notes that the "*…differential subsidence that results (0.003% to 0.1%) is small and is not expected to have a significant impact on buildings*" (NSWCS, 2013). The same report suggests (without reference to a source) that modelling the Walloon Coal Measures in the Surat Basin predicted subsidence between "*50 mm and 200 mm*". Similar estimates have been given by Garthwaite et al. (2015) who note that "*predictions of the magnitude of subsidence*" in the area of greatest recent CSG production "*based on poro-elastic modelling*" indicate that "*subsidence on the order of a decimetre may be occurring*". Garthwaite et al. (2015) did not supply any actual measurements that supported the modelled subsidence estimates.

Finally, while the *potential* for subsidence following ground water extraction may be plausible the situation in the Surat Basin seems somewhat enigmatic. In 2008, CSIRO reported significant impact on water levels in the Condamine Alluvium following several years of extensive, pre-CSG water abstraction for agricultural uses including cotton farming. The Condamine Alluvium is described as poorly consolidated and is potentially one of the most subsidence-sensitive areas. It includes areas of laser-levelled intensive, irrigated lands i.e. areas where significant subsidence might be expected to be readily apparent. While Moran and Vink (2010) reported that "a s*ubsidence bore was established in the Condamine* *in the early seventies and indicates that there may have been minor subsidence due to water extraction",* and while many CSG-impact related assessments point to potential for subsidence, it is perhaps noteworthy that despite the historic, pre-CSG aquifer depletion, no literature or reports could be found describing any significant, associated subsidence in the Condamine.

5.3 Numerical Modelling Studies of Subsidence

There have been a number of numerical modelling studies on the geomechanical aspects of CSG production and associated subsidence. Perhaps the first attempt to model the subsidence associated with the production of natural gas from coal seams was a US study by Fanchi (2002). In his model, Fanchi used the stratigraphy of the Fruitland coal, assumed uniaxial deformation, and that all the compaction occurred within the coal seams. Fanchi estimated that the total surface subsidence over the Fruitland coal, after ten years of gas production, as 7.6×10^{-4} metres. Chamani and Rasouli (2011) reported a numerical simulation of depletion-induced surface subsidence in a coal seam using a finite element approach. Chamani and Rasouli (2011) modelled the deformation of a 14 metre thick coal seam with a Young's Modulus of 2.0 GPa. Their model suggested that as the coal seam's pressure was reduced to 75, 50 and 25% of the original pore pressure that the subsidence would increase from 0.005, to 0.01, to 0.016 metres.

CSIRO researcher, Freij-Ayoub (2012) published a numerical model of methane and water production from a coal seam and estimated the resultant subsidence. Freij-Ayoub looked at three cases. In the simulation for Case 1, in which a coal layer was imbedded in impervious shales (such that all the dewatering and associated volume loss takes place in the coal seam), the estimated subsidence of 0.11 metres near the well and 0.1 metres at fifty metres from the well was an order of magnitude higher than for Case 2 and 3 where the coal seam had a porous permeable aquifer either above or on both sides of the coal seam (with predicted subsidence of 0.016 to 0.01 metres). The higher subsidence rates predicted for Case 1 result from the higher rates of depressurisation of the coal seam. They also reflect the choice of boundary conditions in the model. Freij-Ayoub's numerical model assumed both no-flow boundary conditions at the surface and laterally at 200 metres from the extraction well. Bau et al. (2004) have studied the effects of surface boundary conditions on modelling subsidence in aquifers resulting from fluid withdrawal and found that no flow boundary conditions result in subsidence rates as much as an order of magnitude larger than if permeable boundaries are assumed.

Note that Freij-Ayoub's (2012) model did not account for poroelastic compaction in the sandstone aquifers and rather assumed that the entire dilatational strain engendered by methane desorption was taken up by vertical contraction of the coal seam (uniaxial strain). Neither of these assumptions is likely to be valid. Cui et al. (2012) noted that uniaxial strain "*is not a realistic physical mode* [for the dilatant strain accompanying methane production from coal]". Rather, they state that horizontal displacements accompanying methane production will result in broadening of the vertical fractures or cleats as the coal shrinks. Clearly only a portion of the volumetric strain will be translated into subsidence.

