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Independent Expert Scientific Committee
on Coal Seam Gas and Large Coal Mining Development

Australian Government
Department of the Environment

Background review

Subsidence from coal seam gas extraction in Australia

This background review was commissioned by the Department of the Environment on the advice of the Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining. The review was prepared by Sinclair Knight Merz Pty Ltd and revised by the Department of the Environment following peer review.

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Acknowledgements

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Addendum

Changes to state government departments have occurred since the finalisation of this report by the authors. The Queensland, New South Wales and South Australian Government agencies were contacted and updated information provided in September 2013; however, no guarantees can be made as to the completeness of these updates. Up-to-date information should be sourced from the relevant department.

On 1 January 2013, the Queensland Water Commission (QWC) ceased operations. The Office of Groundwater Impact Assessment (OGIA) retains the same powers as the former QWC under Chapter 3 of the *Water Act 2000* (Qld).

Sinclair Knight Merz Pty Ltd is now Jacobs SKM.

Contents

Summary

This report provides an overview of Australian and international experiences of subsidence and other ground-related movements as a result of coal seam gas extraction, including the methods used to predict the magnitude of subsidence and to subsequently measure that subsidence.

Where large quantities of groundwater are extracted during the coal seam gas extraction process, one of the possible consequences is compaction caused by depressurisation of the coal seam, settlement due to the increased effective stress this generates within the overlying strata and subsidence at the ground surface.

Key points

- Where large quantities of groundwater are extracted during the coal seam gas process, it may lead to a drop or subsidence in the ground surface.
- While there is no confirmed subsidence resulting from coal seam gas development in Australia, the maximum predicted is 850 mm with subsidence gradients of between 100 to 200 mm over 2 km.
- This compares with observed subsidence of up to 83 mm over three years in the United States.
- The predicted subsidence and hence impacts from coal seam gas development are relatively small compared with long wall coal mining. But small movements can be significant in some circumstances and so need to be assessed on a case-by-case basis.
- Predictions are constrained by the absence of observed subsidence and empirical relationships.
- Techniques are available to monitor subsidence; a mixture is preferred to capture the effects at different scales.
- Effective remediation options are limited.

Factors that influence subsidence from coal seam gas extraction

Subsidence associated with coal seam gas is a function of groundwater depressurisation and matrix compressibility of the coal seams and adjacent (overlying and underlying) formations. This is in contrast to coal mining subsidence which is dominated by the physical collapse of strata at depth.

Subsidence is also influenced by the hydraulic connection between the coal seams and adjoining strata, as this will affect the amount of depressurisation and hence the amount of compaction that occurs in these strata. In addition, competent (strong) strata in the overlying sequence can bridge the settlement effects in the coal seam and reduce propagation of the settlement to the surface.

Given the above factors, subsidence is least likely where gas recovery involves minimal volumes of co-produced water, there is limited connectivity between the coal seams and adjoining formations, and the overlying strata are dominated by sandstone and other more competent rocks.

Subsidence estimates and observations

The impact assessments reviewed in this report generally predict subsidence to be minimal. There is no confirmed subsidence resulting from coal seam gas development in Australia, whilst subsidence amounts of up to 83 mm over three years have been observed in the US. In the Surat coal basin in Queensland, company estimates of potential vertical subsidence range from 30 to 850 mm.

Current estimates of potential subsidence gradients across coal seam gas fields range from 100 mm over 2 km (a slope of some 0.005 per cent) to 200 mm over 2 km (a slope of some 0.01 per cent). While this is significantly less than subsidence induced by longwall mining, coal seam gas fields may cover the entire aerial extent of the underground coal seam being targeted and hence may extend over hundreds of square kilometres. Estimates of subsidence are within the natural variability of landscape processes, but significant local effects may arise if variability in the fabric of the landscape results in highly compressible materials propagating their compaction to the surface.

Subsidence prediction and monitoring

There is a long history within Australia of predicting subsidence from underground coal mining by using empirical relationships based on observed subsidence. There is, as yet, insufficient observational information to develop similar relationships to predict subsidence from coal seam gas extraction. A concerted effort is required to gather such information. Numerical groundwater flow models are commonly used to support predictions of subsidence induced by depressurisation of coal seams. They assist in estimating pore fluid reduction and hence the maximum settlement potential. Reservoir simulation models are also used for a wide range of coal seam gas modelling, including estimation of settlement potential.

A number of techniques that apply at varying scales are available to measure land subsidence. Of these, a mixture of broad regional methods combined with local, finer scale measurements are required to cover the large areas that might be affected by coal seam gas development. The technique of choice by coal seam gas developers to date has been the satellite-based remote sensing method ‘InSAR’ combined with local extensometer measurements.

Subsidence impacts and assessment

Due to the broad spatial nature of the predicted subsidence, combined with the relatively small magnitudes of total and differential settlement anticipated, there is expected to be less risk to built infrastructure from subsidence associated with coal seam gas extraction, and any associated groundwater extraction in rural regions, than from longwall coal mining. Even in more densely built up urban areas, given the small magnitudes of total and differential settlement anticipated, the risk of either cosmetic or structural damage to infrastructure, such as roads and buildings, is anticipated to be low. However, each coal seam gas project needs to be assessed on a case-by-case basis because the spatial and temporal conditions are complex and highly variable. Small subsidence impacts may be significant in some cases. Fortunately, the techniques available to monitor for subsidence have reasonable efficacy in detecting ground movement, both at the regional scale and at the site-specific scale, so early warning indicators should be feasible.

Whilst the impact assessments reviewed in this report generally predict subsidence to be minor, it has been suggested that even small changes to the land surface due to subsidence may alter the overland flow paths in rivers and wetlands, potentially initiating new erosion features in susceptible areas. Subsidence may also change the hydraulic properties of affected aquifers, cause localised faulting and fracturing in aquifers, and/or alter the hydraulic connection within and between aquifers and aquitards.

Coal seam gas companies are required to undertake groundwater impact assessments and measure and evaluate the potential for subsidence. Environmental concerns have resulted in a number of approval conditions being applied to coal seam gas developments under the *Environment Protection and Biodiversity Conservation Act 1999* (Cwlth). The Queensland Coordinator General has also imposed a number of subsidence-related conditions. Relevant conditions include the requirement for the monitoring of subsidence due to extraction of groundwater for coal seam gas, provision of a subsidence management plan and remediation of subsidence.

Remediation

The only effective remediation process for regional subsidence from coal seam gas development is to reduce groundwater pumping and return the system to pre-development water pressures. While reducing groundwater pumping is a relatively common remediation method where excessive groundwater extraction has caused subsidence, the capacity of this process to reverse the effects of subsidence caused by coal seam gas extraction is as yet untested and would be heavily dependent on the geological properties of the affected rock strata. In addition, groundwater extraction is necessary to reduce hydraulic pressures within the coal seams to enable coal seam gas to flow and be extracted via the gas wells. Given this, repressurising confined aquifer systems by artificial recharge directly through bores may appear to be the only practical way to slow down or stop land subsidence; however, it too can only be effectively undertaken if gas extraction ceases.

The groundwater that is extracted to obtain coal seam gas (known as co-produced water) must be managed, and coal seam gas companies in Queensland are investigating the feasibility of re-injecting the co-produced water back into geological formations as a means of disposal. However, this will not necessarily provide an effective treatment for limiting potential subsidence impacts because of factors affecting preferred locations and depths of reinjection – including the need to maintain low hydraulic pressures in the producing coal seams as mentioned above. It is also unlikely to be in the interests of the coal seam gas companies to develop wells in areas where there is a high level of connectivity between the coal seams and adjoining formations, as this results in increased costs associated with extracting, treating and discharging the additional co-produced water.

Abbreviations

General abbreviations	Description
ABARE	Australian Bureau of Agricultural and Research Economics
CBM	Coal bed methane
CH_4	The chemical formula for methane
cm	Centimetres
CO_2	The chemical formula for carbon dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSG	Coal Seam Gas
EIS	Environmental Impact Statement
EPA	Environment Protection Authority
EPBC Act	*Environment Protection and Biodiversity Conservation Act 1999*
GA	Geoscience Australia
GAB	Great Artesian Basin
GL	Gigalitres (1000 million litres)
GPS	Global Positioning System
IESC	Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development
InSAR	Satellite Interferometric Synthetic Aperture Radar
JAXA	Japanese Space Agency
LiDAR	Light Detection and Ranging
LNG	Liquefied Natural Gas
L/s	Litres per second
m	Metre
mD	Millidarcys
MDB	Murray-Darling Basin
ML	Megalitres (1 million litres)
mm	Millimetres
MNES	Matters of National Environmental Significance
MPa	Megapascal
NSW	New South Wales
OWS	Office of Water Science
PJ	Petajoules
PVC-U	Polyvinyl Chloride - Unplasticised

General abbreviations	Description
RADAR	Radio Detection and Ranging
US EPA	United States Environmental Protection Agency
US	United States of America
WCM	Walloon Coal Measures
°	Degree

Glossary

Term	Description
Adsorption	Adsorption is the reversible binding of molecules to a particle surface. This process can bind methane and carbon dioxide, for example, to coal particles.
Analytical or numerical methods	Methods based on applying mathematical solutions derived from first principles to calculate how the rock mass will behave when an excavation is made within it.
Aquifer	Rock or sediment in formation, group of formations or part of a formation, that is saturated and sufficiently permeable to transmit quantities of water to wells and springs.
Aquifer connectivity	The degree to which groundwater can transfer between two adjacent aquifers or to the surface.
Aquifer recharge	The amount of water replenishing an aquifer over a given time period.
Aquitard	A saturated geological unit that is less permeable than an aquifer and incapable of transmitting useful quantities of water. Aquitards often form a confining layer over an artesian aquifer
Artesian	Pertaining to a confined aquifer in which the groundwater is under positive pressure (i.e. a bore screened into the aquifer will have its water level above-ground).
Bore/borehole	A narrow, artificially constructed hole or cavity used to intercept, collect or store water from an aquifer, or to passively observe or collect groundwater information. Also known as a borehole, well or piezometer.
Casing	A tube used as a temporary or permanent lining for a bore. Surface casing: the pipe initially inserted into the top of the hole to prevent washouts and the erosion of softer materials during subsequent drilling. Surface casing is usually grouted in and composed of either steel, PVC-U, or composite materials. Production casing: a continuous string of pipe casings that are inserted into or immediately above the chosen aquifer and back up to the surface through which water and/or gas are extracted/injected.
Cleats - butt cleats	Fractures that are perpendicular, or at a high angle, to the coal seam bedding planes.
Cleats - face cleats	Thin fractures that are perpendicular, or at a high angle, to the coal seam bedding planes but also orthogonal to the butt cleats.
Coal seam	Sedimentary layers consisting primarily of coal. Coal seams store both groundwater and gas and generally contain saltier groundwater than aquifers that are used for drinking water or agriculture.
Coal seam gas	A form of natural gas (generally 95 to 97 per cent pure methane, CH_4) typically extracted from permeable coal seams at depths of 300 to 1000 m.
Compaction	The process by which geological strata under pressure reduce in thickness and porosity, and increase in density.
Compressibility	A parameter that determines the potential for compaction. Compressibility

Term	Description
	is typically high for soft clays, intermediate for sands, low (but variable) for coals, very low for consolidated sedimentary rocks such as sandstones and mudstone, and extremely low for competent rocks such as granites and other intrusions.
Compression	A system of forces or stresses that tends to decrease the volume or shorten a substance, or the change of volume produced by such a system of forces.
Confined aquifer	An aquifer that is isolated from the atmosphere by an impermeable layer. Pressure in confined aquifers is generally greater than atmospheric pressure.
Co-produced water	The water that is pumped out of coal seams in order to extract coal seam gas. Also referred to as produced water and associated water. Over time, the volume of produced water normally decreases and the volume of produced gas increases.
Darcy flow equation	The equation that describes the rate and quantity of groundwater flow.
Deformation modulus	The ratio of stress to corresponding strain during loading of a rock mass, including elastic and inelastic behaviour.
Depressurisation	The lowering of static groundwater levels through the partial extraction of available groundwater, usually by means of pumping from one or several groundwater bores.
Desorption	The release of a bound molecule from a host particle into a flowing medium such as a liquid or gas.
Dewatering	The lowering of static groundwater levels through complete extraction of all readily available groundwater, usually by means of pumping from one or several groundwater bores.
Drawdown	The reduction in groundwater pressure caused by extraction of groundwater from a confined formation, or the lowering of the water table in an unconfined aquifer.
Effective stress	Stress applied between the solid matrix materials of rocks and soils. The effective stress of a reservoir or coal seam is the difference between the total stress and the pore pressure.
Extensometer	A stationary instrument set in a borehole that measures vertical movement within the borehole and hence gives a measure of subsidence in time at a single location.
Flowback water	The fluid that flows back, or is pumped back, to surface following hydraulic fracturing but prior to gas production.
Formation water	A term used largely within the petroleum industry for groundwater that occurs within petroleum or gas reservoirs.
Groundwater	Water occurring naturally below ground level (whether in an aquifer or other low permeability material), or water occurring at a place below ground that has been pumped, diverted or released to that place for storage there. This does not include water held in underground tanks, pipes or other works.
Groundwater injection bore	A bore installed to facilitate the injection of liquid (for example, H_20) or gas (for example, CO_2) into an aquifer. Commonly used in Managed Aquifer Recharge schemes or groundwater remediation.
Groundwater	A bore installed to: determine the nature and properties of subsurface

Term	Description
monitoring/observation bore	groundwater conditions; provide access to groundwater for measuring level, physical and chemical properties; permit the collection of groundwater samples; and/or to conduct aquifer tests.
Groundwater pumping/production bore	A bore installed with the primary purpose to extract groundwater for productive use from a particular hydrogeological formation.
Hydraulic conductivity	The rate at which a fluid passes through a permeable medium.
Hydraulic fracturing	Also known as 'fracking', 'fraccing' or 'fracture simulation', is the process by which hydrocarbon (oil and gas) bearing geological formations are 'stimulated' to enhance the flow of hydrocarbons and other fluids towards the well. The process involves the injection of fluids, gas, proppant and other additives under high pressure into a geological formation to create a network of small fractures radiating outwards from the well through which the gas, and any associated water, can flow.
Hydraulic gradient	The change in hydraulic head between different locations within or between aquifers or other formations, as indicated by bores constructed in those formations.
Hydraulic head	The potential energy contained within groundwater as a result of elevation and pressure. It is indicated by the level to which water will rise within a bore constructed at a particular location and depth. For an unconfined aquifer, it will be largely subject to the elevation of the water table at that location. For a confined aquifer, it is a reflection of the pressure that the groundwater is subject to and will typically manifest in a bore as a water level above the top of the confined aquifer, and in some cases above ground level.
Hydraulic pressure	The total pressure that water exerts on the materials comprising the aquifer. Also known as pore pressure.
Hydrostatic pressure	The theoretical pore pressure that would be expected purely from the weight of the overlying rocks on the water in formations.
InSAR	Satellite Interferometric Synthetic Aperture Radar - is a remote sensing technique that uses radar signals to interpolate land surface elevation changes.
Intergranular pressure	The pressure exerted between the grains of a material.
Langmuir isotherm	Describes the relationship between pressure and adsorption. It is used to determine the level of gas saturation and the pressure required to initiate gas desorption within a coal seam. The Langmuir isotherm is used to help determine the financial viability and economic value of the gas return for a coal seam gas field or bore.
LiDAR	Light Detection and Ranging – a remote sensing method used to examine the surface of the Earth.
Macropores	The spaces within the cleat system and other natural fractures in the coal matrix. They are responsible for transport of water and methane through seams. Less than 10 per cent of the gas content, however, resides in macropores (mainly as free gas).
Micropores	The capillaries and cavities at molecular dimensions in the coal matrix that are essential for gas storage in the adsorbed state.
MODFLOW	A 'finite difference' numerical groundwater flow modelling code.

