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

Australian Government
Department of the Environment

Knowledge report

Coal seam gas extraction: modelling groundwater impacts

This report 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. It was prepared by the Coffey Geotechnics and revised by the Department of the Environment following peer review.

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The report was revised by the Department of the Environment following peer review by Dr William Glamore (Principal Engineer, Water Research Laboratory, University of New South Wales) and relevant Queensland, New South Wales and South Australian Government departments.

Disclaimer

Contributors

A workshop held during the review of modelling approaches was attended by representatives from the Australian Government, the coal seam gas industry and regional groundwater modelling experts:

- Mr Sanjeev Pandey of former Qld Water Resources Commission
- Mr John Ross of AGL Energy Limited
- Mr Simon Gossmann and Mr St. John Herbert of Arrow Energy Pty Ltd
- Mr John Grounds and Mr Daniel de Verteuil of QGC Pty Limited
- Mr Todd Gilmer, Dr Kumar Narayan and Mr Glenn Toogood of Santos Ltd
- Dr Noel Merrick of Heritage Computing Pty Ltd
- Dr Frans Kalf of Kalf and Associates Pty Ltd
- Dr Ken Mills and Dr Winton Gale of Strata Control Technology Operations Pty Ltd
- Dr Geraldine Cusack, Science Division, Department of the Environment
- Mr Bruce Gray, Science Division, Department of the Environment.

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Summary

This report describes typical Australian coal seam gas environments and processes involved in coal seam gas extraction and outlines a range of modelling tools and approaches used to simulate groundwater impacts associated with coal seam gas extraction. The physical processes that occur within coal seam gas extraction are identified and the effectiveness of groundwater models to represent hydrogeological conditions at specific scales is discussed. Conceptualisation of the modelling process is specified as requiring rigorous consideration of objectives, assumptions, scale, connectivity of bores, data worth and uncertainty levels. Modelling approaches from simple analytical models to more complex numeric regional groundwater models with many assumptions are discussed. The functionality and optimal spatial resolution of numeric groundwater models are also outlined and summarised. A single modelling approach may not be able to represent a complex environment and therefore testing of assumptions, multiple models or approaches and model development may be necessary. Finally, the report identifies issues to consider when modelling the groundwater impacts from coal seam gas extraction. These may be useful for model evaluations, selection, approach, appropriate application, understanding scale limitations and model uncertainty analysis. Further knowledge requirements and future research areas also identified.

Coal seam gas extraction

Coal seam gas is extracted from coal seams at depths generally more than 200 m below the ground surface. Coal seam gas production involves the extraction of water and gas. Hydraulic fracturing processes can be used to enhance gas productivity. Australian sedimentary basins in which coal seam gas developments typically occur comprise consolidated sedimentary geological units such as sandstone, siltstone, mudstone and coal. The target coal seams vary in their lateral continuity and thickness. The continuity and geometry of target coal seams can significantly influence the extent of groundwater drawdown induced by coal seam gas extraction.

Coal seam gas extraction can create preferential fluid flow paths. Coal seams exhibit a dual porosity system, i.e. coal contains both micropores (within the coal matrix) and macropores (fractures, coal cleats). These structures affect fluid movement by creating non-uniform flow fields with widely varying velocities. For example, in coal the horizontal permeability varies in two horizontal directions and the vertical permeability of coal is typically lower than the horizontal permeability in either horizontal direction. Other factors that can impact flow include the gas content within the total fluid, geomechanical affects and surface-groundwater interactions.

Groundwater modelling, tools and approaches

Groundwater models used for coal seam gas projects can generally be divided into two types. Production-related models operate at the well or well-field scale and are used to predict gas and water production rates. Regional impact models can be used to predict broad-scale impacts of groundwater extraction, (such as depressurisation), potential changes to groundwater quality from induced leakage between aquifers, and other impacts such as changes to connectivity between groundwater and surface water.

The modelling process is an iterative process including conceptualisation, development (selection of variables, parameter estimation), and modelling (baseline simulations,

uncertainty analysis, presentation and documentation of outputs). The modelling process is influenced by, objectives, conditions, data and scale of impact.

Groundwater modelling tools

Groundwater modelling tools can simulate the potential groundwater impacts from coal seam gas production. These include analytical groundwater models and numeric groundwater models. Analytical models use comparatively simple mathematical algorithms and do not account for spatially varying parameters or for conditions that vary over time. These models are often used for preliminary assessments in the vicinity of individual wells.

Numeric groundwater models incorporate a time and spatial stepping procedure to predict groundwater behaviour over time and/or space. Numeric models include finite element and/or finite difference methods, axisymmetric flow models, reservoir models and regional groundwater models. Axisymmetric models assess 2D flow at the well-field scale under symmetrical conditions; reservoir models assess groundwater flow at the mine-scale; and regional groundwater models simulate water flow across larger areas, but are currently unable to estimate complex processes in the immediate vicinity of coal seam gas wells. Other models include solute transport models and surface-groundwater interaction models which can be analytical or numeric models.

Groundwater modelling approaches

Adoption of a particular groundwater modelling approach (including modelling tools) will depend largely on the modelling objectives, scale and geology of the study area, hydrogeological processes to be simulated and available data. These factors are typically identified, illustrated and possibly quantified in a conceptual model prior to developing a mathematical model. Analytical models can be useful for a preliminary assessment, while regional models are most suitable at the regional scale. An additional factor in designing a modelling approach is determining the acceptable level of uncertainty in model outcomes. Multiple approaches may be necessary to address all phenomena of significance.

Issues to consider for groundwater modelling

The report outlines ten issues to be considered when designing an approach to simulate the groundwater impacts from coal seam gas extraction:

- Models should represent the groundwater depressurisation and water flow rates as accurately as possible. The decision to use a multiphase flow model depends on the location and nature of groundwater, geology and acceptable uncertainty levels.
- The number and geometry of model layers should be congruent with available data and adequately represent the geological conditions of the coal seams, as well as the overlying and underlying strata and geological features (such as faults and other subsurface anomalies).
- If hydraulic fracturing has been undertaken or is proposed, the change in hydraulic conductivity of geological materials (including overlying and underlying strata) should be assessed.
- The significance of potential changes in hydraulic properties of the coal due to coal seam gas production should be assessed.
- Horizontal permeability of coal should be accurately represented in regional groundwater modelling, especially where production trials have indicated strong horizontal anisotropy in coal seam hydraulic conductivity.

- Models should include processes that adequately account for groundwater-surface water interactions and follow existing groundwater guidelines.
- Cumulative impacts should include those from the target coal seam gas development and all other groundwater users. If the cumulative impacts are likely to not be unknown or significant then explicit combined modelling of all activities should be undertaken.
- The impacts of coal seam gas developments on water quality should be assessed using qualitative or semi-quantitative methods, where quantitative methods are not possible.
- Assessment of potential impacts should acknowledge uncertainty in the modelling and, where possible, identify the sources of errors (such as conceptual model and parameter uncertainty) and quantify the level of uncertainty.
- Reporting on groundwater impacts should follow national guidelines, be sufficiently detailed to allow reproduction of modelling undertaken and present results in a manner that complies with regulatory requirements. More specifically, modelled impacts should be presented in a way that can be usefully interpreted in terms of uncertainty levels, baseline conditions, and requirements of prevailing water management plans, and should demonstrate an awareness of any concerns associated with the specifics of the proposed development.

Further knowledge requirements

Groundwater modelling parameterisation needs to account for the hydraulic properties of the coal seams, spatially varying hydraulic conductivity, the properties of faults and fractures and changes potentially caused by hydraulic fracturing (if undertaken).

To improve the knowledge base, the report outlines four areas which could be the subject of future research:

- the influence of flow phenomena and geomechanical effects (such as accounting for dual-phase flow, dual porosity of coal, gas liberation from coal and the effects of general groundwater depressurisation)
- surface water-groundwater interactions and access to more detailed groundwater monitoring data sets
- quantifying and reducing model uncertainty
- improved representation of hydrogeologic features, spatially varying hydraulic conductivity to increase our understanding of their influences on local and regional groundwater flow for greater understanding of the regional significance of results.

Abbreviations

Abbreviation	Description
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSG	Coal seam gas
km	Kilometres
m	Metre
ML	Megalitres
PJ	Petajoules
TJ	Terajoules

Glossary

Term	Description
Adsorption	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 systems (e.g. groundwater) will behave when a stress is applied.
Anisotropy	A term used to describe the variation of hydraulic properties of an aquifer due to directional dependence (as opposed to isotropy, which denotes identical properties in all directions).
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.
Biocides	A chemical substance or microorganism that can deter, render harmless, or exert a controlling effect on any harmful organism by chemical and biological means.
Bore, borehole	A narrow shaft bored into (and through) the ground. In this report, it is considered distinct from a *well*.
Boundary condition	Groundwater flow or head conditions applied within (or at the extremities of) the model domain.
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	Natural fractures in coal. They usually occur in two sets that are perpendicular to one another and perpendicular to bedding. The cleats in one direction form first and exhibit a high level of continuity. These are called ‘face cleats’. Cleats in perpendicular to face cleats are called ‘butt cleats’.
Coal seam gas	A form of natural gas (generally 95–97 per cent methane) typically extracted from permeable coal seams at depths of 300–1000 m.
Darcy flow	Liquid flow that conforms to Darcy’s law.
Darcy’s law	A constitutive equation that describes the flow a fluid through a porous medium such as rock or soil.