Both Massarotto et al. (2009) and Ma et al. (2011) have argued for a constant volume model for production of natural gas from coal seams. Ma et al. (2011) state, though without providing supporting reference or documentation, that "*no observed subsidence [has been observed] resulting from methane production from coal*". Similarly Fischer (2001) suggests that "*Subsidence effects [associated with CBM production] appear to be negligible*". A thorough review of the literature carried out during the current study supports the assertion that subsidence if not negligible, is minor in magnitude.

5.4 InSAR and Measurement of Subsidence Associated with Coal Gas Development

Studies of subsidence over CBM fields in the US have only been begun over the last few years, possibly reflecting that fact that no issues related to subsidence appear to have occurred over the four decades or more of CBM production. Galloway et al. (1999) in a comprehensive review of land subsidence in the US for the USGS does not mention any subsidence related to CBM development. Based on a report by the Wyoming Geological Survey (Case et al., 2001), Fisher (2001) noted that for the Powder River basin, "*preliminary estimates of subsidence due to aquifer draw down are insignificant (-0.5 inches [-1.3 cm])*", pp. 9. These estimates were based on simple calculations and Case et al (2001) note that they would be uniform over a large area and not result in significant damage. Despite their calculations, they also note that although significant quantities of water have indeed been extracted from a certain area and sub-coal formation, no surface subsidence has been observed associated with it.

The apparently small magnitude of subsidence associated with CBM development clearly requires a measurement tool with high vertical accuracy and resolution. InSAR or Interferometric Synthetic Aperture Radar is such a tool. SAR is a remote sampling (typically satellite), active microwave imaging method which can provide a view of land movements from multiple sources. The InSAR technique utilises the differences phase of two or more SAR images, acquired from different positions. A significant application of SAR that became widely implemented in the 1990's is the use of InSAR to make high accuracy estimates of the deformation of the earth's surface. Allen (1995) provides a useful overview of the theory and design of InSAR as well as a brief history of its implementation. Allen noted that InSAR provides the capability to derive high-resolution three-dimensional radar images of an area. InSAR is based on acquiring data simultaneously from two slightly displaced antennas. High-resolution maps of the relative elevation of the earth's surface can be computed from radar sensors deployed either on satellites or on high flying aircraft. More recent reviews of InSAR and its application to measuring deformation of the surface have been published by Massonnet and Feigl (1998), Rosen et al. (2000), and Hanssen (2001). There have been a growing number of studies of the effect on surface deformation of large scale pumping of water into aquifers and withdrawal from aquifers (Schmidt and Bürgmann, 2003; Tomás et al., 2005).

More recently the accuracy available from InSAR has improved considerably. More effective methods have been developed to correct for variations in the atmospheric variability, and approaches to reduce the signal to noise ratio by summing SAR images over the same area, acquired over a short period of time. The multi-image stacking approach for InSAR was refined by Ferretti et al. (2001) who introduced the term "*Permanent Scatterers*" to describe the approach. Ferretti et al. (2007) used experimental data to demonstrate that sub-millimetre accuracy was possible from InSAR time series. Mei and Froese (2007) pointed out the potential applications of InSAR to measuring ground deformation associated with oil and gas development by utilising this new approach to achieving sub-millimetre accuracy. These authors suggested that InSAR should be applied to examining the surface deformation associated with "*the removal of methane from coal beds*".

Perhaps the first area of CBM production to be studied was the Powder River Basin (PRB) where two independent analyses were conducted by Grigg et al. (2012) and Semmens et al. (2012). Grigg et al. (2012) used the results of InSAR analysis and information on the rates of groundwater pumping associated with CBM development to model associated land subsidence. Around a decade after Case et al (2001) calculation and observation of subsidence, analysis of InSAR data was considered to be consistent with "*several centimetres*" of subsidence in the Powder River Basin and was spatially associated with areas of active CBM wells.