Term	Description
Overburden	Material of any nature, consolidated or unconsolidated, that overlies a deposit of useful materials such as ores or coal, especially those deposits that are mined from the surface by open-cut methods.
Permeability	The measure of the ability of a rock, soil or sediment to yield or transmit a fluid. The magnitude of permeability depends largely on the porosity and the interconnectivity of pores and spaces in the ground.
Pore-fluid pressure/pore pressure	See Hydraulic Pressure.
Porosity	The proportion of the volume of rock consisting of pores, usually expressed as a percentage of the total rock or soil mass.
Production well	A well drilled to produce oil or gas.
Proppant	A solid material, typically treated sand or man-made ceramic materials, designed to keep an induced hydraulic fracture open, during or following a fracturing treatment.
Radioactive bullet logging	A method used to measure compaction and/or extension of a formation that involves shooting radioactive bullets into a formation at known depths and later surveying the bullets to monitor any changes in position.
RADAR	Radio Detection and Ranging – an object-detection system that uses radio waves to determine the range, altitude, direction or speed of objects.
Reinjection bores	See Groundwater injection bores.
Screen	The intake portion of a bore, which contains an open area to permit the inflow of groundwater at a particular depth interval, whilst preventing sediment from entering with the water.
Settlement	Unless otherwise specified, is the vertical displacement of strata in response to compaction or removal of underlying strata.
Shearing	The relative, near horizontal or low angle movement between two sections of a rock stratum or a number of strata due to failure of the rock along a shear plane.
Specific storage	The amount of water that a portion of an aquifer releases as a result of changes in the hydraulic head usually through pumping.
Specific yield	A ratio indicating the volume of water that an aquifer will yield when all the water is allowed to drain out of it under the forces of gravity.
Storativity	A dimensionless ratio that relates to the volume of water that is released per unit decline in pressure head for a defined vertical thickness of the formation.
Subsidence	Usually refers to vertical displacement of a point at or below the ground surface. However, the subsidence process actually includes both vertical and horizontal displacements. These horizontal displacements, in cases where subsidence is small, can be greater than the vertical displacement. Subsidence is usually expressed in units of millimetres (mm).
Tension	A system of forces which stretch rocks in two opposite directions. The rocks become longer in a lateral direction and thinner in a vertical direction. One important result of tensile stress is that it creates joints or fractures in the rock. Tensile stress is rare because most subsurface stress is compressive, due to the weight of the overburden.
Tilt	The change in the slope of the ground as a result of differential

Term	Description
	subsidence. It is calculated as the change in subsidence between two points divided by the distance between those points. Tilt is usually expressed in units of millimetres per metre (mm/m), or as a ratio of rise to run (mm:mm). A tilt of 1 mm/m is equivalent to a change in grade of 0.1 per cent.
Unconfined aquifer	An aquifer which has the upper surface connected to the atmosphere.
Vadose zone	The ‘unsaturated’ zone, extending from the top of the ground surface to the water table. In the vadose zone, the water in the soil's pores is at atmospheric pressure.
Water quality	The physical, chemical and biological attributes of water that affects its ability to sustain environmental values.
Water table	The upper surface of a body of groundwater occurring in an unconfined aquifer. At the water table, pore water pressure equals atmospheric pressure.
Well	A human-made hole in the ground, generally created by drilling, to obtain water (also see bore).
Yield	The rate at which water (or other resources) can be extracted from a pumping well, typically measured in litres per second (L/s) or megalitres per day (ML/d).

1 Introduction

This background review is one of a number commissioned by the Department of the Environment on the advice of the Interim Independent Expert Scientific Committee on Coal Seam Gas and Coal Mining. These reviews aim to capture the state of knowledge on the water-related impacts of coal seam gas extraction and large coal mining, but do not aim to provide detailed analysis and evaluation of methods for identifying and managing impacts, or to develop such methods.

The focus of this report is on subsidence issues associated with coal seam gas extraction including:

- the different causes of subsidence
- technology and tools for monitoring, measuring and assessing the extent of subsidence
- models to predict the scale and extent of subsidence
- remediation options.

This report provides a summary and synthesis of the relevant and available literature and the expert opinions of the authors. It focuses on issues directly relevant to coal seam gas extraction in Australia whilst issues associated with convention oil and gas production, carbon sequestration and groundwater extraction, and with shale gas extraction in northern America, are discussed only where relevant.

The report presents a general overview of coal seam gas extraction and subsidence, including the hydrogeological settings under which coal seam gas production takes place, the extraction systems, gas desorption and their impacts on groundwater. The causes and effects of subsidence associated with dewatering, depressurising and hydraulic fracturing are investigated, and an overview of the theoretical and analytical considerations associated with predicting and assessing this form of subsidence is presented. Several recent groundwater impact assessments for major coal seam gas developments are discussed, along with issues related to gas extraction and the propagation of subsidence effects. The report then presents a review of techniques for modelling the impacts of coal seam gas subsidence on surface and groundwater resources. It also presents a comparison and review of techniques and technologies for monitoring and assessing the extent of subsidence caused by coal seam gas extraction. The limited options currently available for remediation are briefly considered. The report concludes with a section summarising the findings of the review and lists a number of knowledge gaps identified during the review process.

2 Understanding coal seam gas extraction and subsidence

2.1 Overview

This section provides a general overview of coal seam gas extraction and subsidence issues, including the hydrogeological settings under which coal seam gas production takes place, the extraction systems, gas desorption and their impacts on groundwater.

2.2 Coal seam gas extraction in Australia

Coal seam gas is a naturally occurring gas consisting primarily of methane that occurs in underground coal seams (BREE 2013; Williams et al. 2012; Rutovitz 2011). The gas is adsorbed into the solid matrix of the coal and held in place by pressure exerted by both the weight of the overlying geological formations and the pressure of the groundwater that permeates the coal seams (Freij-Ayoub 2012; GA & ABARE 2010; Miyazaki, 2005). Coal seam gas is extracted by removing the groundwater via wells, which decreases the pressure in the coal seam, releasing the gas from within the coal matrix. Once extracted, the gas can be used for the same purposes as conventional natural gas. The water produced as a by-product during the extraction of coal seam gas is often referred to as ‘co-produced’ or ‘associated’ water (CSIRO 2012a).

Coal seam gas production has a substantial history in the United States of America (US) where it is termed coal bed methane (CBM), with production occurring since the 1970s. In Australia, by comparison, the industry is relatively young, with coal mine methane being produced from the abandoned Sydney Harbour colliery between 1943 and 1949 and the gas sold for industrial and motor fuel (Miyazaki 2005). Commercial production first commenced in 1996 in the Bowen Basin, Queensland (Freij-Ayoub 2012; AER 2010), and in 2001 in the Camden area of the Sydney Basin, New South Wales (AGL 2013). Commercial production has since expanded across Queensland targeting the Surat Basin and Clarence-Moreton Basin. In New South Wales, production is occurring in the Sydney Basin and Gunnedah Basin and resources have been identified in the Clarence-Moreton Basin and Gloucester Basin (Figure 1).

Australia holds significant gas resources, including some six per cent of the world’s coal seam gas, producing in the order of 252 Petajoules (PJ) in 2012 – 8.9 per cent of coal seam gas production globally (BREE 2013; GA & BREE 2012). Coal seam gas is now an integral part of the gas industry in eastern Australia, particularly in Queensland where coal seam gas accounts for 80 per cent of all natural gas use (DNRM 2012; Freij-Ayoub 2012). Of the 2010-11 production of coal seam gas, Queensland produced 97 per cent of Australia’s total coal seam gas production from the Bowen and Surat basins, with New South Wales accounting for the remainder (GA & BREE 2012). Latest market analysis suggests that Queensland’s Surat and Bowen basins contain 92 per cent of Australia’s available coal seam gas reserves (Figure 2; BREE 2013). The location of Australia’s conventional and coal seam gas resources and associated production figures are shown in Figure 3.

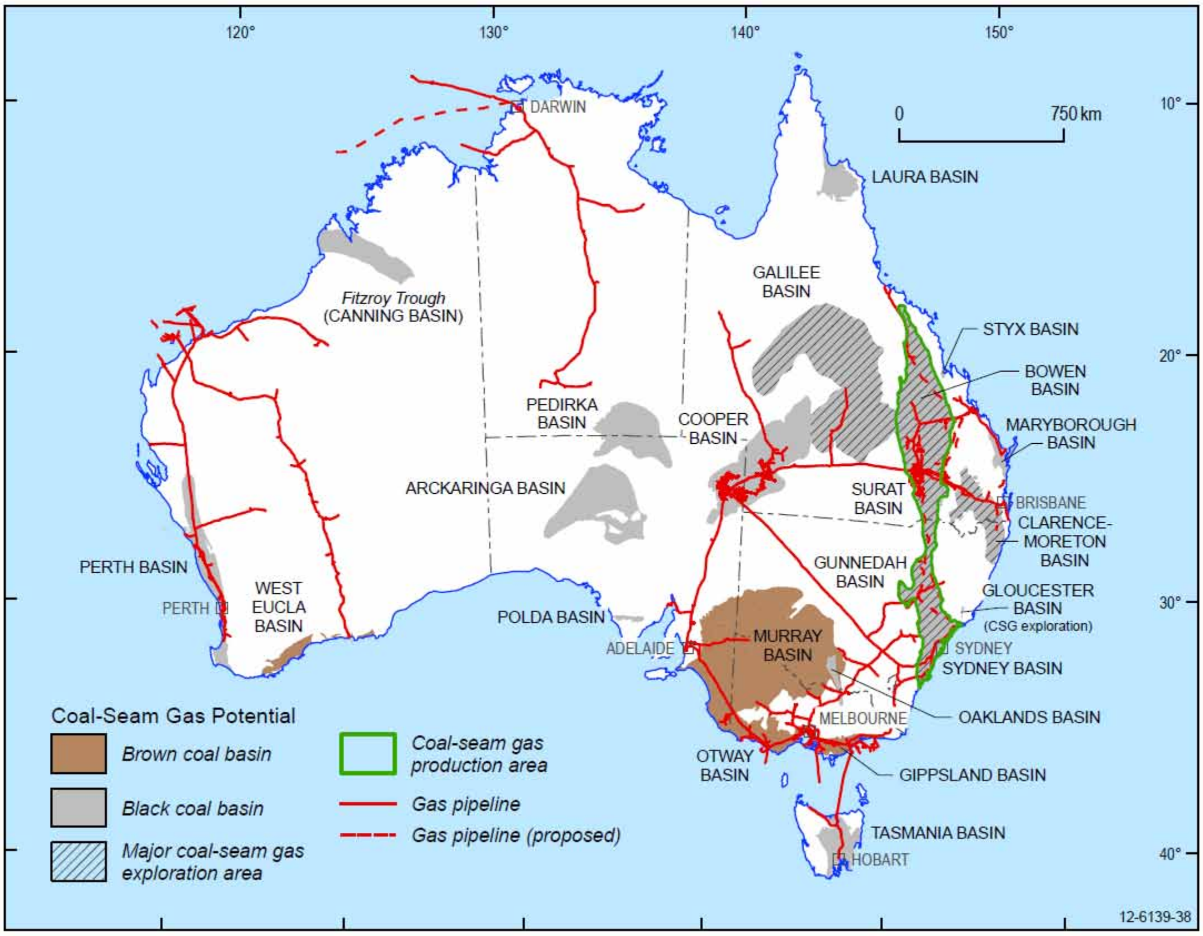


Figure 1 Australian coal basins with coal seam gas potential (© Copyright, GA & BREE 2012).

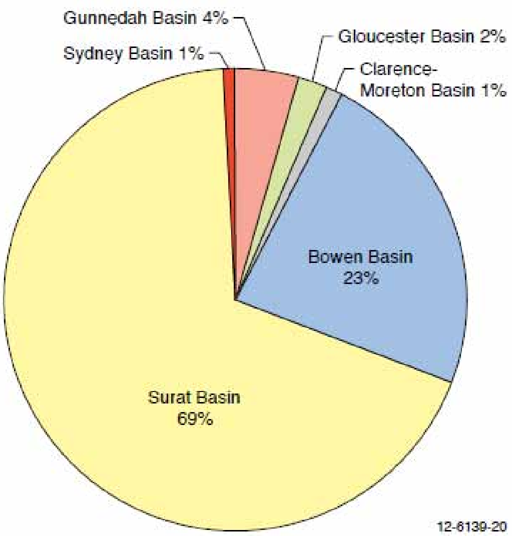


Figure 2 Australian coal seam gas reserves, proven and productive, by coal basin (© Copyright, BREE, 2013; GA & BREE 2012).