Term	Description
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.
Deterministic	A type of mathematical analysis that assumes no randomness in the input data. A deterministic model will thus always produce the same output from a given input data or initial state.
Dewatering	The removal or draining of groundwater by pumping, usually to enable a process (e.g. gas extraction), rather than for water supply.
Drawdown	The reduction in groundwater pressure caused by extraction of groundwater from a confined formation, or the lowering of the watertable in an unconfined aquifer.
Fick's law	Typically refers to Fick's first law: a mathematical law that describes diffusion (the movement of a substance from regions of high concentration to regions of low concentration).
Geomechanical	Relating to the movement/expansion/contraction of soil and rock.
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 there for storage. This does not include water held in underground tanks, pipes or other works.
Guar	The legume from which guar gum is derived. Guar gum is used to increase the viscosity of fluids.
Hydraulic conductivity	The rate at which a fluid passes through a permeable medium.
Hydraulic fracturing	Also known as 'fracking', 'fraccing' or 'fracture simulation'; 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.
Laminar flow	A water flow regime characterised by the flow of parallel layers with no disruption (such as eddies, cross flow or swirling) between the layers.
Langmuir isotherm	A mathematical relationship describing the covering or adsorption of a substance to a solid surface in relation to gas pressure or substance concentration.
Modelling approach	In this report a 'modelling approach' is defined as the use of a specific modelling tool.
Non-aqueous phase liquid	A liquid that is immiscible (does not mix/dissolve over a range of proportions) in water.
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.

Term	Description
Petajoule (PJ)	A measure of energy content equal to 1000 terajoules (TJ), 1 000 000 gigajoules (GJ), 1 000 000 000 megajoules (MJ), 10^{12} kilojoules (kJ) and 10^{15} joules (J). A cubic metre of methane (at standard temperature and pressure) releases 39 MJ during combustion. The volume of methane (at standard temperature and pressure) with an energy content of 1 PJ is 25.6×10^6 m^3 or 25 600 ML.
Preferential flow	Preferential flow refers to the uneven and often rapid movement of water and solutes through porous media (typically soil), characterised by small regions of enhanced flux (such as faults, fractures or high-permeability pathways) that contribute most of the flow, allowing much faster transport of a range of contaminants through that pathway.
Proppant	A solid material, typically treated sand or ceramic, designed to keep an induced hydraulic fracture open either during or following a fracturing treatment.
Regional-scale groundwater models	Models that encompass an entire groundwater system, geological basin or other significant area of interest that extends well beyond the measurable influence of individual bores or borefields.
Saturated flow	Flow through a porous medium (such as soil or rock) in which the void space within the porous medium is entirely occupied by water (as opposed to water and gas).
Stochastic	A type of mathematical analysis that can be used to assess the uncertainty associated with models. It estimates the probability distribution of potential outcomes by allowing for random variation in one or more input parameters.
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.
Unsaturated flow	Flow through a porous medium (such as soil or rock) in which the void space within the porous medium is occupied by water and gas (rather than water only).
Water quality	The physical, chemical and biological attributes of water that affects its ability to sustain environmental values.
Watertable	The upper surface of a body of groundwater occurring in an unconfined aquifer. At the watertable, pore water pressure equals atmospheric pressure.
Well	Borehole in which a casing (e.g. steel piping) has been placed to restrict connection to specific ground horizons/depths.

1 Introduction

This report focuses on the capability of numerical groundwater modelling to simulate the potential groundwater impacts from coal seam gas extraction. The intended audience includes water managers, regulators, state authorities, and interested parties who are not familiar with the details of coal seam gas production or groundwater flow analysis.

This report describes typical Australian coal seam gas environments and processes involved in coal seam gas extraction and outlines a range of modelling tools and approaches used to simulate groundwater impacts associated with coal seam gas extraction. The physical processes that occur within coal seam gas extraction are identified and the effectiveness of groundwater models to represent hydrogeological conditions at specific scales is discussed.

Conceptualisation of the modelling process is specified as requiring rigorous consideration of objectives, assumptions, scale, connectivity of bores, data worth and uncertainty levels. Modelling approaches from simple analytical models to more complex numeric regional groundwater models with many assumptions are discussed. The functionality and optimal spatial resolution of numeric groundwater models are also outlined and summarised. A single modelling approach may not be able to represent a complex environment and therefore testing of assumptions, multiple models or approaches and model development may be necessary.

Finally, the report identifies issues to consider in undertaking groundwater modelling. The issues to consider may be useful for model evaluations, selection, approach, appropriate application, understanding scale limitations and model uncertainty analysis. Further knowledge requirements and future research areas also identified.

The report does not address the impacts of subsidence due to coal seam gas production, consider risk management approaches or provide guidelines for groundwater modelling. It was produced largely using available literature and the author's own experience, groundwater modelling specialists and discussion with coal seam gas industry representatives without focusing on the results of any specific study or research project.

This report should be read in conjunction with the four appendices that cover the issues identified at the workshop, numerical models functionality, regional modelling considerations and an evaluation of modelling approaches. A project-specific early workshop was attended by groundwater modelling specialists and representatives from the coal seam gas industry and their expert opinions were considered in the development of this report. The discussions from the workshop on modelling the groundwater impacts from coal seam gas extraction are summarised in Appendix A. Appendix B outlines the basic functionality of a range of numerical models and there capacity to simulate chemical and physical properties and processes. Appendix C includes two regional groundwater models and one of these models is frequently used by Australian industry, government and an example of this model's application in the United States of America are also provided. The table in Appendix C outlines how the models are parameterised differently and the extent and type of uncertainty analysis undertaken. Appendix D evaluates four types of models for determining groundwater impacts, their advantages and disadvantages, the appropriateness of their application and scale sensitivities.

2 Coal seam gas extraction

Coal seam gas is a type of natural gas extracted from coal seams at depth (generally more than 200 m below the ground surface). It is also referred to as coalbed methane, coalbed gas, or coal mine methane. Coal seam gas is an increasing source of natural gas worldwide, and Australia has significant deposits. Its production requires the extraction of groundwater to depressurise (lower the water pressure) of the target coal seam and allow gas to be released. Coal seam gas developments in Australia are commonly located in rural areas with established groundwater abstraction (such as for agricultural, mining or domestic use). Proposed and existing developments lie within the Sydney, Gloucester, Gunnedah, Bowen, Galilee and Surat Basins within New South Wales and Queensland. The geological conditions in these basins typically comprise consolidated sedimentary rock units (sandstone, siltstone, mudstone), with interbedded coal seams. In parts of these basins, the layered sedimentary rock may be overlain by surficial alluvial deposits associated with creeks and rivers.

2.1 Coal seams and gas occurrence

Coal seams are typically interbedded between low-permeability rock units (strata), and of low thickness relative to other strata within geological basins. Coal seam gas comprises predominantly methane, with smaller quantities of ethane, propane, butane, nitrogen, carbon dioxide and other gases.

Coal seams possess both natural fractures and porous matrix blocks. The fractures are called ‘cleats’, which usually occur in two sets: perpendicular to one another and perpendicular to bedding. The cleats in one direction form first and exhibit a high level of continuity. These are called ‘face cleats’. Cleats in the other direction are called ‘butt cleats’, which are discontinuous and frequently truncated by face cleats. Due to their continuity, face cleats are more permeable than butt cleats, though both provide enhanced permeability compared with the permeability of the intact coal (Laubach et al. 1998).

The cleats divide individual porous matrix blocks that contain pores of varying size (ranging from a few nanometres to more than one micrometre). The nature of the coal structure means that coal exhibits a ‘dual porosity’ (dual region) system. In this system, fluids may be present within the voids or micropores of porous matrix blocks, which possess a certain storage capacity or ‘primary porosity’, and in open fractures (i.e. cleats), which possess a different storage capacity or ‘secondary porosity’. The orientation of face and butt cleats means that coal also exhibits anisotropy: the permeability of face cleats is typically five times that of butt cleats (Massarotto et al. 2003).

Coal seam gas exists in three forms: free gas within the pores and fractures, adsorbed to coal surfaces, and adsorbed within the molecular structure of the coal (Rightmire et al. 1984; Rice 1993; Shi & Durucan 2005a). Most gas held within coal seams is adsorbed to the coal surface in a compressed state (i.e. almost liquid). This adsorbed gas is exploited in coal seam gas production. Gas content within the coal tends to increase with quality (rank) of the coal, depth of the coal seam, and groundwater pressure.

Coal seams adsorb increasing volumes of gas—primarily methane, carbon dioxide and nitrogen—with increasing pore pressure. The sorption behaviour of coal seam gas conforms to a Langmuir isotherm (Robertson & Christiansen 2006) and a Langmuir relationship describes the coal seam compression or expansion behaviour of coal. The Langmuir

relationship describes how the adsorption (coverage) of a substance—in this case, coal seam gases—relates to pressure.

In the field, the gas content of coal can vary significantly depending on the setting, the geological history, and especially the pressure as a function of depth. Figure 1 illustrates the variability of methane content for coal samples from the Bowen Basin and the Hunter Valley (Esterle et al. 2006). The dashed line shown in the chart shows the maximum volume of methane that can be stored per tonne of coal for a representative coal grade. The actual content obtained from testing is below this limit, excluding a few outlying results.

Coal seam gas production is typically undertaken in coals of mid-rank (i.e. low to high-volatile bituminous coals), since desorption of coal seam gas from high-rank coals, such as anthracite, is very slow (Levine 1993; Rice 1993).