A similar study was reported by Semmens et al. (2012) who used 23 paired SAR scenes spanning a period of 15 years (from 1992 to 2007) to use InSAR analysis to construct a "*detailed time series that allows the determination of surface deformation*". Semmens et al. suggested that their results were consistent with subsidence "*on the order of several centimetres*" spatially associated with several areas with high density of CBM wells. They also suggested that there was a linear relationship between the volume of produced water in a specific area and the magnitude of the surface deformation.

The most detailed study of the subsidence associated with CBM development in the PRB is Grigg's PhD dissertation, with details presented at the 2013 meeting of The Geological Sociaty of America (Grigg and Katzenstein, 2013). In this analysis of InSAR data for the PRB, the estimated subsidence from July 3, 1997 to July 27, 2000, was as large as 4.7cm; and from August 5, 2004 to July 26, 2007, it was as large as 8.3cm. Grigg and Katzenstein (2013) note that groundwater extraction for CBM production exceeds 94 million gallons per day and have modelled estimates of hydrogeological impact showing areas of greatest groundwater drawdown amounting to between 100 and 170 meters in head, and further concluded that the areas of greatest drawdown "*are spatially correlated with the major subsidence signals in each interferogram*". Grigg and Katzenstein (2013) conclude that the strong spatial correlation of land subsidence with drawdown of hydraulic head associated with the coalbed methane wells, amounts to "*sufficient evidence that subsidence is associated with CBM production in the Powder River Basin*".

A similar study of subsidence has been carried out in the area of CBM production in the San Juan Basin. This basin has been the largest producer of CBM in North America. Katzenstein (2012) found, from analysis of InSAR data, that dewatering of the coal seams has resulted in measurable (several cm) subsidence above the main area of CBM development.

5.5 Summary, Discussion and Conclusions

Two aspects of subsidence are important in considering whether it is likely to pose any threat to infrastructure or the natural environment. The first is the magnitude of the subsidence and the second is the area across which the subsidence is distributed. Subsidence will have little if any observable impact if gradual changes in magnitude occur over long spatial wavelengths. Damage to buildings and road pavement can occur where differential subsidence takes place on spatial scales equal or less that the buildings footprint. This localised focusing of subsidence depends on the existence of specific geological circumstances, such a sharp lateral changes in compressibility. One phenomenon that results in higher likelihood of subsidence resulting in damage to infrastructure and housing is the reactivation of faults, especially where the compactable layers have different thicknesses on each side of the fault. It should be noted that there have been no reports of any damage associated with the small amounts of subsidence measured in the PRB or in the San Juan basin.

Several reports have proposed that subsidence associated with CSG development is analogous to subsidence observed to follow production from conventional sandstone natural gas reservoirs. Pineda and Sheng (2013) in particular proposed calculating subsidence used equations developed by Geertsma (1973) to estimate subsidence. Hettema et al. (2001) presents several datasets for subsidence associated with gas production from conventional porous reservoirs. Each gas reservoir totalled on the order of 8 centimetres of subsidence over a few decades as the gas was produced. However these porous sand reservoirs have geomechanical characteristics distinctly different from coal reservoirs where the gas is largely absorbed on the surface of micro-pores. As a result, the type of models for subsidence based on compaction of a poro-elastic reservoir, developed by Geertsma (1973), are not appropriate for modelling the geomechanical response of coal to methane production. Most importantly gas reservoirs can have a relatively small surface footprint resulting in a distinct bowl-like area of subsidence. The subsidence associated with a mature CBM field measured by Grigg and Katzenstein (2013) in the PRB has a large spatial wavelength, covering an area of hundreds of square kilometres. Thus CSG development is highly unlikely to create "*subsidence bowls*" of the type referred to by Pineda and Sheng (2013).