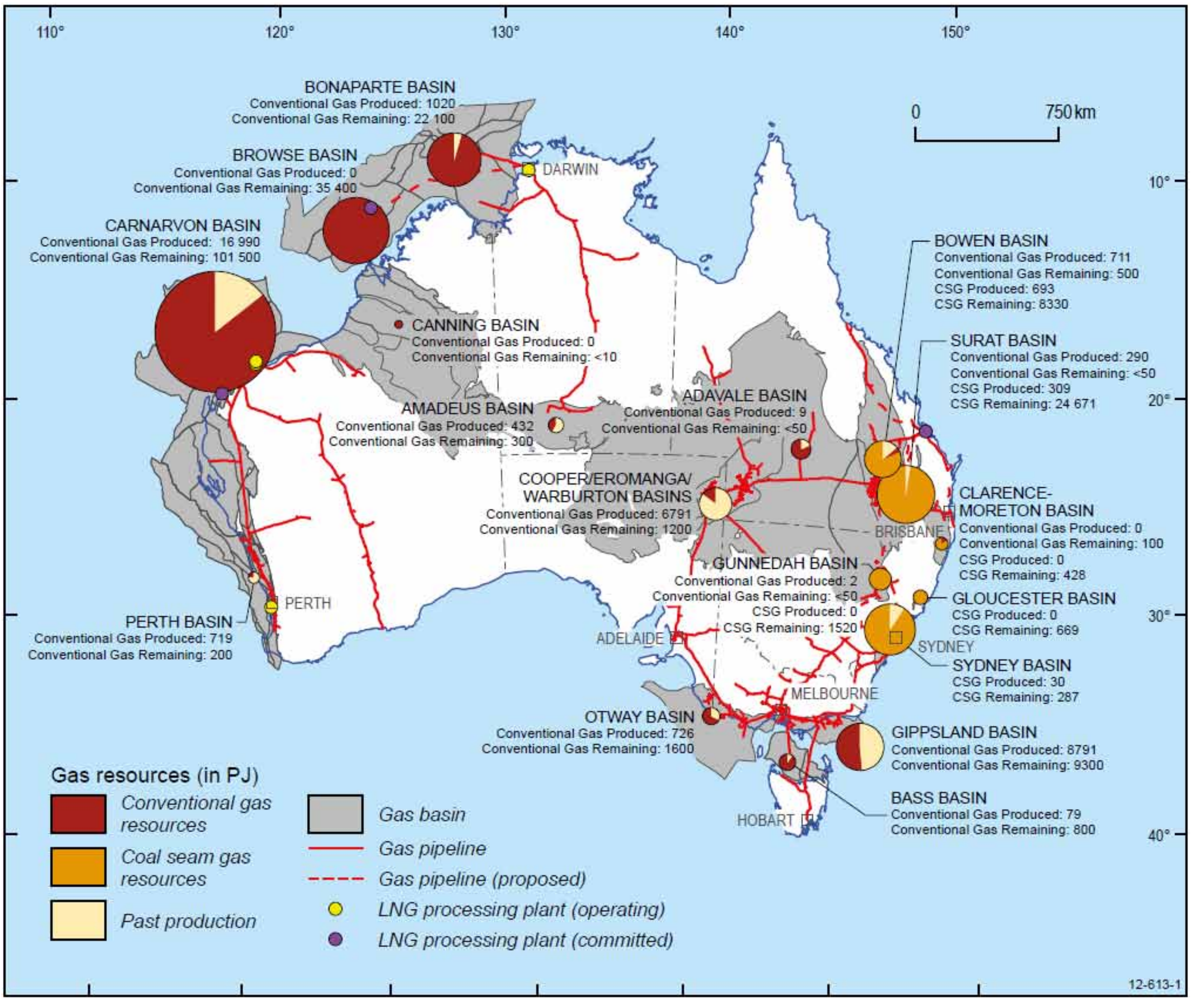


Figure 3 Location of conventional and coal seam gas resources in Australia, and associated production (© Copyright, BREE 2013; GA & BREE 2012).

2.3 Coal seam gas extraction and subsidence

Coal seam gas extraction involves the extraction of groundwater via coal seam gas well to facilitate depressurisation (reducing groundwater levels with consequent lowering of groundwater pressure) of the target coal seam (Figure 4). This depressurisation can cause compaction of the targeted coal measure in the vicinity of the well and any similarly affected aquifers above or below the coal seam. This can, in turn, lead to settlement at the ground surface – a process described as ‘subsidence’.

In some geological settings, the extraction of economic supplies of coal seam gas from coal beds may require more extensive depressurisation of the formations containing the coal. This is generally achieved through local and regional groundwater extraction through multiple wells, leading to compaction of the depressurised zones and potentially to subsidence at the surface. The local response to this compaction is dependent on the local geological conditions and is difficult to predict, but may have consequences for surface infrastructure, water-courses and agriculture (Williams et al. 2012; Rutovitz et al. 2012; Moran & Vink 2010).

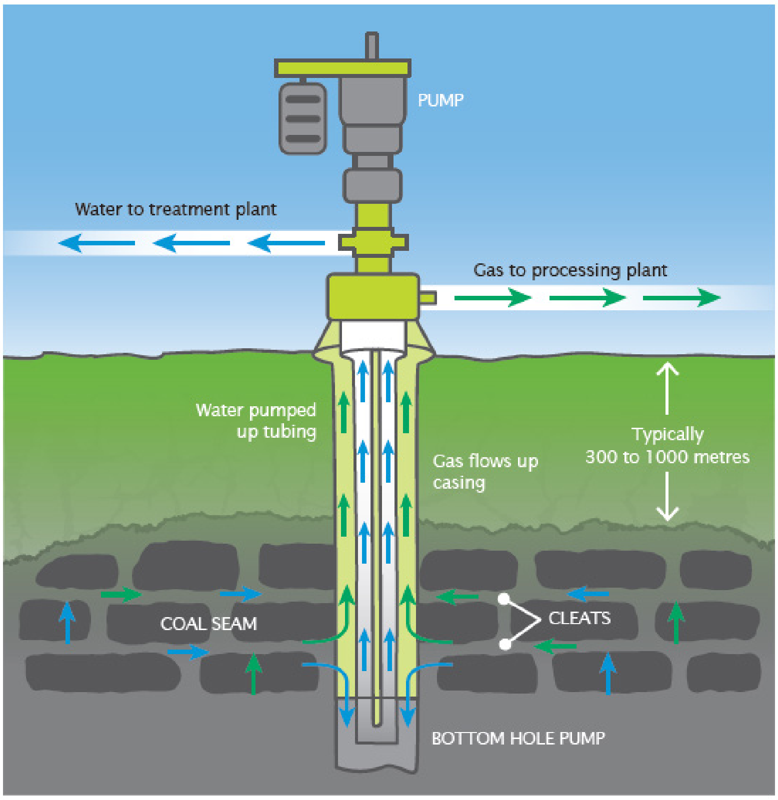


Figure 4 Schematic diagram of the coal seam gas extraction process, showing gas and groundwater extraction (© Copyright, CSIRO 2012a).

There is no confirmed subsidence resulting from coal seam gas development in Australia (NSW Chief Scientist & Engineer 2013). Also, whilst large areas of Queensland have been subject to coal seam gas exploration and development, and significant expansion is planned for both Queensland and New South Wales, the maximum magnitude of ground surface settlement is expected to be less than 850 mm for currently proposed developments (Australia Pacific LNG 2013; Altimara 2012; Coffey Environments 2012; QGC 2012; Santos 2012a; Santos 2012b; WorleyParsons 2010; Golder Associates 2009a; Golder Associates 2009b; MatrixPlus 2009). However, there remains a risk of more significant subsidence due to coal seam gas production in certain hydrogeological conditions such as where water table lowering could occur at or close to the surface within poorly consolidated sediments; or where geological conditions favour differential movement.

2.4 Cumulative impacts

As large numbers of bores are required for optimum production, there is concern about the cumulative impact of multiple bores pumping from the same horizon, each contributing to a regional depressurisation (Freij-Ayoub 2012; QWC 2012a, 2012b, 2012c; Williams 2012; USQ 2011; Rutovitz et al. 2011). Critically, the depressurisation of coal seams may induce depressurisation of adjoining beds which may be of economic and environmental value (Moran & Vink 2010; Hillier 2010). This has two critical aspects:

- pore pressure is not only reduced in the coal seams but also in adjoining beds, helping propagate any subsidence effects
- as water is drawn from adjoining beds into the coal seams more groundwater needs to be pumped from the coal measures to maintain the required pressure, further exacerbating the potential for associated depressurisations.

For these reasons, the gas companies restrict drawdown to the confined coal seams as interference with over and underlying units results in lost pressure and hence, lost revenue. With regard to subsidence calculations, however, consideration of all coal seam gas and related groundwater extractions, and all affected beds in an aquifer and aquitard sequence, should be considered as contributing to any subsidence effects at the surface (Botha & Coot 2004; Biot 1941; Meizner 1928).

3 The hydraulics and geomechanics of subsidence

3.1 Overview

This section of the review investigates the causes and effects of subsidence associated with dewatering, depressurising and hydraulic fracturing, including the hydraulic and geomechanical processes involved in subsidence.

3.2 Depressurisation effects

The depressurisation processes described in the literature, caused by local and regional groundwater extraction associated with coal seam gas extraction, is likely to result in a geological response: compaction of the depressurised zones and potential related subsidence at the surface. This subsidence is thought likely to be proportional to the compressibility of the material being depressurised. Compressibility is typically high for soft clays, intermediate for sands, low (but variable) for coals, very low for consolidated sedimentary rocks such as sandstones and mudstone, and extremely low for rocks such as granites and other intrusives (Hoek 1966; Domenico & Mifflin 1965). The magnitude of the surface settlement will depend on the magnitude and extent of compression in the sub-surface. This in turn depends on the compressibility of the depressurised beds, the thickness and strength of the overburden and other factors such as the natural stress within the rock mass. Estimates from various companies extracting coal seam gas of subsidence gradients across their respective gas fields range between 60 mm to 300 mm over 2 km, giving an estimated angle of tilt of between 0.003 and 0.15 per cent (Altimara 2012; QGC 2012; Santos 2012; Australia Pacific LNG 2011; Golder Associates 2009c).

Coal seam gas fields may cover the aerial extent of the underground coal seam being targeted and hence may extend over hundreds of square kilometres with multiple bores at variable spacings. The requirement to depressurise the seam to release the gas means that extensive areas may be affected, in contrast to most coal mining operations where depressurisation generated from dewatering is commonly focused around the mine. Depressurisation across a coal seam gas field is comparable to dewatering and depressurisation of aquifers for other purposes (Tenthorey et al. 2013; Wilson et al. 2012; Rutqvist et al. 2010). A critical requirement for economic recovery of coal seam gas is to have an effective hydraulic seal above and below the target seam hence the propagation of depressurisation effects is largely contained to the confined aquifer and impacts on adjoining aquitards and aquifers are minimised.

Subsidence associated with coal seam gas is essentially a function of groundwater depressurisation and matrix compressibility of the coal seam and adjacent formations (Freij-Ayoub 2012; Moore 2012; Nelson 2012). This is in contrast to coal mining subsidence, which is dominated by the physical collapse of strata at depth and the accommodation and infilling of the voids by materials from above (Poulsen & Shen 2013; Nelson 2012; Shen et al. 2010). It may be more appropriate to consider settlement caused by coal seam gas rather than subsidence. Coal seam gas related settlement is created through intergranular adjustment at the micro-scale and settlement of any overlying layers (Freij-Ayoub 2012; Moore 2012). Further, there may be limited hydraulic connectivity between the coal seam and overlying beds and competent, or strong, units in the overlying sequence. Consequently, there is potential for overlying competent beds to bridge the settlement effects in the coal seam. This would reduce propagation of the settlement to the surface. Actual surface subsidence is most likely only where a sequence has a high proportion of compressible materials such as clays and peats and high water pressures such as in areas of high artesian conditions. The role that local and regional faulting might play in this process is, however, largely unknown and represents a knowledge gap (IESC 2013). Settlement is least likely where gas recovery involves minimal co-produced water and the overlying sequences of geological formations are dominated by sandstone and other more competent rocks.

3.3 Coal porosity and pore collapse

Coal seams are characterised by dual porosity. They contain both micropores (known as primary porosity) and macropores (known as secondary fracture porosity). Macropores are the spaces within the cleat system, bedding joints, shears and other natural fractures; and are responsible for transport of water and methane through seams (Freij-Ayoub 2012).

Less than 10 per cent of the gas content is free gas that resides in macropores (Figure 5).

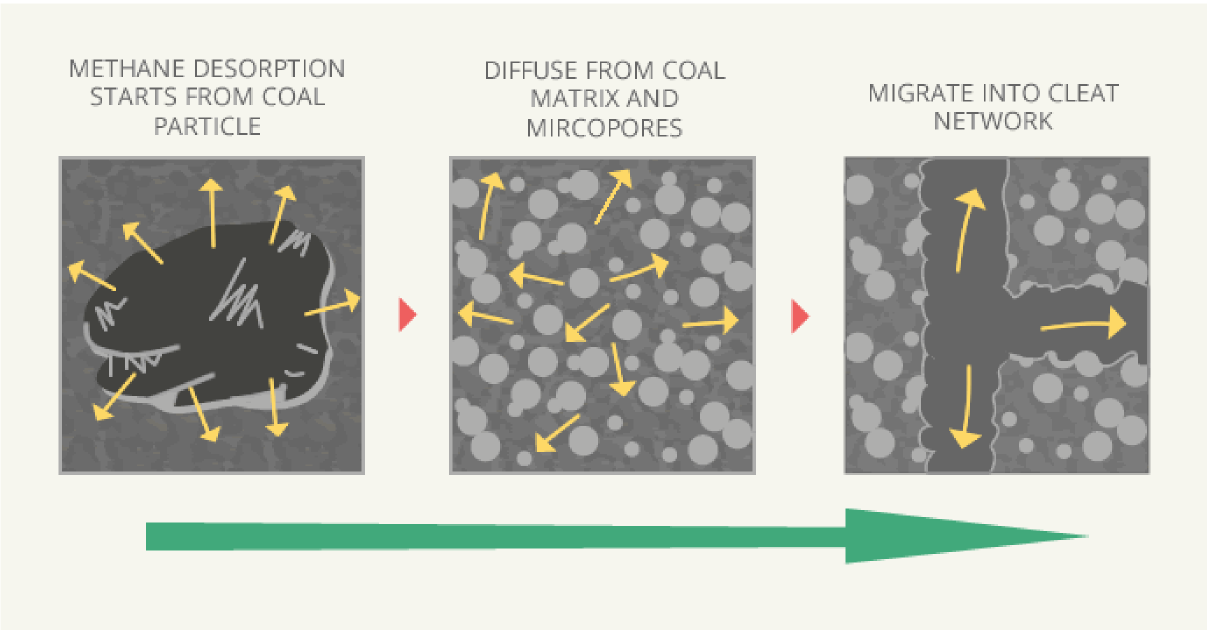


Figure 5 The extraction of coal seam gas requires the desorption of the gas from the coal matrix by lowering the water pressure, diffusion of the gas into the fracture network via microscopic pores in the coal matrix, then migration of the gas to the well via a system of small cleats and fractures within the coal (© Copyright, Sino Oil & Gas Holdings Ltd 2013).