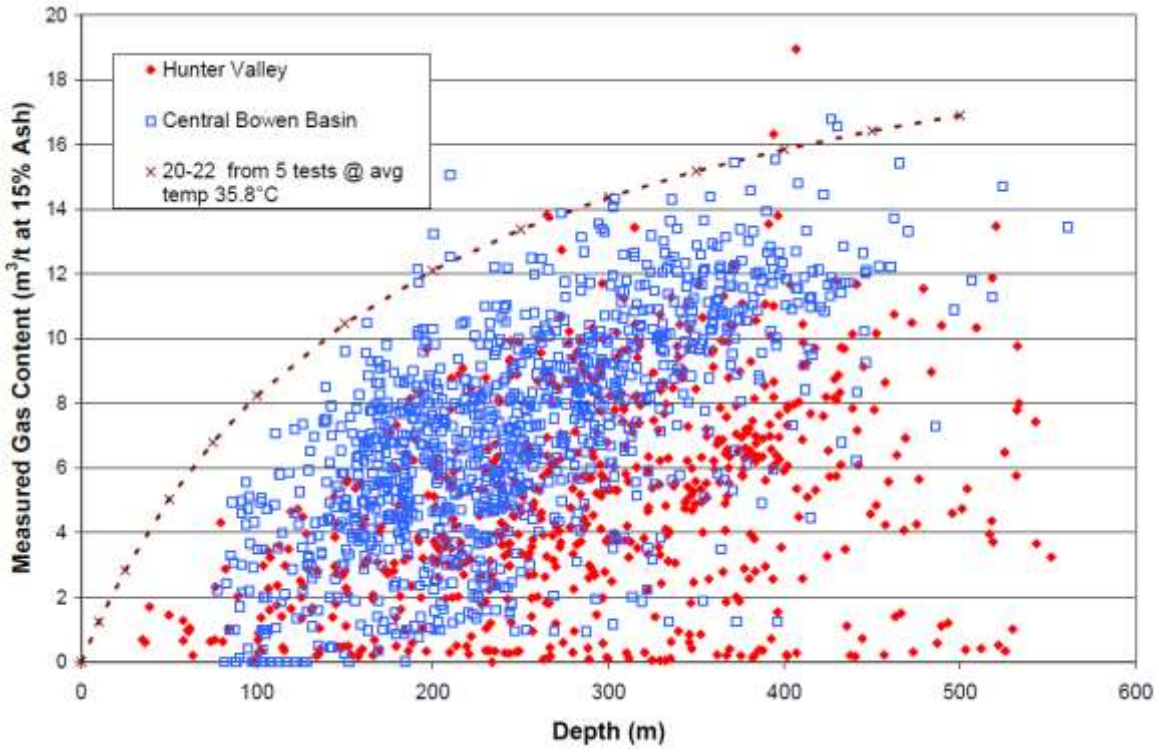

Figure 1 Variation of coal seam gas content against depth for Bowen Basin and Hunter Valley. Dashed line is the methane gas isotherm at the boundary of medium and low-volatile rank coal at a volatile matter dry ash free content of 20–22 per cent

2.2 Gas extraction

Methane gas can be extracted by introducing a more adsorbable gas, such as carbon dioxide; decreasing the methane partial pressure; or decreasing the reservoir pressure. Most of the world's coal seam gas is extracted by reducing reservoir pressure, which is achieved by pumping groundwater out of coal formations. The groundwater level remains above the coal seam, but the reduction in water pressure associated with the groundwater removal causes the coal seam gas to desorb from the coal (i.e. detach from the coal surface).

Enhanced coal seam gas extraction is an emerging technology that uses inert gas stripping (use of nitrogen to flush out methane) or displacement resorption (use of carbon dioxide to displace adsorbed methane). Because carbon dioxide and nitrogen adsorb to coal more readily than does methane, injecting carbon dioxide and nitrogen gas into the coal bed can displace the methane, which can then be collected. As of 2005, enhanced coal seam gas extraction had not been trialled in Australia, but had been trialled in the Unites States and China (Saghafi 2005). Parsons Brinkerhoff (2011) reports that the potential use of carbon dioxide injection to enhance methane production is limited, with no commercial projects in development at the time of reporting. The most referenced commercial-scale carbon dioxide-enhanced coal bed methane project was the Allison Unit Enhanced Coal Bed Methane Pilot in San Juan County in southern New Mexico. This operated from 1995 to 2001, producing some 30 000 tonnes of additional methane resulting from 335 000 tonnes of carbon dioxide injection.

Groundwater is pumped from coal formations using groundwater wells. Well construction first involves drilling a borehole to the depth of the coal seam from which extraction will take place. Target coal seam depths are typically 300 to 1000 m below ground surface. A steel casing (tube) is cemented in place within the borehole, and access to the coal seam is obtained at intervals along the length of the casing. The gas is separated from the groundwater either within the well casing and/or well head, which is preferable, or by compression at a compressor station at the surface. It is then sent to natural gas pipelines.

Bore construction details vary from place to place according to industry practice and regulatory requirements, although bores must be completed in accordance with The Minimum Construction Requirements for Water Bores in Australia (National Uniform Drillers Licensing Committee 2012). Horizontal bores drilled within the target coal seam can be used as an alternative to wells that are vertical only. A submersible pump is installed at the base of the well, and pumps water to the surface to reduce the water pressure within the coal seam, rather than fully dewater the seam. A conceptual diagram of a coal seam gas production well is shown in Figure 2.

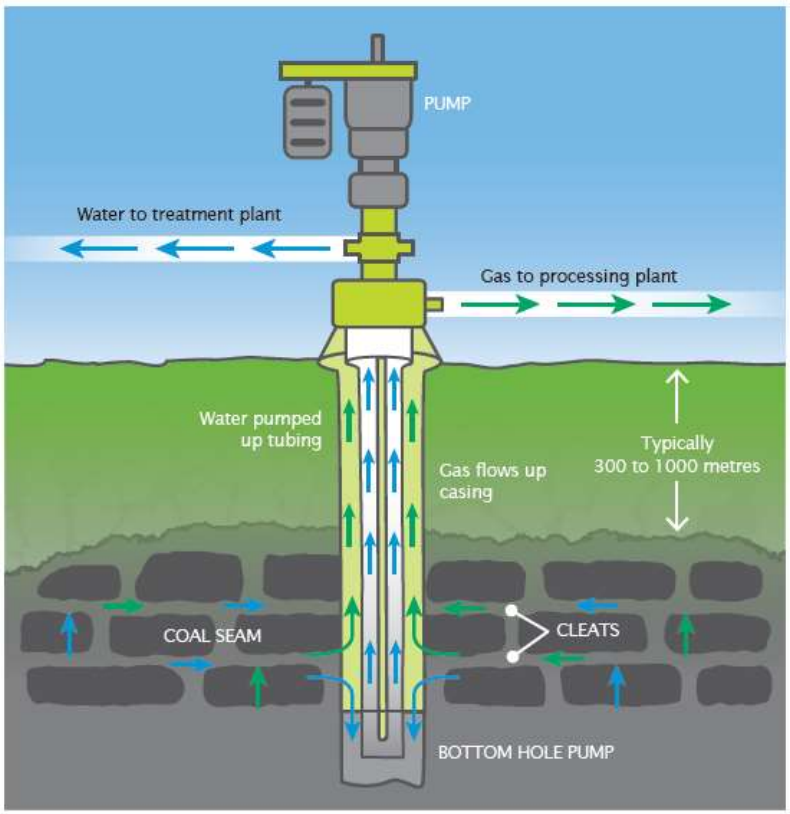

Figure 2 Conceptual coal seam gas production well

Under coal seam gas extraction, gas migrates:

- through fractures within the coal matrix
- by desorbing from coal cleat surfaces
- by diffusion according to Fick's first law through the coal matrix to the cleats (Gas Research Institute 1996).

The gas extraction process undergoes three distinct stages (McKee & Bumb 1987):

- Water is pumped from the coal seam to reduce the pressure. During this time, the predominant fluid flowing within the coal cleats is water, with minor dissolved and free gas. This stage is characterised by single-phase saturated laminar water flow from the coal seam to the well.
- After significant depressurisation (lowering the groundwater level to within 35–40 m of the uppermost coal seam; Queensland Water Commission 2012), gas desorbs from coal surfaces and diffuses from within the coal matrix to the cleats. Individual gas bubbles form, but remain immobile due to their isolation. The immobile gas bubbles partially impede the flow of water within the coal seam. This stage is characterised by single-phase unsaturated water flow within the coal seam.
- Further depressurisation increases gas desorption, such that a continuous gas flow occurs and gas bubbles connect to form continuous pathways to the extraction well. This

stage is characterised by dual-phase flow (i.e. separate water and gas phases) with the coal seam.

These different flow regimes occur in spatial sequence (McKee & Bumb 1987), progressing outward from the well and into the coal seam. That is, two-phase flow occurs near the well, unsaturated water flow occurs at some distance from the well, and saturated water flow occurs at greater distance from the well. The flow occurring within the saturated zone within the seam is laminar and obeys Darcy's law (an empirical relationship that states that the rate of groundwater flow is proportional to the hydraulic gradient). Figure 3 illustrates these flow regimes.

A typical coal seam gas extraction site will comprise multiple wells, referred to as a well field. Well spacing over a well field can vary widely depending on local conditions. For example, Arrow Energy Pty Ltd proposes to install production wells for the Surat Basin Gas Project on 800 m grid spacing, though those wells may be spaced as far apart as 1500 m in an irregular, non-grid-based pattern. This equates to an indicative density of one well per 65 ha (Arrow Energy 2012a). In contrast, the typical well spacing for production in the Powder River Basin is approximately one well per 16 ha (United States Department of Energy 2002), although this may vary over the region; Wheaton and Metesh (2002) quote one well per 311 ha over the Tongue River Member in the Powder River Basin that lies within Montana. Well spacing is selected to obtain the target groundwater depressurisation required over the well field to release the coal seam gas. The required depressurisation will depend on the properties of the aquifer and the gas-bearing coal seam. Additional wells may be installed over the lifetime of the development.