Fear of damages from subsidence associated with CSG development in Australia may have become a potent issue causing concern amongst some stakeholders. Misinformation, disinformation or partial information may have become part of the scientific discourse. As noted in the introduction, Energy-Justice (2005) quoted congressional testimony on the consequences of CBM dewatering by Merschat (2001) as saying that "*there have been incidents where enormous quantities of water have been removed from shallow aquifers*", followed by "*as much as a 40-foot drop (or subsidence) in the surface of the land*". However the next sentence of testimony, not quoted by Energy Justice, states that the "*subsidence resulting from the CBM dewatering operations is anticipated to be minimal*" (Merschat, 2001). Similarly, a submission from NGO the Northern Illawarra Sustainability Alliance (NISA, 2011) to a NSW Parliamentary Coal Seam Gas inquiry included quotes from a story on the ABC 7:30 Report (ABC, 2011). This stated that an executive of "*the CSG company Bandanna Energy*" conceded that subsidence associated with the company's plans posed a subsidence risk. The NISA submission quoted a Bandanna executive as stating "*Substance [sic] could be anywhere from zero up to perhaps a metre, based on preliminary work*." The submission suggests that this "*comment illustrates the [CSG] industry's untested confidence*". The ABC report, however noted that Bandanna Energy is a coal exploration company attempting to establish a long-wall mining operation and is not involved in CSG development. Thus the one metre of subsidence estimate refers to the surface expression of long wall mining, not CSG development. Without extensive, multi-layered reference and citation reviews, such discrepancies are difficult to detect and incomplete reporting poorly informs public concerns.

Estimates of subsidence associated with future CSG development in Australia ranging from decimetres to ten metres that have been widely quoted. The subsidence values quoted by Williams et al. (2012), NSWCS (2013), and Garthwaite et al. (2013) range from 10 metres to several decimetres. The upper-side of the range of these subsidence estimates reviewed above, are one to two orders of magnitude larger than those actually observed in the US CBM fields (with newly developed, high resolution technology).

There are two approaches to estimating the nature and magnitude of future subsidence that will occur associated with the development of Australian CSG fields. The first is to use geomechanical based computer modelling. The second is to use data on actual subsidence measurements made for mature CBM fields in the US using InSAR. In fact, predictive modelling coupled with confirmatory measurements might be considered to be the best approach allowing calibration (history matching) of geological models which are necessarily loaded with assumptions and simplifications.

It is clear from the review of the geomechanical computer simulations of subsidence associated with gas production from coal that the resultant estimates of surface deformation are not reliable. The results are dependent both on the algorithm used to relate coal pore pressure to compaction and the choice of boundary conditions. The models that predicted the largest amounts of subsidence all included unrealistic assumptions. In the future accumulation of data from down-the-bore-hole extensometers combined with InSAR studies will enable refinement of geomechanical models and a better understanding of the nature and factors controlling compaction during dewatering.

In Queensland, particularly in the Surat Basin, companies pursuing CSG development are developing extensive monitoring networks including tiltmeters, extensometers, InSAR analysis, and geodetic survey monitoring. The recent baseline surface deformation measurements from December 2006 to February 2011 using InSAR by Duro et al. (2012) are consistent with the US observations. Duro et al. (2012) conclude that the Surat and Bowen basins are essentially stable with only minor surface deformation over the last five years. They note that only 0.3% of the points in their study have ground motion values greater than 15mm/year. They also note that none of the existing CSG fields correspond with measurable surface subsidence values.

In 2015, CSG operator Santos reported an INSAR update to the Australian Government, Department of the Environment … "*No direct correlation between ground deformation and exact locations of the CSG activities is evident and the localised displacements measured over the Santos GLNG CSG fields (accumulated values of up to 20 mm) are likely due to superficial processes in the soil.*" (Santos, 2015)

The Chief Scientist of NSW's report (NSWCS, 2013) concludes that "*given the early stages of the* [development of CSG in the Surat Basin]" there is no "*definitive confirmation of actual subsidence*" caused by CSG development. This review has found measured subsidence from in the USA fields with years CSG production over a long spatial wavelength of no greater than 9 cm. Of five recommendations in the Chief Scientist of NSW's preliminary report (NSW, 2013), the third is to carry out a "*pre-major-CSG*" subsidence baseline "*using appropriate remote sensing data*" followed by "a*n annual whole-of-State subsidence map*" so that any significant cumulative subsidence can be understood and addressed.