Micropores, on the other hand, consist of the capillaries and cavities at molecular dimensions in the coal matrix that are essential for gas storage in the adsorbed state. Up to 98 per cent of the methane is thought to be adsorbed in the micropores (Freij-Ayoub 2012; Gray 1987). This storage capacity is in contrast to conventional gas reservoirs where the methane and generally a few per cent of other heavier hydrocarbons are trapped in the pores of a permeable host formation. Consequently, coal seams can contain six to seven times as much gas per unit volume as the conventional reservoirs (Freij-Ayoub 2012). This also means that traditional methods used to estimate groundwater flow using numerical models based on single phase (water) flow through rocks is fraught with difficulty and generally overestimates the amount and flow of water in the coal system. This issue is further compounded by the fracture-dominated flow regime in coal seams, which can only be approximated using the conventional Darcy flow equations for groundwater movement. Where coal seams are a small proportion of the total formation being investigated, there is closer approximation to Darcy flow than where the coal seams are a significant proportion of the sequence.

The permeability of the seam is critical to gas recovery and hence economic viability. Most gases and water will move through the system of macropores and fractures, known as cleats, which provide the permeability that is essential for bulk fluid flow (Freij-Ayoub et al. 2011). There are two types of cleats: face and butt. Face cleats are the thin fractures that are parallel to the bedding plane of the coal seam. They tend to be relatively continuous along the seam and generally occur in pairs. They run longitudinally until they are intersected by butt cleats that are perpendicular or at a high angle to the bedding planes (Figure 6).

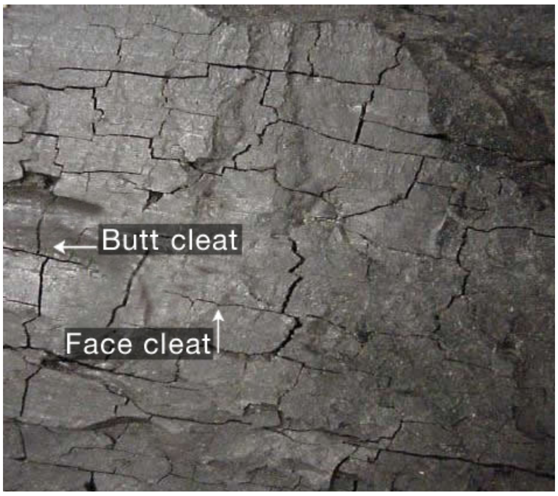


Figure 6 Face and butt cleats; view is looking down on the bedding plane. Note the more continuous nature of the face cleats and the termination of the butt cleats at the face cleats (© Copyright, Underground COAL 2013).

The angle between the face and butt cleat is orthogonal (that is, about 90°). The spacing between cleats varies according to factors such as the age of the coal, mineralisation and the carbon content, but is normally less than 25 mm but can be greater (Dawson & Esterle 2010; Xiaojun & Bustin 2006; Laubach et al. 1998; Laubach & Tremain 1991). The approximate width of the aperture and the length of the face and butt cleat spacing in some Australian coal samples are provided in Table 1.

Table 1 Face and butt cleat spacing in Australian coals (© Copyright, Underground COAL 2013).

Cleat	Spacing
Face cleat spacing	10 – 25 mm
Butt cleat spacing	10 – 22 mm
Aperture	0.1 – 2 mm

Face cleats are more prevalent than butt cleats and provide the dominant connected horizontal paths for fluid flow, though butt cleats may provide pathways for fluids and gases to move from one face cleat to another. The spacing of face cleats can range from 2 mm to several centimetres. If the face and butt cleats are interconnected through a seam then permeability will be higher for a given level of stress or pressure. Larger-scale discontinuities such as fractures, bedding joints and faults can enhance this permeability. Typical permeabilities of coal seams range from 0.1 to 100 millidarcys (mD) (see, for example, Freij-Ayoub 2012), which compares to typical conventional gas reservoirs and aquifer permeabilities of 5 to 500 mD[1]. Permeability tends to decrease with increasing depth (see Figure 7, Figure 8, Figure 9).

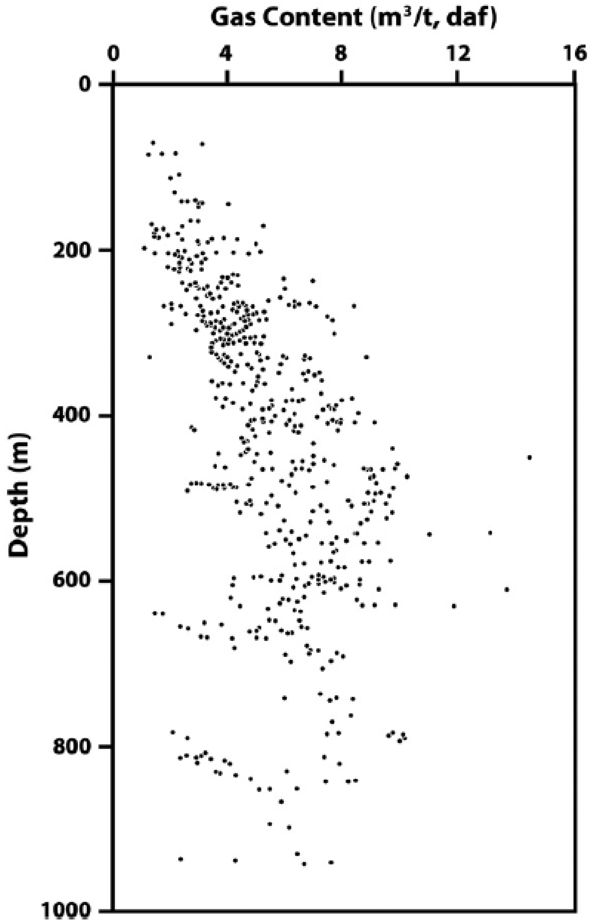


Figure 7 Relationship between depth and gas content in an Australian coal basin (© Copyright, Moore 2012). Note that there is a trend of increasing gas content with depth down to about 600 m. However, the data is highly variable about this trend, most likely related to local geological conditions and coal composition.

[1] A Darcy is approximately 10^{-8} cm^2 in SI units, or equivalent to a medium that permits a flow of about $1cm^3/s$ of a fluid with a viscosity of 1 mPa.s with a pressure gradient of 1 atmosphere/cm acting across an area of 1 cm^2. Sandstone, for example, would have a permeability of about 1 Darcy. In groundwater studies, hydraulic conductivity (K=m/s) is more commonly used to describe the flow characteristics of water through a medium. A sandstone would have a hydraulic conductivity of about 10^{-3} cm/s. Permeability is a component of hydraulic conductivity and is a property of the porous media, not the fluid.

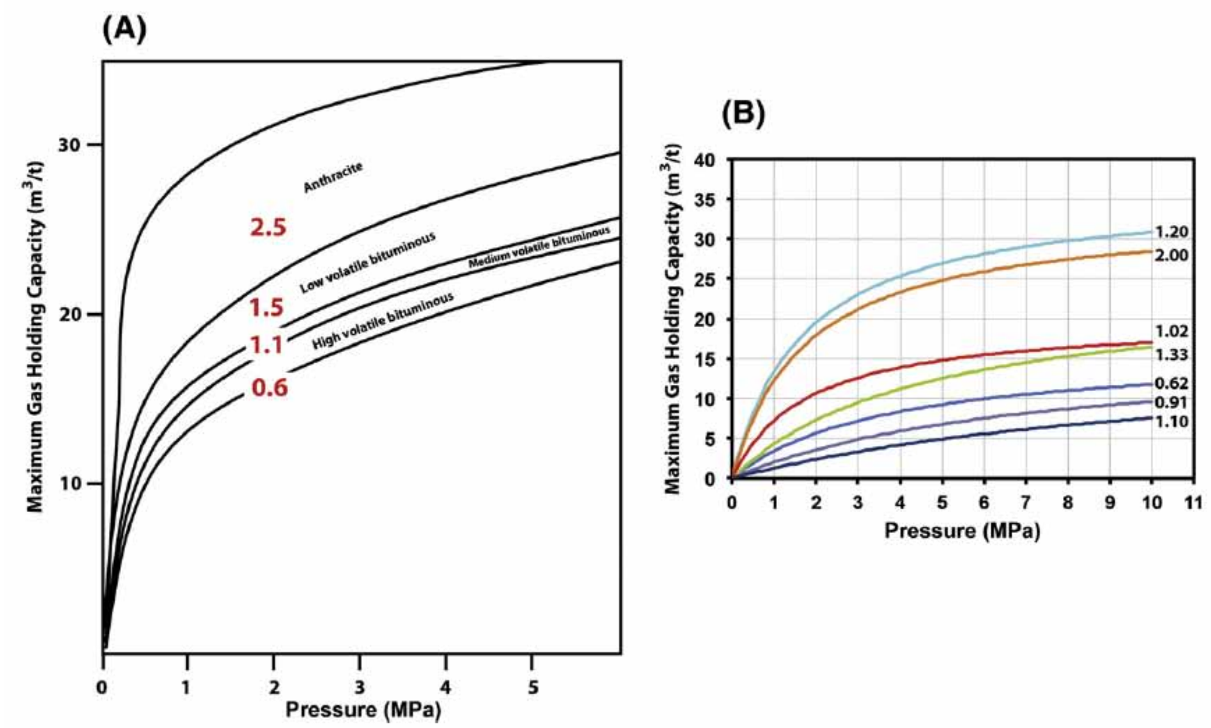


Figure 8 Adsorption isotherms related to rank (© Copyright, Moore 2012): (A) Isotherm graph from Kim (1977) relating coal rank to maximum gas holding capacity (at 0 °C; red numbers are approximate mean–maximum vitrinite reflectance). Although rank–gas relationships shown are in general correct, they are far from universally observed in the field. (B) Adsorption isotherms from different coal ranks from different basins around the world. Mean–maximum vitrinite reflectance is noted to the right of each isotherm. Note that there is no systematic trend of higher rank with higher gas holding capacity.

In the Bowen Basin, for example, permeabilities decrease on average from about 100 mD at 200 m to 0.1 mD at 400 m, though there was large observed variability in values at the local scale (Moore 2012; Esterle et al. 2006). Adsorption capacity increases with increasing coal rank and vitrinite content for a given level of pressure and temperature (Wang & Ward 2009). The ability to desorb methane is also influenced by the permeability and level of saturation within the coal seam.

As a rule of thumb, significantly more groundwater is present and needs to be pumped in the Queensland coal measures, with an order of magnitude less water derived from northern New South Wales coal fields and an order of magnitude less again in the southern New South Wales coalfields (Ross 2012). As subsidence can be directly (though not totally) related to water extraction in the coal seam gas industry, subsidence is more likely in the Queensland Surat and Bowen Basins fields where larger quantities of water need to be extracted to depressure the targeted coal measures.

The exact amount of depressurisation is a function of the inherent gas content for the coal seam and the incipient pore pressure exerted by the groundwater in the coal seam. Extraction is governed by the Langmuir adsorption isotherm[2], which has to be determined for

[2] The Langmuir Isotherm determines the maximum gas holding capacity at a given pressure and temperature and is used by industry to help determine the financial viability and economic value of the gas. Viability is also influenced by a range of other factors, including depth, rock type, production coasts, gas price and access to markets.

each field, and sometimes each bore, and determines the viability and economic value of the gas return. Adsorption isotherms are also related to coal rank (see forward, section 5, Figure 11). For the conditions in coal seam gas reservoirs in Australia, typical depths of extraction range from around 200 m to 1000 m, with reservoir pressures expected to range from approximately 3 MPa to 10 MPa (CSIRO 2012c; CSIRO 2012d). In the Walloon Coal Measures of the Queensland Great Artesian Basin, the pressure head on the waters confined in the coal seams have to be reduced to within 35 m of the top of the coal beds for effective desorption and gas separation. Typical gas contents are 5 m^3 to 10 m^3 per tonne of coal (see forward, section 5, Figure 10 and Figure 11) (Moore 2012).

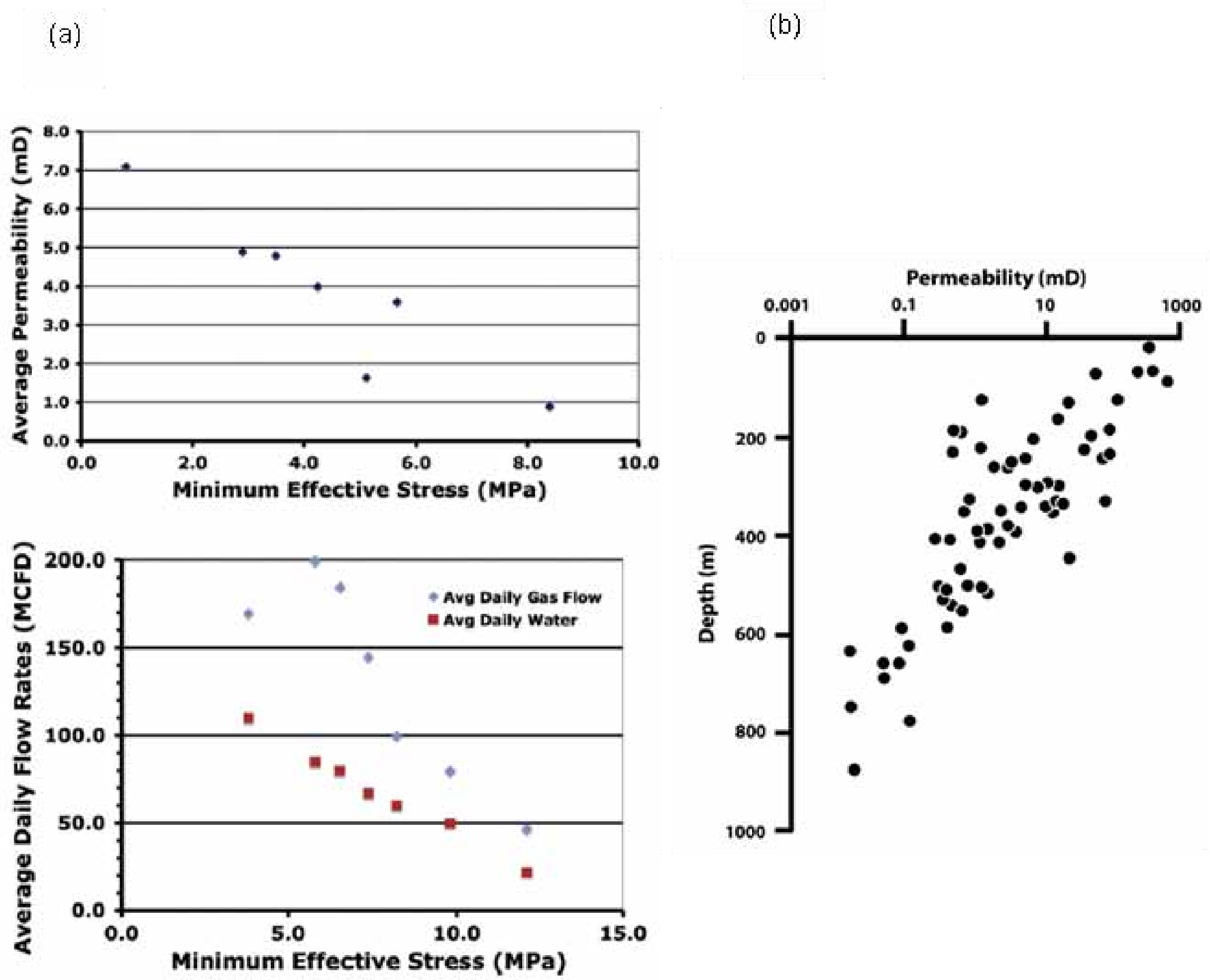


Figure 9 (a) Minimum effective stress influence on permeability and gas and water production in the Cedar Cove area, Black Warrior Basin, Alabama and (b) in-situ coal bed permeability versus depth in a Permian coal basin in Australia (© Copyright, Moore 2012).