Groundwater extracted during coal seam gas production is called produced water (also known as co-produced water or coal seam water). The volumes of produced water under coal seam gas production are large relative to those extracted from conventional gas reservoirs. Produced water typically possesses elevated salinity and may require treatment (such as reverse osmosis) before disposal or use for other purposes, including agriculture. Produced water that has been treated may be re-injected into the ground (either in the vicinity of the well field or elsewhere), depending on regulations and availability of suitable aquifers.

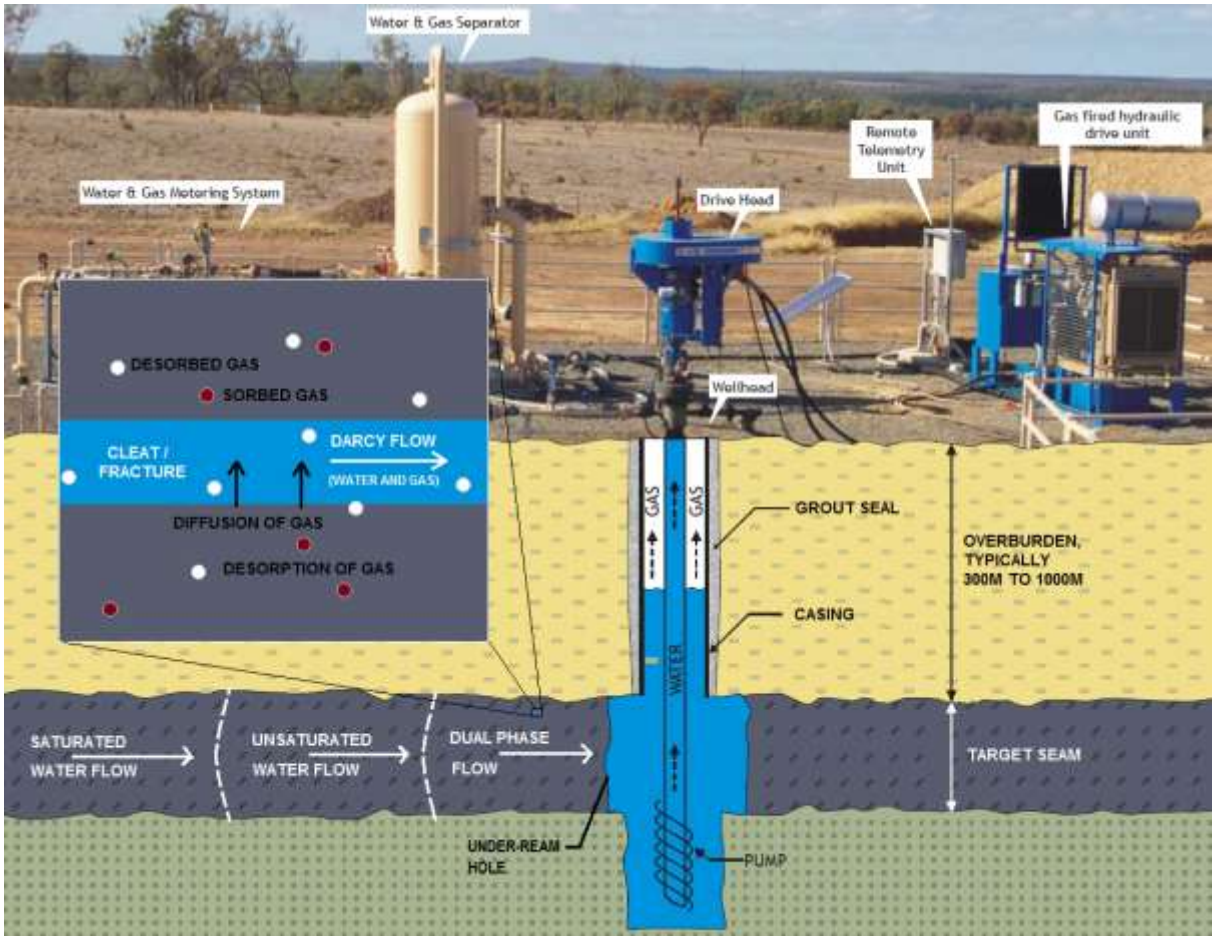

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Figure 3 Flow of water and gas to well within a coal seam

2.3 Hydraulic fracturing

Hydraulic fracturing increases the permeability of coal seams in the vicinity of a well to enhance gas productivity and reduce the number of wells required. It is also called hydraulic fracking/fraccing, hydrofracking/hydrofraccing, or simply fracking/fraccing.

The hydraulic fracturing process involves pumping a slurry down a well under sufficient pressure to dilate existing narrow coal fractures. The slurry comprises a proppant (a material that keeps a fracture open, typically sand) and a hydraulic fracturing fluid. The fluid may be water, oil, acid or multiphase-based. Gelling agents that increase the viscosity of the slurry are added to hold and distribute the proppant into the fractures. Conventional gels include cellulose derivatives or guar derivatives, although other gels may be used.

Hydraulic fracturing fluid is recovered after the fracturing process, while the proppant material remains in the open fractures, thereby maintaining their increased permeability. Typically, hydraulic fracturing slurry comprises more than 97 per cent water and sand (Queensland Government 2011), with the remainder being additives to control the pH, maintain the viscosity of the fluid or break down the gel at the conclusion of hydraulic fracturing, and reduce the growth of microorganisms.

Hydraulic fracturing can unintentionally cause fracture penetration to shallower strata. This creates hydraulic connections (groundwater flow paths) between the target coal seams and

shallower formations. Such connections may drain groundwater from shallower aquifers when coal seams are dewatered for gas production. This increases the amount of produced water without additional gas extraction, thereby reducing the efficiency of gas production. The influence on shallow aquifers and their ability to recover from groundwater drawdown/leakage due to coal seam gas production depends on the individual setting.

The length, width and hydraulic characteristics of fracture propagation due to hydraulic fracturing can be assessed using both indirect and direct fracture diagnostic techniques (United States Environmental Protection Agency 2004).

Indirect techniques include modelling pressures, production (injection) data analyses, use of geological information to estimate the shape and dimensions of fracture propagation, and use of radioactive tracers. In the latter technique, a radioactive tracer is added to the proppant fluid. The tracer is selected for its chemical properties, half-life and toxicity level to minimise potential contamination. The recovery of the tracer can then be tracked to assess the extent of hydraulic fractures.

Direct techniques include tiltmeter and microseismic mapping, in which instruments are placed within boreholes and on the surface to measure ground deformation and vibration as a result of hydraulic fracturing.

Microseismic monitoring involves installation of downhole geophones to measure minor seismic events (movements) that occur during hydraulic fracturing. The movements are the result of changes in stress and fluid pressure along natural existing fractures, bedding planes and areas of rock weakness. Tracking these minor seismic events allows the propagation of fractures due to hydraulic fracturing to be mapped.

Based on seismic data, Davies et al. (2012) found that due to hydraulic fracturing, 80 per cent of existing fractures within United States shales propagated vertically upwards between approximately 30 and 80 m. Johnson et al. (2010) analysed tiltmeter and microseismic monitoring data from hydraulic fracturing tests in the Walloon Coal Measures of the Surat Basin, Queensland. The majority of data suggested vertical fracture heights of between 50 and 130 m at depths of approximately 600 to 700 m below ground surface.

Further, data relating to the potential natural hydraulic connection between coal beds and overlying or underlying aquifers is limited. The National Research Council (2010) cites only one study (Riese et al. 2005) that explored this phenomenon in United States coal seam gas fields, and states that this is a significant information gap.

2.4 Water and gas yield

During the initial depressurisation stage of coal seam gas production, groundwater is extracted at a constant and relatively high rate, and the volume of gas extracted is low. Following depressurisation, water production reduces significantly and gas production increases. After the gas production rate peaks, water production is relatively low and gas production continues at a gradually reducing rate. These trends are illustrated in Figure 4.

Some coal seams possess ‘free gas’ within the coal cleats (fractures), allowing early gas production before significant depressurisation: for example, the Anderson, Canyon and Wyodak seams within the Fort Union Coals of the Powder River Basin (United States Department of Energy 2002). However, this is not common in Australia.

The volumes of extracted gas and produced water vary widely between different well fields. For example, the range of production was between 0.004 and 78.0 (mean 3.9) PJ of gas per ML water per coal seam gas operational facility in Queensland for the financial year 2010–

2011 (Queensland Government 2012). The upper production rate of 78.0 PJ of gas per ML of water is equivalent to approximately 2 Gm^3 of gas (approximately four times the volume of Sydney Harbour) per ML water. A typical coal seam gas field in the Surat Basin contains approximately 5.1 PJ/km^2 of recoverable gas (Origin Energy 2012).

Gas fields for the Arrow Energy Pty Ltd Surat Basin Gas Project are expected to achieve peak production of approximately 1050 TJ/day at an estimated four or five years after commencement, after which production at a declining rate is expected to continue for a further 20 years (Arrow Energy 2012a).