It is likely that the magnitude of subsidence associated with CSG development in the Surat Basin of Queensland will be broadly similar to that associated with the CBM fields in the US. The estimated that the annual withdrawal of water associated with CBM development is 1.3 x 10^{11} litres per year, based on the daily estimate of greater than 94 million gallons per day (Grigg and Katzenstein, 2013). In comparison USQ (2011) has estimated the total water production from the four CSG projects in the Surat basin will sum to 2.0 x 10^{11} litres per year for approximately 5 years. These water production rates are the same order of magnitude as those for the PRB and thus it is plausible to assume that the maximum subsidence rates associated with the Surat Basin projects will be similar, that is on the order of 0.02 to 0.05 metres per year for the 5 years of maximum withdrawal. If total maximum subsidence in the area of most intense water withdrawal tapers to zero over a spatial scale of the producing fields the *gradient* of subsidence will be negligible.

Overall, analysis of the information gathered in this paper suggests that subsidence is one of the lower risks associated with CSG development, a conclusion consistent with Geoscience Australia's initial advice to the Commonwealth Government (Goescience Australia & Hamermehl, 2010). Of the various approaches to estimating subsidence, the InSAR measurements associated with the mature CBM fields in the US are arguably the most reliable.

CHAPTER SIX:
Summing Up Working Paper

To paraphrase Cook et al. (2013), in the context of natural gas production from coal rather than shale, the CSG/CBM industry can have a significant impact on the landscape, ecosystems, on both surface and groundwater, on the atmosphere, and on communities. For all these reasons the nature and magnitudes of the changes brought about by this industry need to be carefully studied and understood. The criteria used by regulators to evaluate an industry’s performance should be based on rigorous scientific analysis. Both project operators and regulators need to have sufficient transparency with data relevant to environmental impacts that they can gain the public’s trust and establish a social license for the gas companies to initiate and continue development of the resource.

In the context of understanding the potential impact of CSG in Australia it is surprising that so little attention and emphasis has been given to the track record of CBM development in the US and Canada. The vast majority of discussion in Australia in government reports, academic commentary and internet blogs seems to have focused on information from shale gas development in the US. In almost all cases this comparison is inappropriate and misleading. Our study has argued that the vast literature on coal bed methane development in North America can go a long way to informing many of the concerns expressed about CSG development in Australia and indeed the veracity of initial modelling predictions. In this context it should be noted that scientifically documented evidence of significant environmental damages from the past three to four decades of CBM development in the US is very limited.

Understanding the role of legacy wells is likely to be important in evaluating methane contamination of groundwater. Monitoring methane and CO2 fluxes in soil around old water wells, coal borings and so on can help understand the spatial distribution and controls over natural gas migration. There are sufficient anecdotal reports of methane seeps, ebullition from lakes, streams and water wells, recorded prior to any CBM/CSG development to be assured that methane migration was present prior to gas field development. Based on a comprehensive study in Alberta and a review of US data, Armstrong et al. (2009) concluded that "*Gas migration impacts of limited extent have been documented in relation to [CBM] development from 'wet' coals in the USA*". As a broad generality their conclusion is supported by the available evidence.

The cumulative effects of dewatering associated with CSG on regional aquifers including potential impacts on stream flow have typically been identified as key topic for future study (Vink et al. 2008; Geoscience Australia & Habermehl, 2010). However the lesson from decades of study of large scale water flow in CBM basins in the US has been that such models may give highly misleading results unless model developments are preceded by detailed water chemistry fingerprinting of various aquifers utilising a variety of natural isotopic tracers, and a detailed understanding of the effective vertical permeability in the strata above and below the coal seams being dewatered and of the detailed heterogeneity of both horizontal and vertical permeability.

This paper has reviewed a wide range of approaches to mitigation of potential environmental issues associated with development of natural gas reservoirs in coal seams. One challenge to project developers is to layout the well sites and infrastructure in such a way that the impacts are minimised. Understanding the issues that have occurred in US and Canadian CBM fields can provide guidance to industry and government in Australia in dealing with the complex environmental challenges posed by CSG development

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