During the removal of gas and groundwater the decline in pore pressure creates an increase in the effective stress and a decrease in permeability (Moore 2012). As production occurs from the coal seam, the changes in pressure cause changes in the porosity and permeability as the pressure of the gas and water inside the pores decreases, causing the macropores and cleats to collapse under the weight of the overlying rocks, restricting permeability (see, for example, Moore 2012 and Nelson 2012). Then, as depressurising continues, the gas further desorbs and the coal matrix shrinks, increasing permeability (Moore 2012; Pan & Connell 2012; Harpalani & Chen 1997; Harpalani & Chen 1995; Harpalani & Chen 1992).

3.4 The potential role of hydraulic fracturing in subsidence

In areas with coal seams with expected high gas volumes but with low permeability, the technique of hydraulic fracturing may be used to facilitate an increase in permeability and enhance gas recovery. Hydraulic fracturing is variously known as ‘well stimulation’, ‘hydraulic fracture simulation’ or ‘fraccing’. It has been used in the petroleum industry overseas for over 60 years and in Australia for over 40 years. Hydrocarbon-bearing formations are ‘stimulated’ to enhance their flow to the wellhead. It involves the injection of fluid, proppants and other materials (which may include gases like nitrogen or carbon dioxide) under high pressure into a geological formation from which the hydrocarbons are to be extracted (APPEA 2013; Origin Energy 2013; SCER 2013; Australia Pacific LNG 2012; QGC 2012; Santos 2012; Van Bergen et al. 2006; US EPA 2004).

Hydraulic fracturing increases the internal damage to the cleats and butts and may promote additional failure faces within the seam. This may in turn promote increased contraction within the affected coal seam as gas and water flows out of the coal seam and effective stress increases (Moore 2012). The introduction of additional proppants to support the generated fractures increases the grain volume and may partially compensate for any matrix contraction. Two potential risks to groundwater resources due to hydraulic fracturing were identified by the US EPA in their 2004 report:

- Water quality impacts from hydraulic fracturing fluids being injected into aquifers or into coal seams with existing direct hydraulic connectivity with adjacent aquifers.
- The formation of new hydraulic connections between coal seams and aquifers.

Either, or both, of these processes – coal seam fracturing and increased hydraulic connectivity – have the potential to facilitate depressurisation in the coal seam and in any adjacent and interconnected aquifers. This review of the literature indicates that the contrasting effects of cleat failure and fracture support have not as yet been assessed; and that the impact of hydraulic fracturing has not been incorporated into any estimates of subsidence (see, for example, Origin Energy 2013; SCER 2013; Australia Pacific LNG 2012; QGC 2012; Santos 2012). Further detailed assessment of fractured bore locations, stress within fractured coal seams and observed subsidence would help to determine whether any additional or differential effects might be expected.

Technological improvements in horizontal drilling techniques within the petroleum industry are leading to a number of coal seam gas developers using ‘surface-to-in-seam drilling’, or horizontal drilling, which is reducing the requirement for conventional hydraulic fracturing (Ross 2012; Rutovitz et al. 2011; Mathew 2005; Miyazaki 2005). This technique, however, cannot be used in all situations. The thin and irregular nature of the Walloon Coal Measures in Queensland, for example, precludes the use of this technique. The more massive and thicker seams in the Sydney Basin mean that this technique has been used in the Camden area (Ross 2012). It has also been used in the Moranbah Gas Project in Queensland (Mathew 2005).

3.5 Drawdown, depressurisation, inter-aquifer connectivity and connection with surface deposits

The general theory of the hydraulics of drawdown indicates that when a well is pumped, the hydraulic head around the well declines and a cone of depression will develop in the aquifer

(Freeze & Cherry 1979). This means that the direction of groundwater flow will be altered. For confined aquifers, which are isolated from other aquifers and the surface by less permeable units, or aquitards, the change in head relates to the expansion of the water as pressure in the aquifer is reduced and reduction in pore space as the aquifer compacts (Fetter 2001). This is a function of a rock's specific storage. If pumping continues and no recharge to the aquifer occurs then the cone of depression will expand indefinitely. However, most confined aquifers are not completely isolated from sources of recharge. Recharge via vertical leakage from overlying or underlying aquitards is usual, and additional leakage can be induced as the hydraulic gradient, comprising the pressure differential between water in different connected locations, is altered through pumping. The water contributed by the aquitard comes not only from storage from within the aquitard, but also from leakage through it from overlying or underlying unpumped aquifers. The contribution of water from other unpumped aquifers increases as pumping continues and relatively less water comes from aquitard storage. Equilibrium will be reached after a certain time due to leakage through the aquitard from adjacent aquifers. When such conditions are reached the aquitard serves merely as a water transmitting medium, and water from storage can be neglected (Fetter 2001; Freeze & Cherry 1979).

In a multi-layered aquifer system composed of two or more aquifer layers separated by aquitards (for example, the Great Artesian Basin), the influence of the pumping well can be transmitted to other non-pumped layers. This alters the hydraulic gradient between units and results in aquifer interference. The resulting change in hydraulic gradient in the other non-pumped layers and the nature of interference will depend upon the hydraulic characteristics of the aquifers and aquitards. This may propagate through a series of stacked systems if there are incomplete, or imperfect, seals between units through leaky aquitards. However, despite recent reconceptualisation exercises such as those of CSIRO (CSIRO 2012a; CSIRO 2012b; CSIRO 2012c; CSIRO 2012d; CSIRO 2012e), studies of aquifer interconnectivity in Australia are relatively rare – the hydraulic properties of aquifers are often poorly understood and those of aquitards rarely documented (see, for example, CSIRO 2012b and Bradshaw et al. 2010).

Groundwater extraction to reduce water pressure in the coal seams will generally lead to substantial depressurisation and dewatering of the coal seams, subsequently leading to compaction within the coal seam and potentially altering the hydraulic and physical conditions of the coal seam itself. Depending on the degree of aquifer connectivity, this may lead to changes in overlying or underlying aquitards and aquifers as well, due to the induced pressure differential between the coal seam and those aquifers. The potential depressurisation of any overlying or underlying aquifers may further exacerbate subsidence issues. The potential for leakage needs to be examined as depressurisation of all beds in a sequence must be evaluated to assess potential for settlement.

3.6 Influence of the geological environment in subsidence

The likely cumulative impacts of extracting coal seam gas water on surrounding aquifers will depend upon the structure and attributes of the geological environment. This may act to either enhance or preclude any aquifer interference that occurs as a consequence of a change in hydraulic conditions from coal seam gas production. A review of recent studies (such as Coffey Environments 2012; WorleyParsons 2010; Golder Associates 2009b; Golder Associates 2009c; Golder Associates 2009d; Matrixplus Consulting 2009; URS 2009) suggests that the following attributes of the geological and hydrological environment form important considerations when estimating subsidence:

- aquifer depressurisation within the coal seam and adjoining aquifers, and the quantity of water being produced over time
- the predominant depositional sequence structure of the basin and the distribution of rock types
- lateral extent of coal seams
- presence and nature of unconformities and the relationship with coal seams and aquifer units
- the extent and location of fractures, folds and faulting
- the proximity of coal seams and aquifers (vertical distance between coal seam and aquifer) and their connectivity
- rock hardness and elasticity values
- the hydraulic properties, particularly vertical hydraulic conductivity, of intervening strata
- erosional features, particularly geologically recent alluvial systems that may bring producing alluvial aquifers into contact with coal sequences.

The magnitude of the hydraulic connectivity risk as a consequence of coal seam gas production is largely related to the intervening distance between an aquifer and the coal seam, and the hydraulic properties of the intervening material. Greater vertical distance between the coal seam and aquifer, and lower vertical hydraulic conductivity of the intervening material, typically promotes a lower risk of hydraulic connectivity and aquifer interference. A greater hydraulic risk exists where intervening material is absent due to a geological unconformity or where aquifers directly overlie or underlie the coal seam, such as in the Condamine alluvium in central Queensland (Hillier 2010; Moran & Vink 2010). A higher risk of connectivity results in a greater potential for settlement as a greater thickness of materials will be impacted and potentially compressed. Less connected systems are likely to be more competent and hence exhibit less total settlement.

4 Modelling coal seam gas subsidence: theoretical considerations

4.1 Overview

This section includes an overview of the theoretical and analytical considerations associated with predicting and modelling this form of subsidence. Issues related to gas extraction and the propagation of subsidence effects are identified and discussed. Recent coal seam gas impact assessments are also reviewed.

4.2 Causes of subsidence: dewatering and depressurising

The removal of groundwater from coal seams to facilitate methane desorption and subsequent coal seam gas extraction can cause subsidence due to the reduction in the pore pressure within the coal seams. Desorption of methane from coal seam gas extraction causes matrix shrinkage and increased coal seam permeability. However, the associated pressure reduction causes increased effective stress and therefore decreased coal seam permeability. There is a balance between these two processes (Harpalani & Chen 1997). This shrinkage may also contribute to subsidence of the overburden, but this is generally thought to be in the range of millimetres to centimetres based on conventional studies overseas (Wilson et al. 2012; Myer 2003; Poland et al. 1984a).

The effective stress of a reservoir or coal seam is the difference between the total stress and the pore pressure. During the removal of gas and groundwater the decline in pore pressure creates an increase in the effective stress and a decrease in permeability (Pan & Connell 2012; Harpalani & Chen 1997; Harpalani & Chen 1995; Harpalani & Chen 1992). The change in effective stress is a dynamic process resulting in compression of the coal seam until a new equilibrium is reached (Nagel 2001). Coal seam thickness and seam compressibility also control the potential for compaction. These parameters are constant and not changed by coal seam gas production.

A distinction needs to be made between dewatering, depressurising and hydraulic fracturing. For dewatering to occur, the amount of water removed leads to desaturation of the water-bearing unit. The water table is physically lowered and a zone of partial saturation develops. During depressurisation, the aim is for the water-bearing unit to remain fully saturated. Only the pressure surface relating to the hydrostatic pressure in the unit will reduce. Dewatering rates are governed by the specific yields of the unit and depressurisation rates are governed by the specific storage. Dewatering significantly lowers pore pressure and the increase in effective stress can increase the potential for micropore collapse within the coal matrix. Depressurisation, meanwhile, results in a lowering of pore pressure and the increase in effective stress causes the matrix to shrink. In dewatering, any subsidence is propagated through physical compression. In depressurisation, settlement is propagated through the re-alignment of the matrix materials as the effective stress increases. This can be propagated directly to the surface if the materials above the pumped unit are assumed to be homogeneous and compressible. Under these circumstances, dewatering may result in 30 to 50 per cent transmission of the total subsidence generated in the coal seam (thought to be in the range of tens of centimetres), while depressurisation can theoretically propagate 90 per cent of the coal seam compaction to the surface.

Given that most coal seam gas coal seams are several hundred or more metres below the ground and sit within a sequence of varying lithologies, usually containing a significant thickness of competent rocks such as sandstones and/or other fractured rocks, the depth and amount of compaction of the coal is likely to result in small disturbance to the land surface. In this situation, dewatering would result in settlement and this would be propagated through the competent layers via faults and joints. Depressurised units, however, would uniformly compact and this would be supported by any competent overlying units and these would act to bridge across any deeper compacted units and little subsidence would be transmitted to the surface, unless transmitted through the competent layers via faults and joints.

4.3 Principles of settlement and material compressibility

Rock mechanics is the understanding of the behaviour of geological materials. Rock mechanics principles are discussed here as a context for settlement behaviour of depressurised coal seam gas layers at depth. When pressure is applied to a clay-rich soil, the soil can undergo three types of compression depending on the increase in effective stress. The three types of settlement are:

- elastic settlement (reversible)
- consolidation settlement (not reversible)
- long-term creep settlement (not reversible).

The deformation modulus for each type of settlement is highly dependent on the type of settlement envisaged. Elastic settlement generally occurs when the applied load is low relative to the confining overburden-related stress to which the soil or rock is exposed. Elastic settlements are relatively small, occur over short time periods (for instance, six months) and are reversible if the load is removed. This means that the soil or rock will largely rebound to its original thickness after the event (Davis & Reynolds 1996).

If the initial applied load is much higher, the soil undergoes consolidation settlement and permanent compaction and reduction in the voids within the soil occurs. The water is squeezed out of the voids with resultant changes to internal structure. Consolidation settlement occurs over a longer period and results in greater settlement. If the load is removed, the soil will not rebound to its original thickness and is permanently compressed and deformed. Consolidation settlements may take place over a few years until the grains of the soil are in equilibrium with the applied stress. This time dependent behaviour is a function of the drainage path and permeability of the materials being dewatered/depressurised. Once full consolidation has occurred, the clayey soil may undergo creep behaviour. Creep settlement occurs over tens of years and is very small and is an intrinsic property of the material. The magnitude of creep settlement is not dependent on the applied stress (Davis & Reynolds 1996).

With consideration of the above types of settlement and the properties of coal measure rocks, it is considered that on application of an increase in effective stress due to depressurisation, the principal mode of settlement will be consolidation settlement rather than elastic and/or creep settlement. For this reason, selection of deformation parameters appropriate to such behaviour of geological materials should be carefully considered for each site.

Subsidence occurs when the effective stresses on materials increase, causing the materials to contract. The focus of the discussion above has been on vertical stresses with the assumption that effective stresses are reasonably uniform over large areas and that most deformation will occur in the vertical direction. While this is not true in all cases (such as, for example, Connell 2009; Burbey 1999; Burbey 2001), it is a reasonable approximation for the condition of depressurising a coal seam over an extensive area.