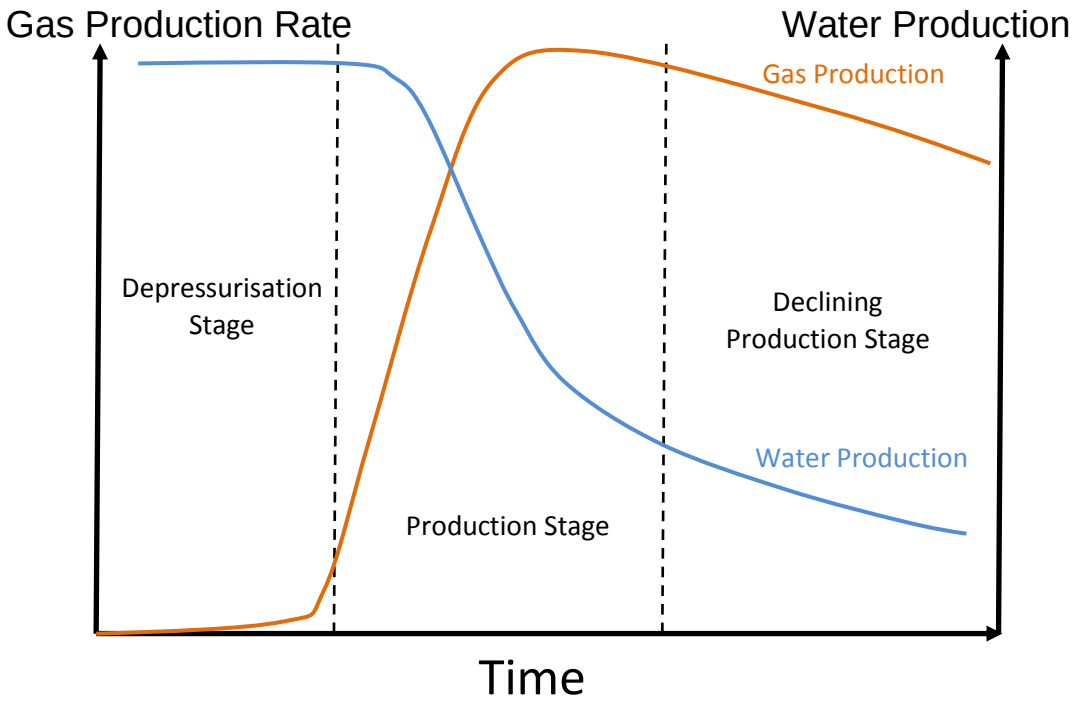

Figure 4 Conceptual gas and water extraction rates with time

2.5 Typical coal seam gas regional environment

Australian coal seam gas developments are often located in rural areas that have established agricultural and domestic use of groundwater. Existing and proposed developments lie within the Sydney, Gloucester, Gunnedah, Bowen, Surat and Galilee Basins within New South Wales and Queensland.

The geological conditions in these basins typically comprise consolidated sedimentary rock units (sandstone, siltstone, mudstone), with interbedded coal seams. In parts of these basins, the layered sedimentary rock may be overlain by surficial alluvial deposits associated with creeks and rivers.

Coal measures are the geological sedimentary unit in which potentially multiple coal seams are interbedded within a sedimentary profile. The coal seams themselves can range in thickness from centimetres to many metres. They may be laterally continuous, or they may pinch out, resulting in laterally discontinuous seams. For example, the Gloucester Coal Measures of the Gloucester Basin contain multiple continuous, relatively thick coal seams,

while coal within the Walloon Coal Measures of the Surat Basin is in the form of discontinuous and relatively thin seams. Figure 5 shows the geological profile in the vicinity of coal seam gas developments in the Camden and Surat Basins.

The geological units are generally layered, but may exhibit geological features, such as faults, folds, intrusions, slides and other subsurface anomalies, which may penetrate multiple geological units within the sequence. The target gas-bearing coal seams are typically greater than 300 m below the ground surface.

The geological materials of sedimentary basins, including those in which coal seam gas production occurs, exhibit wide-ranging hydraulic parameters. Nevertheless, broad characterisation of the hydraulic characteristics of each sedimentary basin is possible. The hydraulic characteristics are dependent on the local and regional hydrogeological conditions, which are the result of the tectonic setting and structural history of the basin.

As a result of these geologic histories, coal permeability in the Gloucester, Sydney and Bowen Basins is relatively low, and sufficient groundwater depressurisation can be attained in a coal seam gas well field to produce gas within days or weeks. The produced gas and water volumes are relatively low, and commercially viable production requires a greater number of wells per square kilometre. In contrast, the relatively high permeability coals of the Surat Basin have higher water and gas production rates, and commercially viable production is possible with lower density well spacing, but it can take months to attain target depressurisation levels (Holmes & Ross 2009).

Groundwater quality, or chemistry, is affected by geological conditions, recharge characteristics (proximity to recharge zones, recharge rates and groundwater flows), and groundwater residence time in the host geological units.

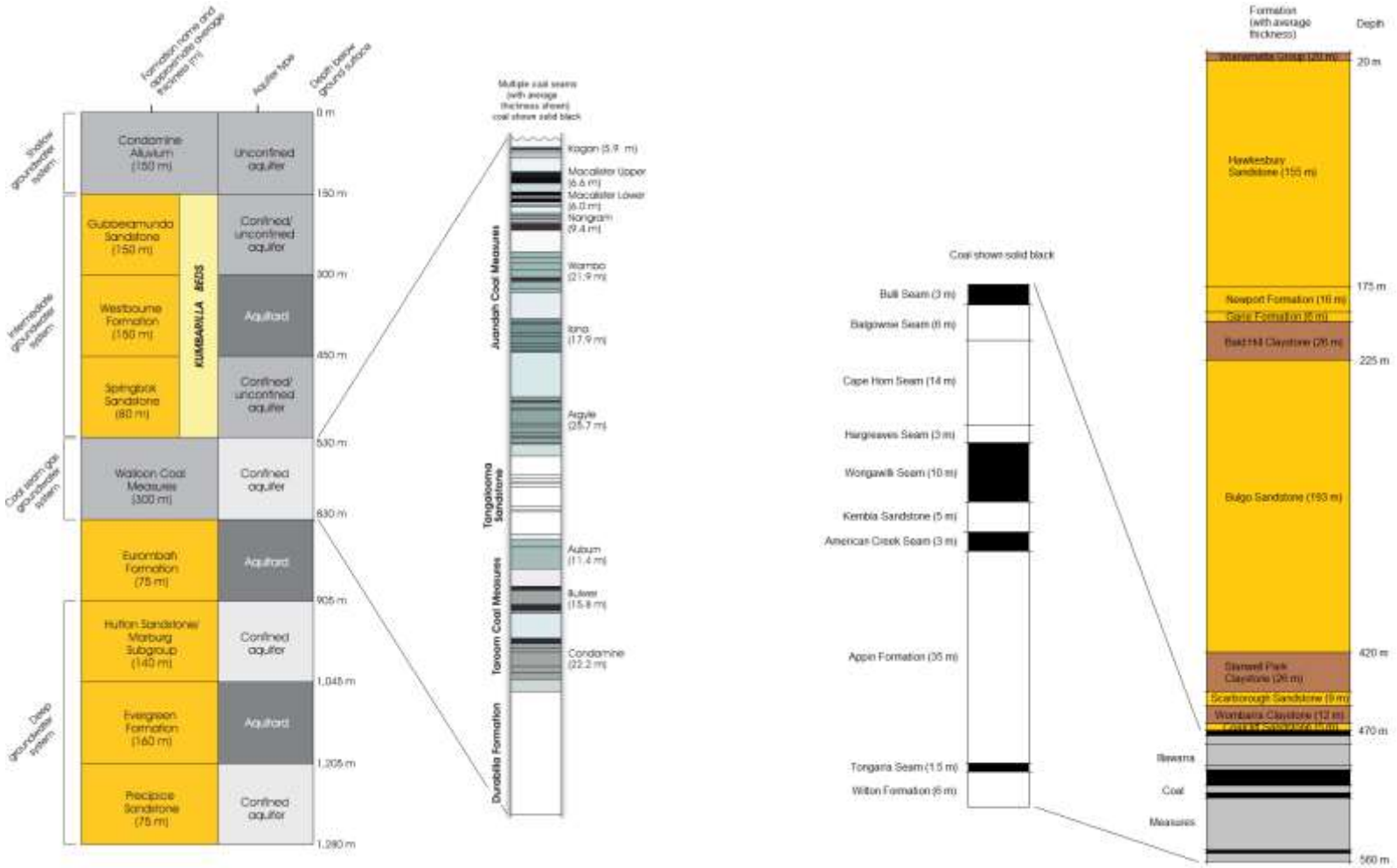

Figure 5 Geological profile in the vicinity of coal seam gas development for the Surat Basin (left) and Camden area of the Sydney Basin (right)

3 Physical processes of coal seam gas production

3.1 Dual porosity

Coal seams exhibit a dual porosity system, in which the coal material possesses both micropores (primary porosity, within the coal matrix) and macropores (fracture porosity, comprising the coal cleats). These structures affect fluid movement by creating non-uniform flow fields with widely different velocities.

Where such phenomena occur, the macropore flow is often referred to as preferential flow. Preferential flow leads to a non-equilibrium situation with respect to the pressure head or the solute concentration, in that flow occurs more readily along cleats and bedding partings, while water contained within pore spaces within the coal blocks takes time to be released and join flow along the preferred flow paths.

The process of gradual drainage of gas or water from micropores in the coal blocks is not captured in groundwater modelling tools that do not account for dual porosity coal. The significance of this effect depends upon the time scale for migration of water (or gas) from within the coal matrix blocks to the cleats. Where changes in groundwater level are slow in comparison with this time scale, the behaviour can be modelled by assuming water is fully released from within the blocks. The validity of this assumption depends on the hydrogeological conditions, and requires assessment on a case-by-case basis. This would typically be the case away from the pumping wells, where groundwater level changes would occur gradually over time. Where changes in groundwater level are rapid compared with the time scale for release of water from the blocks (such as may be the case in coal seam gas well fields), this release can be disregarded in the short term, because the water from within the blocks does not have time to contribute to the flow process. For the intermediate situation, such simplified treatment may be inadequate to address important aspects of the groundwater response to coal seam gas production.

A method for modelling flow in dual porosity systems was developed by Warren and Root (1963). It considers movement of water from the primary porosity (within the blocks) to the secondary porosity (fracture system). A series of charts is provided illustrating the impacts on pressure change resulting from dual porosity effects. Gerkhe and Van Genuchten (1993) discuss approaches to modelling dual porosity systems and present a finite element approach.