4.4 Modelled predictions of subsidence

In Queensland, QGC, Santos and Arrow (Coffey Environments 2012; WorleyParsons 2010; Golder Associates 2009b; Golder Associates 2009c; Golder Associates 2009d; Matrixplus Consulting 2009; URS 2009) used the results from finite difference (MODFLOW) numerical groundwater flow models coupled to an analytical approximation of compaction theory, to assess the possible subsidence impacts from coal seam gas groundwater extraction in the Surat and Bowen coal basins (Figure 10). The groundwater flow models were calibrated to groundwater heads and the sensitivity of the models to changes in the aquifer storativity were examined in some cases (Schmid et al. 2013). Estimates of specific storage varied across proponents and the various models, and are set out in Table 2 (USQ 2011). These models were not intrinsically allowed to vary as a function of water loss; hence, consideration of changes in storativity during depressurisation and the potential for volume changes over time were not examined. Table 3 provides a summary of subsidence estimates, predominantly for Queensland coal seam gas companies; Figure 10 shows the location of the companies' production areas.

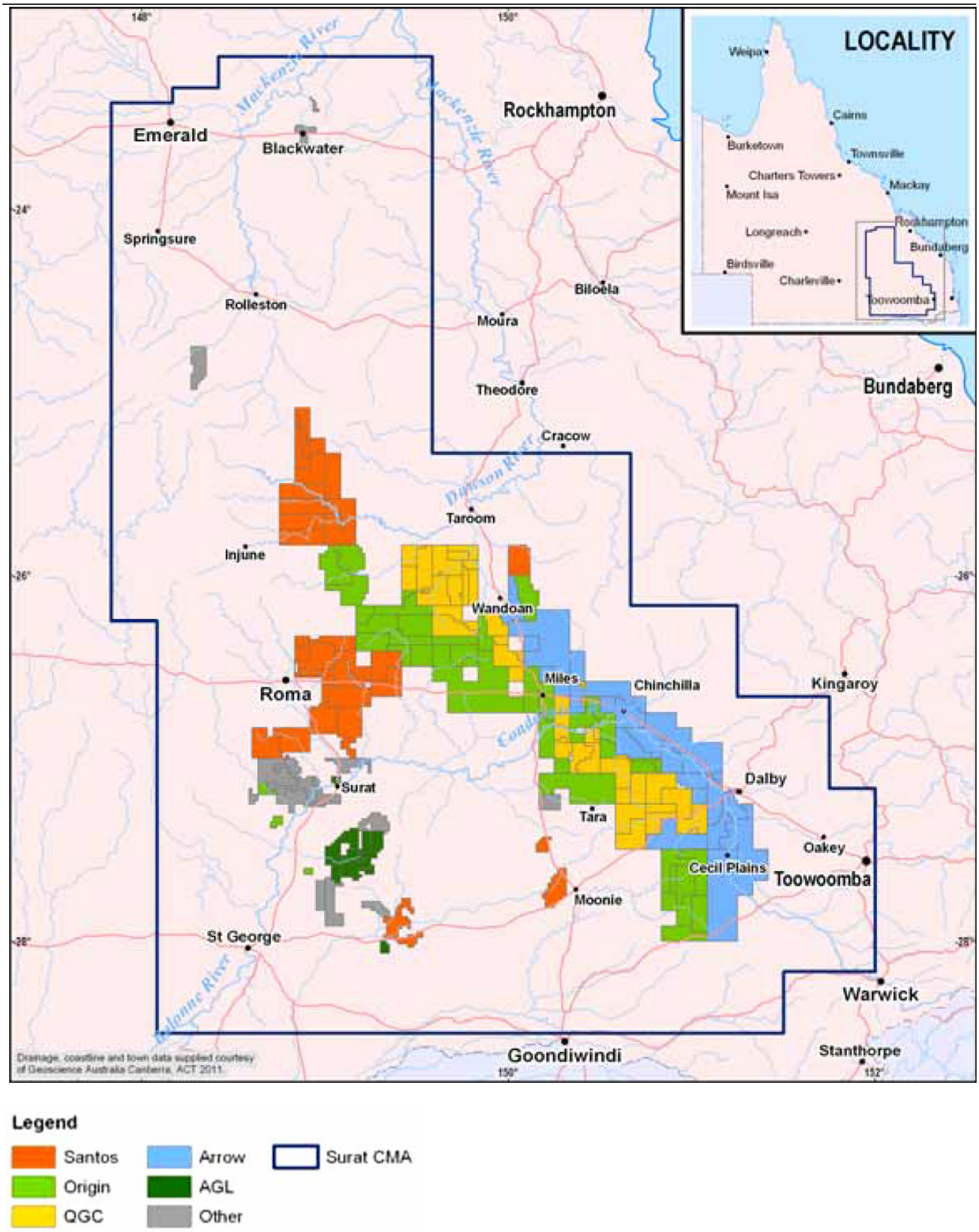


Figure 10 Location of major coal seam gas production areas by company (© Copyright, Queensland Water Commission 2012a; Queensland Water Commission 2012b).

Table 2 Variation in specific storage parameters used by different proponents (coal seam gas 1 to 4) across the same coal seam gas formations in South-east Queensland (© Copyright, USQ 2011). Note: specific storage here is actually storativity, except for the uppermost unit A.

Unit	Aquifer / confining unit	Specific storage (m^{-1})			
		CSG 1	CSG 2	CSG 3	CSG 4
Cainozoic & Alluvium	A	0.000005	0.001 / 0.0005	0.0001	0.0008
Rolling Downs Group	C	0.0001		0.00001	0.00005
Bungil	A	0.0001	0.005 / 0.0005	0.00001	0.00005
Mooga	A		0.005 / 0.0005	0.00002	0.00005
Orallo	C		0.005 / 0.0005	0.00001	0.00005
Gubberamunda	A	0.000003	0.005 / 0.00005	0.00002	0.00005
Westbourne	C	0.00001	0.0005 / 0.00005	0.00001	0.00005
Springbok – upper	A	0.000003	0.0005 / 0.00005	0.00002	0.00005
Springbok – lower	C				
Walloon Upper	C	0.00001	0.0005 / 0.00005	0.000006	0.00005
Walloon Coal Seam (Macalister)	A	0.000003	0.0005 / 0.00005	0.000006	0.00005
Walloon (Macalister Mudstone)	A	0.00001	0.0005 / 0.00005	0.000006	
Walloon (U Juandah Sst)	A	0.000003			
Walloon (L Juandah Mudstone)	C	0.00001			
Walloon (L Juandah Coal seam)	A	0.000003		0.000006	0.00005
Walloon (L Juandah Mudstone)	C	0.00001		0.000006	0.00005
Walloon (Tangalooma Sandstone)	A	0.000003			0.00005
Walloon (Taroom Mudstone)	C	0.00001			0.00005
Walloon (Taroom Coal Seam)	A	0.000003	0.0005 / 0.00005	0.000006	0.00005
Walloon (Taroom Mudstone)	C	0.00001	0.0005 / 0.00005	0.000006	0.00005
Eurombah Fm	C	0.00001		0.000005	0.00005
Upper Hutton	A	0.000003	0.0005 / 0.00005	0.000008	0.00005
Lower Hutton	A	0.000003			0.00005
Evergreen	C		0.0005 / 0.00005	0.000005	0.00005
Precipice	A	0.000003	0.0005 / 0.00005	0.000008	0.00005

Table 3 Modelled predictions of subsidence, predominantly in the Surat and Bowen coal basins in Queensland, by coal seam gas companies.

CSG company	Max. total water extraction	Estimated subsidence	Technical report
Australia Pacific LNG	170 ML/d	50 mm - 850 mm Less than 500 mm	Australia Pacific LNG (2013: pp. 88) WorleyParsons (2010: pp. 87)
Arrow Energy	131 ML/d	Not provided	Coffey Environments (2012: pp74-77)
Queensland Gas Company	189 ML/d	Northern gas fields: 180 mm (for coals 1360 m deep) Central gas fields: 80 mm (for coals 950 m deep) Southern gas fields: 140 mm (for coals 670 m deep) 200 - 300 mm for coals 1360 m deep 30 - 100 mm for coals 670 - 950 m deep	QGC (2012: pp. 113, 162) Golder Associates (2009a: pp. 118, 144)
Santos	14 ML/d	Roma gas field: 200 mm over 2 km (0.01% or 1:10 000) Arcadia Valley gas field; 100 mm over 2 km (0.005% or 1:20 000) Fairview gas field: 100 mm over 2 km (0.005% or 1:20 000) Roma gas field: 280 mm (for coals 275 m deep) Arcadia Valley gas field: 150 mm (for coals 90 m deep) Fairview gas field: 150 mm (for coals 90 m deep) Roma gas field: 55 mm (for coals 480 m deep) Roma gas field: 115 mm (for coals 960 m deep) Arcadia Valley gas field: 30 mm (for coals 650 m deep) Arcadia Valley gas field: 70 mm (for coals 1440 m deep) Fairview gas field: 30 mm (for coals 650 m deep) Fairview gas field: 70 mm (for coals 1440 m deep) Not expected to occur in the Roma, Fairview or Arcadia Valley gas fields	Santos (2012a: pp. 39) Santos (2012b: pp. 123-124) Golder Associates (2009b: pp. 89) MatrixPlus Consulting (2009: pp. 2, 66, 75)
AGL Energy	0.013 ML/d (total in 2012)	Camden gas fields: 'a few millimetres' and 'negligible' (for coals 800 m deep)	AGL (2007: pp. 820-21); Ross (2012); Frolich and Sanders (2010: ES9, 1-8, 15-7, 18-4 and 6)
Queensland Gas Company	342 ML/d (total average)	Not provided	QWC (2012b: pp. 59)

Table 3 sources: Origin (Australia Pacific LNG 2013; WorleyParsons 2010), Arrow Energy (Coffey Environments 2012), Queensland Gas Company (QGC, 2012; Golder Associates, 2009a), Santos (Santos 2012a; Santos 2012b; Golder Associates 2009b; MatrixPlus Consutants 2009), and AGL (Ross 2012; AGL 2007). Modelled estimates of maximum water extraction rates (QWC 2012b; Ross 2012; Schlumberger Water Services 2011) are also provided, for comparative purposes.

Queensland Gas Company used their GEN2 3D groundwater flow model to assess subsidence impacts. The model was peer-reviewed for fit-for-purpose and calibrated and an uncertainty analysis was undertaken. Fit-for-purpose here refers to the model's capability to model and predict the regional groundwater response to proposed coal seam gas production. As such, it was not assessed specifically for use as an estimator of subsidence, but would provide a good estimate of regional storativity parameters. Queensland Gas Company is developing the first regional dual-phase numerical groundwater model (GEN3) which will provide improved insight into depressurisation and its consequences for the Walloon Coal Measures. Queensland Gas Company estimated settlement rates for the Walloon Coal Measures as varying between 80 mm in the central gas fields, increasing to 145 mm in the south and 180 mm in the north. This is settlement at depth within the coal measures units alone. Calculations for the adjacent, and competent, sandstone indicated less than 5 mm settlement. Propagation to the surface was considered unlikely.

For the Santos estimations, sensitivity analysis for storativity showed an approximately linear relationship with depressurisation across a range of specific storage values. A four-fold increase in storativity resulted in a two-fold difference in predicted depressurisation and water extraction rates. The sensitivity analysis demonstrated that the use of a greater sensitivity estimates resulted in a greater water extraction rate. This was balanced to some extent by a reduced area of dewatered aquifer. For the Comet Ridge 3D groundwater flow model the sensitivity of storativity was not considered (Matrixplus Consulting 2009; Golder Associates 2009a; Golder Associates 2009b).

For Santos, the maximum subsidence calculated by Golder Associates (2009b) was:

- Roma Field – for an average depth to the coal seams of 480 m, calculated subsidence was 55 mm. For a maximum coal depth of 960 m, calculated subsidence was 115 mm.
- Arcadia and Fairview Fields – for an average depth to coal seams of 650 m, calculated subsidence was 30 mm. For the maximum coal depth of 1440 m, calculated subsidence was 70 mm.

Based largely on revised modelling outputs, Santos (2012) later calculated subsidence as approximately 200 mm over a distance of 2 km for the Roma field, and 100 mm over a distance of 2 km for the Arcadia Valley and Fairview Fields. Santos stated that:

> *'…this impact will not result in a change to surface water or groundwater flow paths, resulting in no impact on the hydrological cycle or any surface infrastructure…'*
>
> © Copyright, Santos (2010)

For the Arrow 3D groundwater flow model, the model sensitivity to changes in storativity of the Juandah and Taroom Coal Measures units were examined separately to all of the other formations. For these two coal measures, model outputs had only a limited sensitivity to a reduction of storativity, whilst outputs had a much greater sensitivity to an increase in the storativity. For all other formations, model outputs were highly sensitive to any changes in the storativity (Schlumberger Water Services 2011).

A groundwater flow model was developed (QWC 2012a; QWC 2012b) to assess the cumulative impacts of coal seam gas production by all proponents in the Surat Cumulative Management Area with water production volumes supplied by the proponents. The sensitivity of the model to changes in specific storage was not examined (QWC 2012d). The model drawdown results were then coupled to an analytical model which converted drawdown to change in pore pressures as inputs to the subsidence calculation. Maximum subsidence was calculated for the different coal seam gas fields in and below the Surat Basin. Estimated values reportedly ranged from 80 mm to 280 mm.

Australia Pacific LNG (AP LNG) used a similar approach, coupling the simplified analytical model to their finite element (FEFLOW) groundwater flow model to estimate the cumulative impacts of subsidence across their South-east Queensland tenements. Preliminary modelling by WorleyParsons (2010) for AP LNG predicted subsidence of less than 500 mm. More recent company estimates (AP LNG 2013) reported a calculated maximum of up to 850 mm.

All proponents assumed linear elastic theory to calculate settlement using simplified compaction formulae. The potential compaction of each hydrostratigraphic unit was estimated and summed to produce a map of potential risk of compaction. Cumulative compaction of up to one metre was therefore reported, though it was noted that compaction is unlikely to be expressed at the surface as the shallower consolidated and competent rock will to some extent operate as a bridge to prevent the downward movement. In other words, only the first stage of compression was considered to operate across the coal seam gas fields under the assumption that the timeframe and changes in pressure were insufficient to instigate consolidation or long-term creep.

4.5 Groundwater impact assessments for major coal seam gas developments

Given these predictions, regulators have imposed approval conditions that require coal seam gas proponents to model, monitor and plan for any potential impacts due to this process. The coal seam gas companies have responded with estimates of impacts, monitoring schedules and management plans to satisfy the approval conditions. For example, concern for Matters of National Environmental Significance (MNES) resulted in a number of approval conditions on coal seam gas companies under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) (Bourke 2010). Conditions include monitoring of subsidence due to extraction of groundwater for coal seam gas production across all development areas and provision of a subsidence management plan.

In addition to the EPBC Act, the Commonwealth *Water Act 2007* also requires consideration of subsidence related impacts of mining operations on floodplains that underlie groundwater systems forming part of the Murray-Darling systems. The Australian Parliament's Senate Rural Affairs and Transport References Committee (2011) also made recommendation for the management of coal seam gas production related subsidence in the Murray-Darling Basin:

> *"The committee recommends that all future approvals require independent comprehensive monitoring of regional earth surface movements to assess whether any measurable subsidence is occurring. Where subsidence occurs and has an adverse effect on land management or the natural environment, for example by altering drainage, the responsible gas companies would be liable for any necessary remediation. Further all gas exploration and/or production in an area subject to subsidence or impacts from subsidence not foreseen in the EIS should cease until action is taken to ensure that no further damage will occur. Where subsidence occurs*

in a gas producing region the onus lies with the gas companies to demonstrate that the subsidence is not a result of gas production activities."

4.5.1 Queensland

In addressing Commonwealth and state regulatory requirements, the major coal seam gas companies have undertaken groundwater impact assessments to measure and evaluate the potential for coal seam gas extraction-induced subsidence. Examples of conclusions from company assessments are set out below:

- The AP LNG groundwater impact assessment states:

  'The risk of land subsidence associated with the extraction of water and natural gas from consolidated underground reservoirs such as the Walloon Coal Measures is minimal. While subsidence due to groundwater extraction is known to occur in unconsolidated sediments (and primarily in highly compressible clays), its occurrence in consolidated formations is far less common. Groundwater in the GAB [Great Artesian Basin] is stored in consolidated, confined, porous sandstone aquifers with limited compressibility.'

  and

  'There is a risk of some subsurface compaction associated with those regions where the coal seams reside at greater depth, and are therefore subject to greater drawdowns during coal seam gas development. However, all or part of this compaction is unlikely to be expressed at the surface (as land subsidence) as the overlying consolidated and competent rock formations will serve to attenuate any downward movement caused by compaction of the coal seams. Therefore, on the basis of the initial assessment, the potential risk of land subsidence as a consequence of associated water production in the project case and cumulative case is considered low.'

- QGC's groundwater impact assessment states:

  'In the case of the Project Area, based on the assumed extent of depressurisation of the WCM coal seams, elastic settlement will likely progress to the surface and result in surface subsidence. The magnitude of the settlement has been estimated at 30 to 100 millimetres for the average depths to coal and 200 to 300 millimetres for the maximum depths.'

- The Santos groundwater impact assessment states:

  'As an indication of the amount of subsidence that could occur, the elastic response of the depressurised coal seams was estimated based on an assumed rock mass modulus of two gigapascals and total thickness of ten metres for Arcadia and Fairview and 25 metres for Roma. The calculated surface subsidence is:

  Roma Field – for an average depth to the coal seams of 480 metres then calculated subsidence is 55 millimetres. For the maximum coal depth of 960 metres, calculated subsidence is 115 millimetres.

Arcadia and Fairview Fields – for an average depth to the coal seams of 650 metres then calculated subsidence is 30 millimetres. For the maximum coal depth of 1,400 metres, calculated subsidence is 70 millimetres.'

- The Arrow groundwater impact assessment states:

  'Based on the literature assessment [not cited], it is considered that the risk of land subsidence is not high but nevertheless cannot be entirely ruled out, and it is recognised that the major pressure reductions will occur in geological formations comprising consolidated rock. Because of the significant depth to the coal bearing formations, and the large areal extent of the depressurisation, the likely effects of any subsidence are considered unlikely to have significant impact on structures at the surface, and in particular any settlement that could occur is likely to be widespread and without differential movement.'

In response to government approval conditions, these same companies (Queensland proponents) are currently undertaking ongoing ground movement assessments (Morris 2013; Altamira 2012; and, for example, Burke 2010). Activities include:

- establishment of pre-production (baseline) conditions across tenement areas through satellite imagery
- development of a future ground movement (if any) comparison against the baseline program
- provision of an effective method for assessing potential future ground motion and any cumulative impacts.

The proponents have entered into a collaborative program to monitor and evaluate the potential for subsidence as an impact from coal seam gas extraction. Following their individual and combined assessment of the potential for subsidence, the industry has indicated that it expects no discernible hydrologic implications due to coal seam gas extraction, based on deformation rates thus far established.

4.5.2 New South Wales

Groundwater extraction for coal seam gas operations in New South Wales are generally much lower than those experienced in Queensland. Current production for wells in the Camden region is in the order of 4.8 ML/year, which is one to two orders of magnitude less than for Surat Basin wells (Ross 2012; AGL 2007). Consequently, the subsidence impacts from depressurisation are thought to be considerably less. An assessment of potential subsidence impacts in the Camden region due to coal seam gas development was carried out by Mine Subsidence Engineering Consultants (AGL 2007; MSEC 2007), who concluded that 'the potential for subsidence to occur as the gas is extracted is almost negligible'.

4.5.3 International case studies

A search of international literature for examples of coal seam gas extraction-induced subsidence and its measurement returned few actual examples. In the Powder River Basin, Wyoming US, preliminary estimates of subsidence due to aquifer drawdown for coalbed methane generation were found to be approximately 12 mm (Case et al. 2000) and several centimetres (Grigg & Katzenstein 2013) in two separate studies. For example, in the Powder

River Basin, InSAR data collected from 1997 to 2000 and 2004 to 2007 indicate 47 mm and 83 mm of subsidence respectively, with the major subsidence signals correlating spatially with the areas of greatest groundwater drawdown (Grigg & Katzenstein 2013). In the east-central part of the study area, the largest subsidence values of 40 mm and 60 mm were correlated with large clusters of coal bed methane pumping wells (Grigg & Katzenstein 2013).

Several investigations into other types of anthropogenic dewatering subsidence have also been undertaken in the US, particularly in California, though these relate to subsidence due directly to groundwater extraction from an aquifer, rather than from coal seams (Katzenstein 2013).

4.6 Coalbed methane reservoir simulators

Modelling of coal seams based purely on the movement of water tends to over-estimate the water volume produced for a given depressurisation, and hence over-estimates the relative changes in pressure, when compared to dual-phase models. The latter can only model single bore effects so are impractical for whole-of-gas-field dynamics. A number of simulators have recently been developed to overcome these limitations of scale and coupling of water and gas movement.

To determine the consequences of changes to pore pressure on settlement, the dual-phase fluid flow model must be coupled to a model that determines the effect on the physical structure of the coal seam materials, the changes to cleat spacing and concentration and the structural changes that are induced by exchanging water and gas.

CSIRO has developed a coupled numerical model for gas drainage from coal seams (Connell 2009). Simulation of gas migration in coal seams requires an approach that combines flow with geomechanical behaviour. The CSIRO-developed simulation tool FLAMED, numerically solves this problem during gas production and can improve the prediction of potential paths for gas migration in coal seams. CSIRO's modelling involved coupling the existing coal seam gas reservoir simulator SIMEDWin with the geomechanical simulator FLAC3D.

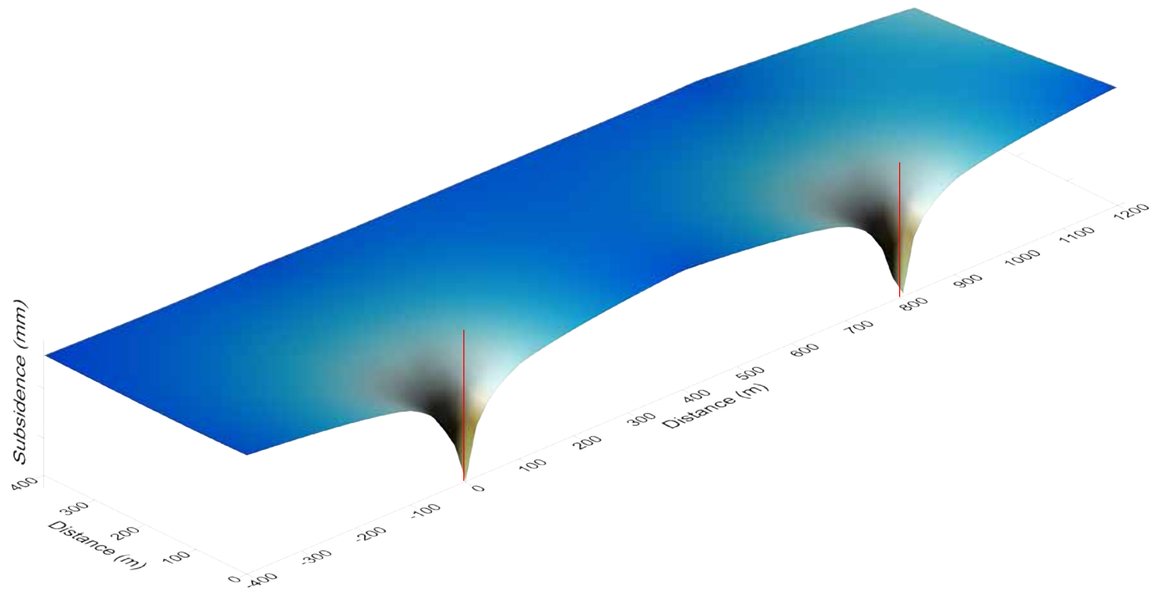
SIMEDWin (the windows user interface version of SIMED II) simulates gas migration representing the two-phase water and gas flow in the dual porosity coal structure, where gas is stored through adsorption. FLAC3D simulates the geomechanical response of the coal and the adjacent non-coal geological formations to fluid pressure and gas content changes imported from SIMEDWin. Coupling SIMEDWin with FLAC3D gives FLAMED the capability to simulate coal seam gas migration with geomechanical behaviour for a simulation of vertical stress pattern during depressurisation. Other modelling tools include COMET, TOUGH2, CMG, Eclipse, FAST CBM, and FEKETE (Esterle 2013; Moore 2012).

For example, modelling software such as FLAMED produce outputs that support:

- improvement of the prediction of gas production from coal seams
- the ability to investigate other geomechanical effects during gas production
- better understanding of the complex mechanical behaviour of coal under the presence of carbon dioxide or methane and water
- determination of geomechanical effects around gas production wells to allow for coal matrix shrinkage and associated stress changes.

This latter capability enables the estimation of subsidence effects during coal seam gas production, with maximum modelled effects in the order of centimetres (Freij-Ayoub 2012). These kinds of models can also predict the damage to the coal seams during coal seam gas production, and can incorporate geomechanical rock failure in the coal seams, where stress may be both in shear and tension; and may be problematic for coal seams surrounded by aquitards (Freij-Ayoub 2012).

Other modelling capabilities are also becoming available, including analytical and numerical transient groundwater response models, such as MODFLOW, FEFLOW and SEEP/W, often with associated 2D and 3D outputs (Gray et al. 2013; Morris 2013; Rotter & Best 2013). A typical prediction output is shown in Figure 11.



Note. Scale on z-axis is in 10 mm increments.

Figure 11 Schematic 3D modelled example showing predicted potential ground subsidence in the vicinity of two theoretical production wells (© Copyright, Gray et al. 2013; Rotter & Best 2013).

5 Technology for monitoring, measuring and assessing the extent of subsidence caused by coal seam gas extraction

5.1 Overview

In this section, various techniques and technologies for monitoring and assessing the extent of subsidence caused by coal seam gas extraction are compared and reviewed.

5.2 Available methods

A number of techniques at varying scales are available to assess land subsidence. Of these, a mixture of broad regional methods combined with local calibrations are required to cover the large areas of several hundred square kilometres that may be affected by coal seam gas groundwater extraction. The technique of choice by coal seam gas developers has been satellite-based remote sensing combined with local extensometer measurements. Table 4 shows a range of techniques and their resolutions. Selected techniques are discussed further below.

5.3 InSAR

Satellite Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technique that uses radar signals to interpolate land surface elevation changes. InSAR is a cost-effective solution for measuring land surface deformation on a regional scale, while offering a high degree of spatial detail and resolution. InSAR can detect how much the ground surface has subsided or uplifted by measuring the distance between it and a spacecraft. This is accomplished by measuring the differences between radar signals transmitted to the ground surface from the same point in space at different times, usually months or years apart. The radar data is combined into an interferogram image, which shows the magnitude of the differences between the successive signals, detecting movement as little as five to 10 mm (Grigg & Katzenstein 2013; Altimara 2012). InSAR is less expensive than other methods, providing millions of data points over areas as large as 10 000 km^2.

Ordinary radar on a typical Earth-orbiting satellite has a very poor ground resolution of about 5 to 6.5 km because of the restricted size of the antenna on the satellite. Synthetic Aperture Radar (SAR) takes advantage of the motion of the spacecraft along its orbital track to mathematically reconstruct an operationally larger antenna and yield high-spatial-resolution imaging capability on the order of tens of metres (Galloway et al. 2000).

Successful measurements using InSAR requires stable radar reflectors. High precision measurements of the change in the position of the reflectors are made by subtracting or ‘interfering’ two radar scans made of the same area at different times. The change in the position of the reflectors represents the magnitude and direction of subsidence.

Table 4 Methods of measuring land subsidence (© Copyright, UNSW 2011).

Method	Measurement	Resolution[3] (mm)	Samples/survey[4]	Spatial scale
Spirit level	Vertical	0.1-1	10-100	Line-network
Geodimeter	Horizontal	1	10-100	Line-network
Borehole extensometer	Vertical	0.01-0.1	1-3	Point
Tape extensometer	Horizontal	0.3	1-10	Line-array
Invar wire extensometer	Horizontal	0.0001	1	Line
Quartz tube extensometer	Horizontal	0.00001	1	Line
GPS	Vertical and horizontal	20 (vertical) 5 (horizontal)	10-100	Network
Geotechnical survey	Vertical and horizontal	1-5	Operator controlled	Local
Radioactive bullet logging	Horizontal	10	1	Point
3D laser	Vertical and horizontal	1-2	Holographic images	Local
LiDAR	Range	1-10	Custom flight paths	Areas
RADAR	Range	3-5 km	Single swaths	Regions
Seismic	vertical	1-2 km		Line
InSAR	Range	5-10	100 000-10 000 000	Map pixel[5]

Both GPS and InSAR were used to detect and measure land subsidence in the Coachella Valley, California, between 1996 and 1998 (Sneed et al. 2001). The results indicated that InSAR produced more spatially detailed data over large areas and was useful where vertical land-surface changes were previously unrecognised or outside the geodetic network. The detailed spatial resolution of InSAR also generated maps complemented by the coarse spatial resolution of the GPS network.