Implementing a dual porosity model carries computational overheads and complexities, and it is not generally incorporated into general-purpose regional groundwater modelling tools. One difficulty with models that directly address dual porosity behaviour is the lack of data on parameters that control the process, such as fracture spacing, matrix permeability, matrix and fracture porosity and permeability. The unavailability of such data leads to uncertainty associated with model predictions.

To accurately model groundwater flow in the near-field, models need to account for the dual porosity nature of coal. This is important for design of well fields. The scale over which dual porosity effects are important is not typically considered in regional modelling of groundwater flow. This represents an implicit assumption that is not tested in relation to simulating groundwater impacts from coal seam gas extraction. The groundwater drawdown and

produced water volumes predicted by the model may differ depending on whether or not a dual porosity system approach is undertaken.

Models that account for dual porosity coal are discussed in Section 6. The list of groundwater modelling software provided in Appendix B indicates which software accounts for dual porosity systems.

3.2 Anisotropic nature of coal

Anisotropy describes the condition under one or more of the hydraulic properties of an aquifer vary according to the direction of flow. Coal is anisotropic, and it exhibits properties that differ according to the direction of movement and the orientation of the cleats, and this influences macropore flow. Face cleats are aligned in one direction, and typically have higher permeability than butt cleats. The horizontal permeability in the direction of face cleats (K_f) is typically five to ten times higher than the horizontal permeability in the direction of butt cleats (K_b), as shown in Figure 6. Further, the vertical permeability (K_v) is typically lower than the horizontal permeability (in either horizontal direction) (Massarotto et al. 2003). While coal exhibits both horizontal and vertical anisotropy, the relative magnitude varies with cleats and directionality.

Modelling of groundwater flow through coal seams therefore requires consideration of both the horizontal and vertical anisotropic nature of coal. The modelling tools widely used for regional groundwater impact assessment (such as MODFLOW and FEFLOW) can account for these factors.

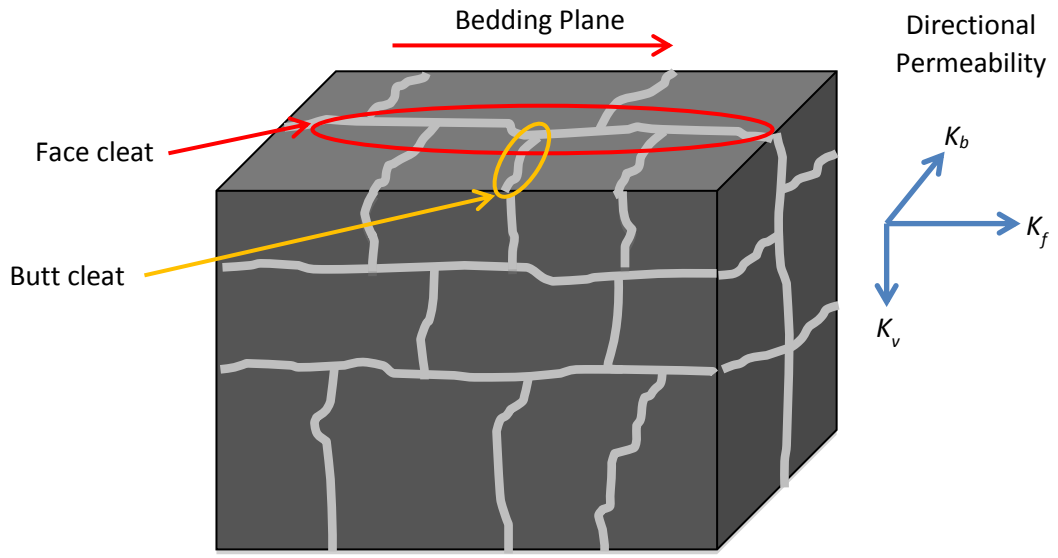

Figure 6 Permeability anisotropy of coal

3.3 Dual-phase flow and unsaturated flow

As discussed in Section 2.2, gas extraction involves three distinct flow stages, which propagate spatially from the well into the coal seam and are distinguished by the presence of gas within the total fluid. The three flow stages are saturated single-phase water flow, unsaturated single-phase water flow, and dual-phase (water and gas) flow (Figure 3).

To accurately model groundwater flow in the near field, models need to account for multiphase flow (i.e. either single or dual phases) and variably saturated water flow (i.e. water flow may be saturated or unsaturated). Regional groundwater impacts in the far field may not require such behaviour to be modelled if the influence of dual-phase flow and unsaturated flow are insignificant over this scale. The impacts of regional-scale dual-phase flow on groundwater under coal seam gas extraction are relatively unknown. Typically, dual-phase behaviour is not considered when assessing regional groundwater impacts of coal seam gas extraction in Australia. Research to identify the influence of this neglect on regional predictions would be of benefit as regional-scale models are an important tool for determining cumulative impacts.

3.4 Geomechanical effects

During coal seam gas production, the permeability of coal may be modified in the following ways:

- Reduction of groundwater pressure (by pumping) increases stress carried by the coal matrix. This causes compaction and closure of fractures (cleats), reducing the permeability within the coal. (Note: injection of water can result in the reverse phenomenon).
- Desorption of coal seam gas causes the coal matrix to shrink, while re-adsorption causes it to expand. The shrinkage of the matrix increases fracture openings, thereby increasing the permeability of open fractures (cleats).

Of these two permeability modification mechanisms, matrix compaction and reduced fracture permeability tends to dominate during the early stages of production, when large reductions in groundwater pressure yield small volumes of gas. In contrast, matrix shrinkage tends to dominate during later stages of production, when large volumes of gas are associated with relatively small continuing reductions in groundwater pressure (Morad 2006). Thus, the permeability of coal typically reduces during the early stages of production, and increases during later stages.

Wu et al. (2011) discuss these processes, review background literature and present a model for analysis of methane recovery. Their model incorporates the effects of coal shrinkage from gas desorption, changes in permeability due to stress changes, dual-phase flow, and stress changes in the coal. Capturing these processes within a numerical model significantly increases the complexity of the model formulation, and typically restricts model application to behaviour in the vicinity of an individual extraction well.

Figure 7 illustrates the modification in coal permeability due to pore pressure changes, based on three different types of comparative analysis for determining permeability. As depressurisation progresses (i.e. pore pressure decreases), coal permeability decreases, and then rises. The detail of the relationships illustrated in Figure 7 will change according to the modulus (stiffness) of the coal, as well as its structure (cleating), porosity, initial gas content and gas sorption properties.

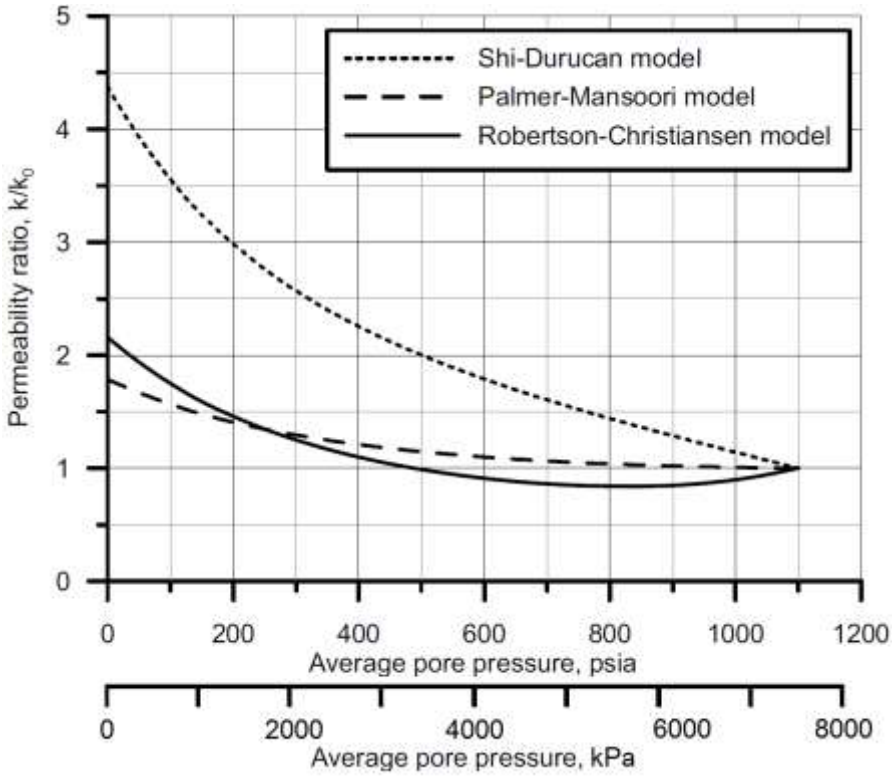

Figure 7 Permeability modification of coal due to pore pressure changes predicted by three different models (k/k_0 is the ratio of the current permeability to the initial permeability)

3.5 Hydraulic fracturing

The purpose of hydraulic fracturing is to increase the permeability of target coal seams, as well as the extent of hydraulic connection within them. Hydraulic fracturing is typically undertaken before coal seam gas production, but is sometimes conducted during the production phase in an attempt to increase production. Groundwater modelling should take into account permeability changes induced by hydraulic fracturing, because they may increase groundwater flow within the aquifer system, and also cause hydraulic connections between the coal seam and overlying or underlying stratigraphic units.