A further investigation for this same region, covering the period 1998 to 2000 (Sneed et al. 2002), revealed the InSAR-generated maps were more useful for determining land-surface changes in urban areas than were the GPS measurements, and the GPS measurements were more useful for determining changes in agricultural areas. However, five locations had both GPS and InSAR measurements that were comparable and these measurements agreed reasonably well. The study also highlighted that the localised character of the subsidence signals look typical of the type of subsidence characteristically caused by localised pumping; however, the subsidence also may be related to tectonic activity in the valley.

[3] Resolution attainable under optimum conditions.
[4] Number of measurements attainable under good conditions.
[5] A pixel is typically 30 to 90 m^2 on the ground.

InSAR has also been used to map regional-scale land subsidence caused by aquifer-system compaction in the Antelope Valley, California. A correlation between the regions of maximum subsidence and declining water levels was observed from 1993 to 1995. In a different area of the same valley, approximately 25 mm of additional subsidence was measured by InSAR, even though groundwater levels had been recovering since 1990, indicating a delay in the effects of groundwater pumping-induced subsidence due to the presence of thick aquitards (Galloway et al. 1998; Galloway et al. 2000).

In the south-western Santa Clara Valley, land-surface uplift of up to about 25 mm was determined by InSAR measurements over a period of five years. This uplift was attributed to groundwater recovery following a reduction of groundwater pumping and increased recharge (Ikehara et al. 1998).

Altamira (2012) demonstrated the effectiveness of InSAR techniques across the Surat and Bowen coal basins using ALSO imagery sourced from JAXA, the Japanese Space Agency. The Altamira study reported 96.7 per cent of the differential movement across the study area (some 55 000 km^2) being in the order of -8 mm to +8 mm per year. More significant, localised subsidence displacement was also detected at selected sites in the study area (reported subsidence at selected non-coal seam gas sites ranged from approximately +65 mm to -156 mm over four years).

Some advantages of InSAR include (Galloway et al. 2000):

- actual spatial resolution is typically in the order of 100 m or better
- under favourable radiometric conditions, 10 mm to 5 mm resolution is possible in the line-of-sight of the radar
- cost-effective for measuring subsidence on a regional scale.

A key disadvantage of InSAR is that (Dixon et al. 2006; Sabins 1996):

- accuracy is dependent on the sensor, image processing methods, ground-truthing and the atmospheric conditions when the measurements were acquired.

5.4 Borehole extensometer

An extensometer is a stationary instrument that measures subsidence in time at a single location. Extensometers consist of a vertical shaft in the order of more than 10 m deep and approximately 10 cm in diameter encased in a metal tube. A thin metal rod or wire passes through the tube and is anchored at the bottom of the bore in cement. The rod or wire extends to the surface where it is attached to a device that calculates the distance from the bottom of the rod or wire to the topographical surface on which it rests. As subsidence occurs, the length of the rod or wire between the bottom of the bore and the measurement device at the surface becomes smaller. The monitoring device records the change in distance as local subsidence. Extensometers report subsidence that occurs between the bottom of the bore to the topographical surface with a vertical accuracy near 3 mm (Reed & Yuill 2009).

By way of example, the Queensland Government has recently installed a bore line in the Condamine Alluvium that will be used to monitor subsidence on a transect across the alluvium on an ongoing basis (Moran & Vink 2010). The Queensland coal seam gas companies have also employed extensometers in the Surat region to monitor subsidence (Morris 2013).

Some advantages of extensometers include:

- detailed subsidence measurements can be achieved for a point source of subsidence, such as near a pumping bore
- extensometers measure near continuous subsidence during the period of instrumentation.

A key disadvantage of extensometers is:

- multiple extensometers are required to assess subsidence over a broad area, and to measure the cumulative subsidence due to the cumulative impacts from multiple pumping bores.

5.5 Radioactive bullet logging

This method involves shooting radioactive bullets into a formation at known depths. Each bullet contains a low strength, long-lived radioactive source, generally Caesium. The positions of the bullets are later resurveyed by a gamma-ray sonde and any change in position is used to measure compaction or expansion. The sonde may have up to four gamma ray detectors, which minimises the effect of unintentional tool movement by detecting two radioactive markers almost simultaneously.

A key advantage of bullet logging is:

- measurement error can be as low as 1 cm per 100 cm.

A disadvantage of bullet logging is (Poland et al. 1984a):

- logging time of approximately 20 m per hour is required for accurate measurements.

6 Remediation options

6.1 Overview

Limited options for remediating subsidence-related impacts were identified during this review. The options currently available are briefly considered below.

6.2 Potential options for remediation

Commonwealth and state approval conditions for coal seam gas developments include requirements to monitor, report and make good any observed subsidence associated with coal seam gas extraction. Current estimates of subsidence impacts are projected to be negligible, but local effects may present if variability in the fabric of the landscape results in highly compressible materials propagating their compaction to the surface.

The only effective remediation for regional subsidence would be to reduce groundwater pumping and return the system to pre-development water pressures. Reducing groundwater pumping is a common remediation method where excessive extraction has caused subsidence. For the coal seam gas industry, however, the extraction is necessary to bring pore fluid pressures down, so is an unavoidable consequence of operations.

If water pressures have to be regained, the following are standard measures to accomplish this (Poland et al. 1984b):

- substituting surface water
- conserving the application and use of water
- re-circulating and reusing treated water by industrial plants
- decreasing irrigated areas or industrial plants using large quantities of water
- moving the bore fields to tap more permeable (less compressible) deposits
- changing the depth range of perforated intervals in bore casings or screens to tap less compressible deposits
- regulating water distribution.

6.3 Artificial recharge at the surface

Land subsidence usually results from compaction of compressible confined aquifer systems due to intensive withdrawal of groundwater and consequent decline of artesian head. Because confining beds restrict the vertical downward movement of water from the land surface, artificial recharge of confined system(s) by application of water at the land surface directly overhead ordinarily is not practicable. However, the geology of the system may be such that the confined aquifer system may crop out at or near the margins of the ground-water basin. If this outcrop area is near enough to the subsiding area, artificial recharge on the outcrop area may raise the local water table and also the potentiometric head in the confined system (Poland et al. 1984b).

6.4 Reinjection bores

Repressuring of confined aquifer systems by artificial recharge directly through bores may prove to be the only practical way to slow down or stop land subsidence in a particular area. At the Wilmington oil field in southern California, repressuring of the oil zones to increase oil production and to control subsidence reduced the subsiding area from 58 to 8 km^2, over a period of 11 years, and locally the land surface had rebounded as much as 0.3 m (Mayuga & Allen 1969; Poland et al. 1984b). As with any other type of aquifer re-injection, the water quality needs to be carefully considered to minimise clogging of the bore screen and the formation. Risks associated with induced seismicity should also be considered (Gibson & Sandiford 2013; Royal Society & Royal Academy of Engineering 2012).

6.5 Current Australian practice

Some of the coal seam gas companies operating in Queensland are currently undertaking investigations to assess the feasibility of re-injecting associated water. Although re-injection can arrest and reverse surface subsidence, it has not been the main reason for the re-injection feasibility assessments; re-injection provides a convenient and practical method of disposal of associated water as opposed to storage and evaporation in surface dams. The construction of new evaporation dams is no longer a preferred disposal option of the Queensland Government. The suitability of water for re-injection depends on its hydrochemical character.

Reinjection of associated water extracted from Walloon Coal Measures back into the Walloon Coal Measures is not likely to be feasible during coal seam gas operations without storing water for significant periods of time. That is, until the gas production ceases, possibly not for 10 to 15 years. Reinjection into other aquifers affected by dewatering of the Walloon Coal Measures is the preferred option for the Queensland Government (Moran & Vink 2010).

A small risk identified overseas is that minor seismic activity can be generated when water is rapidly re-injected into pumped formations (Gibson & Sandiford 2013; Royal Society & Royal Academy of Engineering 2012). Appropriate hydrogeological investigations need to be carried out to ensure that re-injection is not going to reactivate pre-existing faults and joints, or create new shear planes from the sudden change in pressure distribution.

7 Summary and knowledge gaps

7.1 Overview

The section summarises the key findings of the review, including the knowledge gaps identified during the review.

7.2 Summary: coal seam gas extraction and subsidence

The extraction of large volumes of water from coal seams from the Surat and Bowen coal basins to enable coal seam gas production has been predicted to lead to compaction and associated settlement within the coal seams and other strata over time. While the effects of this settlement may propagate to the surface, bridging is likely to be a mitigating factor where extraction targets are in excess of 300 m deep and overlain by rocks of sufficient competency. This bridging effect is likely to minimise subsidence effects at the land surface. In the Surat and Bowen coal basins in Queensland, company estimates of land surface subsidence range from 30 mm to 850 mm.

Numerical groundwater flow models such as MODFLOW and FEFLOW are commonly used to predict subsidence induced by depressurisation of coal seams. They assist in estimating pore reduction volumes and hence, the maximum settlement potential. Reservoir simulation models are also used for a wide range of coal seam gas modelling, including estimation of settlement potential. Currently, all modelling undertaken by scientists for the development of coal seam gas operations in Queensland suggests that the subsidence impact from coal seam gas operations will be minimal and that it may prove to be of a similar magnitude to background landscape movement. Landform monitoring technologies are capable of detecting sub-centimetre changes in surface heights and these can be used to evaluate changes to the land surface during coal seam gas extraction activities.

InSAR has been used internationally to effectively measure and assess the magnitude of anthropogenic subsidence. The four coal seam gas companies operating in Queensland are collaborating in a regional InSAR study of historical and current earth surface movements to provide additional certainty for regulators and to address public concerns (Altamira 2012). In addition, the Queensland Government has recently installed a bore line in the Condamine Alluvium that will be used to monitor subsidence on a transect across the alluvium on an ongoing basis (Moran & Vink 2010). This combination of precise remote sensing and targeted ground measurements currently represents best practice for monitoring the subsidence-related impacts of coal seam gas extraction.

The techniques being employed by coal seam gas companies to monitor for subsidence (a combination of InSAR, extensometers and bullet logging) are capable of detecting the predicted amount of subsidence. Current subsidence management plans are following global best practice and should provide adequate data and information to enable early and on-going warning of any subsidence.

In the US, where coal seam gas has been extracted for several decades, there are emerging examples of land subsidence that can be attributed to coal seam gas extraction, ranging from 47 mm over three years to 83 mm over a further three years (Grigg & Katzenstein 2013; Grigg et al. 2012). Primary subsidence issues remain associated with shallow groundwater extraction in largely unconsolidated and clay-rich sediments. There may be a concern in Australia in areas where shallow coal seam targets immediately underlie alluvial systems, such as the Condamine Alluvium in Queensland. In this situation, propagation of dewatering effects may lead to direct settlement in the unconsolidated sediments. However, coal seam gas operators are unlikely to have an interest in developing coal seam gas wells in areas where there is extensive connectivity between the coal seams and over- and under-lying formations. This should limit the amount of depressurisation in formations outside the coal seams being targeted, hence settlement is likely to be focused within the coal seams and propagation to the surface minimised.

In the largely rural regions of Australia that are currently being developed there is unlikely to be a significant risk from subsidence due to groundwater extraction. In more urbanised areas, given the small magnitudes of total and differential settlement anticipated, and their broad spatial extent, the risk of either cosmetic or structural damage to infrastructure such as roads and buildings is anticipated to be low. However, each coal seam gas extraction project needs to be assessed on a case-by-case basis as the local spatial and temporal conditions are complex and highly variable; and even small potential subsidence impacts may be significant in some circumstances. Even small changes to the land surface due to subsidence may alter the overland flow paths in rivers and wetlands, potentially initiating new erosion features in susceptible areas. Compaction and associated settlement may also change the hydraulic properties of affected aquifers, particularly their storage, transmission, and conductive properties; and could lead to additional localised faulting and fracturing in aquifers and aquitards, altering the hydraulic connectivity within and between aquifers.

With the recent development of coal seam gas activities in Australia, there is currently little measured data to evaluate actual consequences of coal seam gas extraction on subsidence. For example, information on thresholds for the management of subsidence, particularly in relation to built and natural assets, is limited. This complicates monitoring and assessment processes and regulatory decision making, as it is difficult to compare estimates of subsidence or observed ground movement with thresholds of movement at which damage is likely to occur. Rigorous scientific investigations designed to inform the development of such management thresholds would help reduce uncertainty and strengthen regulatory decision making.

At present the only effective remediation process for regional subsidence is to reduce groundwater pumping and return the system to pre-development water pressures. While reducing groundwater pumping is a relatively common remediation method where excessive extraction has caused subsidence, the capacity of this process to reverse the effects of subsidence caused by coal seam gas extraction is as yet untested and would be heavily dependent on the geological properties of the affected rock strata. The extraction of groundwater is necessary to reduce pore fluid pressures within the coal seams to enable coal seam gas to flow and be extracted via the gas wells. Consequently, repressuring confined aquifer systems by artificial recharge directly through bores may prove to be the only practical way to slow down or stop land subsidence, but can only be undertaken if gas extraction ceases. While coal seam gas companies in Queensland are investigating the feasibility of re-injecting co-produced water to provide a solution for its disposal, this is unlikely to provide an effective treatment capable of limiting potential subsidence impacts.

Data to inform modelling is currently limited and the existing methods of prediction of subsidence from coal seam gas extraction are relatively simplistic and not likely to correctly reflect the deformation and bridging strength properties of the full profile above the depressurised and compressible zone. A further limitation on the estimation of settlement is the lack of information on actual storativity and specific yield characteristics and variability across coal basins. The input hydrological and geological parameters generally refer to values that have been developed for unconsolidated alluvial aquifers for dewatering studies.

There is at present limited coal seam gas subsidence monitoring data and information in the public domain. Geotechnical data for Australian rocks and geological formations are also limited. The collection, collation, and public reporting of such data across coal basins would help improve the science underpinning coal seam extraction.

Further work could be undertaken to improve geotechnical type software tools that can assign appropriate deformation and stress conditions to reflect more realistic behaviour for depressurised zones and related settlement. To help reduce uncertainty and strengthen the scientific rigour of associated geotechnical investigations, it is important to confirm the magnitude of settlement and other ground movement over time at each site and within a region. There is significant scope to improve the capacity to model and predict time-dependent subsidence behaviour. There is a long history of development of empirical equations that are applicable for underground coal mining operations and that allow forward predictions of potential settlement effects. There is, as yet, insufficient empirical information in the coal seam gas industry to develop similar relationships. A coordinated, combined effort is required to gather such information.

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