3.6 Solute transport

It can be important to predict the transport, or migration, of dissolved substances (solutes) within groundwater, such as salts, under coal seam gas operations. Such information may be useful in the following contexts:

- The groundwater extracted from aquifers under coal seam gas production may be saline, rendering it unsuitable for certain uses. Predicting the groundwater quality of produced water can be useful for assessing potential uses or likely treatment options for produced water.
- If there are hydraulic connections between aquifers either above or below the coal seams from which coal seam gas is extracted, groundwater quality in aquifers adjacent to the coal seams may be affected by the quality of the groundwater being drawn in from more remote aquifers (e.g. saline water drawn from shallow aquifers to deep aquifers, due to deeper coal seam gas operations). Impact assessment may include simulating the

potential impact of operations on the groundwater quality of prominent and/or near-seam aquifers.

- The migration of additives in hydraulic fracturing fluids may be of concern. Impact assessment may include simulating potential migration of chemical compounds within hydraulic fracturing fluids.
- Re-injection of untreated produced water may alter the groundwater quality of aquifers in the vicinity of the points of injection. For example, untreated produced water may be more saline than native groundwater.

3.7 Surface water–groundwater interaction

Due to the required extraction of groundwater, coal seam gas production may affect surface water by either increasing or decreasing their interaction with groundwater. A surface water–groundwater interaction involves any flow of groundwater between aquifers, rivers, streams, lakes, seas, wetlands, marshes, swamps or estuaries.

When surface waters are not significantly affected by groundwater fluxes, models that represent surface waters by standard boundary conditions are expected to be sufficient to adequately model behaviour. However, when surface waters are significantly affected by groundwater flow exchange (e.g. changing from a gaining to a losing stream), a coupled surface water–groundwater modelling approach may be required. The Australian groundwater modelling guidelines (Barnett et al. 2012) provide guidance on suitable modelling approaches for surface water–groundwater interaction. Rassam et al. (2012), Rassam and Werner (2008) and Rassam et al. (2008) also provide useful guidance. Consideration should also be given to *Guidelines for groundwater protection in Australia* (Australia and New Zealand Environment and Conservation Council 1995). To reduce uncertainty in groundwater model outputs, the boundaries must reflect actual flows so accurate predictions of groundwater impacts can be determined.

3.8 Potential impacts of coal seam gas extraction

Coal seam gas production poses a range of potential impacts to water-related and water-dependent ecosystems. For a particular coal seam gas development, identifying the most significant risks will require an understanding of the local setting. Groundwater modelling may be required to simulate the potential degree and extent of impacts from coal seam gas production.

Two coal seam gas production processes that could have negative impacts on groundwater are depressurisation and disposal of produced water. Other events, such as accidents or human errors, could also have negative water-related impacts.

Depressurisation of local and adjacent connected aquifers could result in:

- reduced groundwater supply to existing and future groundwater users
- reduced flows to groundwater dependent ecosystems including
  - altered groundwater baseflow to streams, rivers, lakes or ponds, as well as delayed groundwater response to recharge and/or discharge
  - reduced water availability in sensitive wetlands or swamps by compromising underlying horizons upon which groundwater may be perched.
- modification of the location and/or flow rate of hillside groundwater springs

- ground subsidence

Storage and disposal of produced water could result in:

- overflow of produced water from containment, with potential loss of the water resource and/or contamination of the aquifer receiving the overflowing water
- impacts associated with produced water re-injection, such as changes to groundwater quality and modification of hydraulic properties in the vicinity of the injection location.

Accidents or human error could result in:

- leaks, spills or seepage into shallow aquifers
- vertical leakage within groundwater systems through incorrect or incomplete well installation.

4 Introduction to modelling the impacts of coal seam gas on groundwater

4.1 What is modelling?

A model is a human construct developed to represent a real-world system. It is used to provide a better understanding of the real-world system; for example, by studying the system for the purpose of controlling or optimising it, or to predict how the system will react to hypothetical changes. In the natural sciences—physics, geology, biology and chemistry—models that are used to simulate natural systems and predict impacts are almost exclusively mathematical. They simulate natural processes using one or more governing equations (usually differential equations), and associated boundary and initial conditions. The model consists of a set of matrices of system parameters that define the initial system conditions according to the adopted discretisation of time and space.

The process of modelling involves the use of the model in conjunction with an algorithm to solve the governing equations and produce outputs of interest. The algorithm is a set of mathematical operations representing the governing equations, which usually take the form of a computer program. The governing equations may be solved analytically (i.e. directly) or numerically. The numerical solution of the governing equations under the imposed boundary and initial conditions is collectively known as numerical modelling. Algorithms used in numerical modelling can be complex, depending on the number of natural processes (and corresponding governing equations) being solved, and the detail to which the natural system—and therefore, the boundary and initial conditions—is discretised. An algorithm may be modular, and is usually known as a package or platform. Barnett et al. (2012) refer to the algorithm as themodel code'.

A mathematical representation of a series of natural continua that comprise a natural system has inherent uncertainty. This is due to the limitations imposed by the ability of the governing equations to replicate the system, and the uncertainty inherent in making measurements of physical properties of the system (for use in conditioning the model). Barnett et al. (2012) summarise these major sources of uncertainty as error in field measurements, and failure to capture the complexity of the natural system.

4.2 Groundwater modelling objectives

Groundwater modelling plays an important role in assessing the potential water-related impacts from coal seam gas production. Modelling objectives focus on simulating the potential impacts to inform environmental planning decisions and support design of mitigation measures to reduce or avoid such impacts. Simulations often form part of environmental impact assessments for development approval, but may also be undertaken to review conditions during production.

Models used to simulate the water-related impacts from coal seam gas production tend to focus on the following aspects:

- predicting the depressurisation of aquifers (drawdown of groundwater levels) and recovery of those aquifers when production ceases. This includes aquifers that are

hydraulically connected to the coal seams being depressurised, and at both the near-well scale and regional scale. Predictions of groundwater drawdown may be used to assess potential impacts on existing groundwater users (e.g. loss of groundwater availability to water supply wells/bores), groundwater-dependent ecosystems (e.g. availability of groundwater to wetlands or springs), or surface water (e.g. baseflow to rivers and lakes). For example, regional impact models may be used to assess reduction in groundwater flows to surface water, such as lakes or streams (e.g. Schlumberger Water Services 2012)

- estimating the volume of produced water and its quality. This information is required to plan and design treatment, use and disposal of produced water
- simulating the impact of re-injection of (potentially treated) produced water on groundwater levels and quality
- predicting changes to groundwater quality (e.g. through mixing water of different qualities due to vertical leakage induced by groundwater depressurisation)
- predicting changes in connectivity between groundwater and surface water (see Brunner et al. 2009; Brunner et al. 2011).

Groundwater abstraction for purposes other than coal seam gas production may simultaneously take place in the vicinity of coal seam gas well fields. For example, groundwater abstraction for irrigation, industrial, mining or domestic use, or from existing coal seam gas well fields, will further draw groundwater levels down in the vicinity of a proposed well field. The impacts of all groundwater abstraction can be cumulative. Therefore, the impacts from adjacent coal seam gas development production and other groundwater users (such as for agriculture, industry or domestic use) should be assessed along with the impacts of the specific coal seam gas development under study. Cumulative impacts need to be considered in concert with other modelling objectives and processes.

Groundwater models may also be used to assess the potential impact of hydraulic fracturing on aquifer properties (including interconnectivity of aquifers and enhanced permeability), and estimate groundwater depressurisation to support predictions of potential ground subsidence (Coffey Geotechnics 2014).

Contamination of aquifers by leaks or spills at the ground surface, or incorrect well installation, is normally associated with equipment failure or human error during coal seam gas development or operation. It is therefore not a specific focus of groundwater modelling; however, such work has been the focus of the Australian Government's National Assessment for Chemicals Associated with Coal Seam Gas Extraction in Australia project.

4.3 The modelling process

Modelling typically comprises the following three stages:

- Development of a conceptual (hydrogeological) model:
  - characterisation of the hydrogeological conditions, including the stratigraphic units, geometries and time scales of flow components within the system
  - identification of the water inputs and outputs (e.g. pumping activities, rainfall recharge, surface water interaction) for the broader hydrogeological and hydrological system under study
  - simplifications in the representation of the natural system are made, subject to data availability and the scale of the representation.

- Development of a mathematical model, which may include the following:
  - selection/development of an analytical model, or building a numerical model (typically using computer software) to represent the system:
    - simplifications in the representation of the system may be made in accordance with model objective, available data and knowledge of the system, and the capabilities of the analytical model or numerical modelling tool adopted
    - the conceptual model of the natural system is transferred to a mathematical description (using matrices) to allow deterministic analysis.
  - selection of parameters and parameter values to represent the system:
    - assumptions must be made to parameterise the system. The relevance, accuracy and adequacy of parameters to represent the system is considered at this stage (or preceding stages) of the modelling exercise
    - the model is calibrated to measurements of the natural system. This is the process of conditioning the model representation with available observations to produce a tool for deterministic use. It involves matching model results to historical observations, such as water levels, and can provide confidence in the model's ability to accurately simulate potential impacts
    - observations used for calibration are known as calibration targets and comprise measurements of hydraulic head, shallow and deep groundwater fluxes (e.g. extraction from a well or baseflow to a river), and hydraulic conductivity measurements.
- Modelling:
  - use of the model to determine various required outputs, including:
    - simulation of baseline data (as a reference) and predicted impacts
    - assessment of the uncertainty in the outputs calculated using the model. The two most important sources of uncertainty are errors in measurement of observations, and shortcomings in the conceptual model used to describe the natural system
    - analysis and presentation of simulation results. This should include presentation of the uncertainty associated with model results.

Groundwater modelling is an iterative process. The conceptual model and mathematical model are continuously revised as the modelling exercise progresses and more data become available.

In all three stages, and particularly in the first stage, collaboration between groundwater modellers, hydrogeologists and coal seam gas project managers is essential. This communication process can help the modellers gain insights from the stakeholders and help stakeholders to understand the model's limitations. Quality assurance processes and reviews are needed in the early stages and throughout the modelling lifecycle. Uncertainty estimations for the simulated impacts of coal seam gas also need to be calculated and reported.

The modelling process will be influenced by the:

- particular groundwater processes to be simulated. Individual phases of the coal seam gas production process that may be relevant to modelling are:
  - depressurisation phase
  - stable production phase
  - declining production phase
  - groundwater recovery (post-production).
- spatial scales over which groundwater flow occurs. These can be categorised as:
  - near-well—flow in vicinity of the production well
  - near-field—flow in vicinity of the well field, typically extending beyond the most outer well of the well field to distances of up to the typical well spacing distance
  - far-field—flow at distance from the well field, typically at distances greater than the well spacing distance beyond the most outer well of the well field.

Groundwater models used for coal seam gas production projects generally fall into one of two broad categories: production-related models and regional impact models.

Production-related (near-well and near-field) models are used to predict gas and water production rates. Because water production rates are relevant to groundwater impact assessment, they are sometimes used to help simulate potential impacts to groundwater due to production in the vicinity of production wells.

Regional (far-field) impact models are used to directly simulate the water-related impacts from coal seam gas production. They are not suitable for near-well analysis. However, they can be designed with boundary conditions to represent well-field processes that are appropriate for simulating regional groundwater impacts. For example, constant groundwater head conditions can be applied within the well field to represent the depressurisation condition imposed by coal seam gas production, or groundwater pumping rates can be applied at locations within the well field to represent the groundwater extraction imposed by coal seam gas production.

4.4 Model development

4.4.1 Model parameters

The development of models requires data to delineate geological strata; geological features, such as faults, folds, intrusions, slides and other subsurface anomalies; and surface water systems, such as rivers. Data are also needed to identify the location of groundwater monitoring and groundwater abstraction wells, and to characterise groundwater recharge zones.

Additional data are required to define the hydraulic properties of geological materials and to model boundary conditions, which represent features such as lakes, streams, or areas of particular groundwater flow conditions. Because ground conditions are naturally heterogeneous, models require some simplification to be tractable. Surface recharge to the groundwater system should involve consideration of unsaturated zone flow processes and surface lithologies.

The method of obtaining model parameter values, and the spatial or time scale at which those values were obtained, is important. For example, the movement of surface water often occurs at relatively smaller time scales (i.e. faster) than the movement of groundwater. A model that incorporates both surface and groundwater flow should consider consistency between the times scale of such input data.

Similarly, aquifer properties—such as hydraulic conductivity—are assessed by aquifer tests over specific spatial and temporal scales. Assessed aquifer property values can be different for the same aquifer, depending on the scale of the test (e.g. Schulze-Makuch et al. 1999).

Developed models must adopt parameter values that are consistent with their own model (discretisation) scale (see also Section 5.2). This means that where only local-scale (in the order of tens or hundreds of metres) aquifer test results are available—as is most often the case—the results must be adjusted to suit a regional-scale model (in the order of kilometres). Adjusting smaller-scale hydrogeological properties, which are typically attained through field testing, into those of a larger scale for modelling is called 'upscaling'. Moore et al. (2013) discuss the challenges associated with upscaling hydraulic parameters for coal seam gas modelling.

Upscaling and the appropriate selection of model input parameters, such as hydrogeological property values and geological delineation, are critical for all regional modelling—not just modelling that relates to coal seam gas. They remain among the challenges of groundwater modelling. Detailed discussion of upscaling and model parameterisation is not within the scope of this report.

4.4.2 Connectivity of bores

Modelling studies should recognise that existing monitoring and groundwater supply bores—if not properly constructed and maintained—may provide hydraulic connection between hydrogeological units exposed to the bore-screened interval. For bores screened over substantial depths, this may provide a pathway for movement of water from one hydrogeological unit to another. Water bores not constructed in compliance with the Minimum Construction Requirements for Water Bores in Australia (National Uniform Drillers Licensing Committee 2012), or those fail after installation, may also allow groundwater movement from one hydrogeological unit to another. Where multiple bores are present, these may allow the effects of coal seam gas extraction to be communicated to the overlying groundwater system.

Assessments of potential bore interconnection should be made based on reasonable assumptions about the number, age, construction materials, local hydrogeological conditions, and physical condition of boreholes in the vicinity of the modelled coal seam gas development. An assessment should also be made of the potential impact of this effect on the vertical hydraulic conductivity of the units spanned. The effects of interconnectivity created by a number of such bores distributed over an area can be modelled by a calibration adjustment (typically an increase) of the relevant vertical conductivity values in the areas affected. For example, Hart et al. (2006) demonstrated that failed well integrity, leading to leaky wells, could account for changes in vertical hydraulic connectivity spanning one to three orders of magnitude.

4.5 Preface to model uncertainty

Model uncertainty is an important consideration for all aspects of groundwater modelling, from the modelling objectives, approaches, development and inclusion of cumulative impacts to the final simulation of potential impacts on groundwater from coal seam gas production.

A numerical model of a hydrogeological system does not represent a unique combination of processes and parameters—that is, different combinations of processes and input parameters can produce equivalent results of measured groundwater levels and produced water volumes. This is termed model ‘non-uniqueness’. For this reason, it is best practice for modelling studies to reduce uncertainty in input parameters where possible, and analyse the uncertainty inherent within modelling results (predictions). Assessment of the uncertainty associated with model predictions permits a more informed approach to management decisions (see also Section 7.2.4).

Where data are limited—particularly for regional groundwater modelling studies—assumptions must be made regarding hydrogeological conditions. An assessment of the reliability of input data, and the uncertainty relating to input data values, is therefore an important aspect of modelling studies. The uncertainty in model input parameters imparts an uncertainty to model predictions, which must also be subject to an analysis of uncertainty.

Quantifying and reducing model uncertainty is a key area for further research into the simulation of the potential groundwater impacts from coal seam gas extraction.

5 Groundwater modelling tools

This section discusses groundwater modelling tools (i.e. software packages) that can simulate the potential groundwater impacts from coal seam gas production. A range of models with different functionality are tabled in Appendix B and examples of their applications are in Appendix C. The modelling tools are categorised as analytical, axisymmetric, reservoir or regional and an evaluation of these modelling approaches are tables in Appendix D. We discuss modelling of geomechanically induced hydraulic property changes to coal, and of surface water-groundwater interaction, as well as tools to assess uncertainty associated with model predictions. Numerous modelling tools are referred to for illustrative purposes, and reference to particular modelling tools does not constitute an endorsement of those tools.

5.1 Analytical models

The simplest modelling approach is the use of analytical models. These models have solutions that are expressed in a comparatively simple mathematical form (e.g. Theis 1941; Glover & Balmer 1954; Hantush 1965). Their simplicity means they are less time consuming to develop and use than numerical models. In cases where data are limited, they can provide equivalent accuracy (and a more efficient approach) to modelling natural systems compared with numerical models. They can also more efficiently characterise uncertainty associated with the analysis. However, they cannot account for spatially varying parameters or for conditions that vary over time.

Analytical models are sometimes used to assess the potential groundwater impacts from coal seam gas production. For example, S.S. Papadopulos & Associates Inc. (2006, 2007) adopted the simple analytical Glover-Balmer method (Glover & Balmer 1954) to perform preliminary assessment of stream depletion due to coal seam gas production in the San Juan and Piceance Basins, South Western United States. However, analytical methods can require numerous broad assumptions. For example, the Glover-Balmer method assumes a linear stream fully penetrating a homogeneous, isotropic, semi-infinite aquifer with single-phase (water only) horizontal flow, which may be an oversimplification of the conditions in areas where ground conditions vary. Figure 8 shows graphical representations of the Glover-Balmer analytical model. A study sponsored by the Kansas Water Resources Research Institute and published in the National Groundwater Association Journal compared the accuracy of a regional model, which used the modelling tool MODFLOW, to the analytical Glover-Balmer model for assessment of stream depletion (Norwest Corporation 2012). The authors concluded that the analytical solution significantly over-predicted stream depletion, due to oversimplification.

Assumptions inherent in analytical approaches may be applicable under specific geological geometry, hydraulic connections, and adopted parameters relevant to those settings. But, they are not amenable to more complex hydrogeological conditions, or where pumping occurs from multiple wells within a complicated watershed (Spalding & Khaleel 1991).

Analytical models can address multiple geological layers and multiple coal seam gas (or water supply) wells, but are restricted to linear systems with consistent properties. They cannot adequately model complex geological geometries or heterogeneous hydraulic conditions. Further, analytical models cannot account for complex flow behaviour, such as dual porosity and dual-phase flow in coal, and are relatively crude in their treatment (if any) of geomechanical effects. For these reasons, analytical methods are generally useful only in

preliminary assessment, or for where data are limited (i.e. data are insufficient to adequately parameterise a more complex numerical model), or where behaviour in the vicinity of individual wells is of primary interest.

Layered analytical modelling methods were developed by Neuman and Witherspoon (1969). Similar methods have been used by others to implement analytical modelling of multilayered groundwater systems (e.g. Best & Booker 2000; Hunt 2008). These models contain a number of simplifying assumptions concerning the uniformity of aquifers, and contain restrictions in the nature of boundary conditions that can be applied. They are typically limited to conditions where hydraulic parameters are not expected to change with time over the duration modelled.

Glover-Balmer analytical solution for stream depletion from a pumping well

$$q/Q = erfc\left(\sqrt{\frac{L^2 S}{4tT}}\right)$$

where:
q/*Q* is the ratio of stream depletion to pumping rate for time *t*
L is the distance from the pumping well to the stream (usually referred to as 'a' not 'L')
T is the transmissivity of the aquifer
S is the storativity of the aquifer
erfc is the complementary error function (a probability function that returns a proportion between 0 and 1 for the input value).

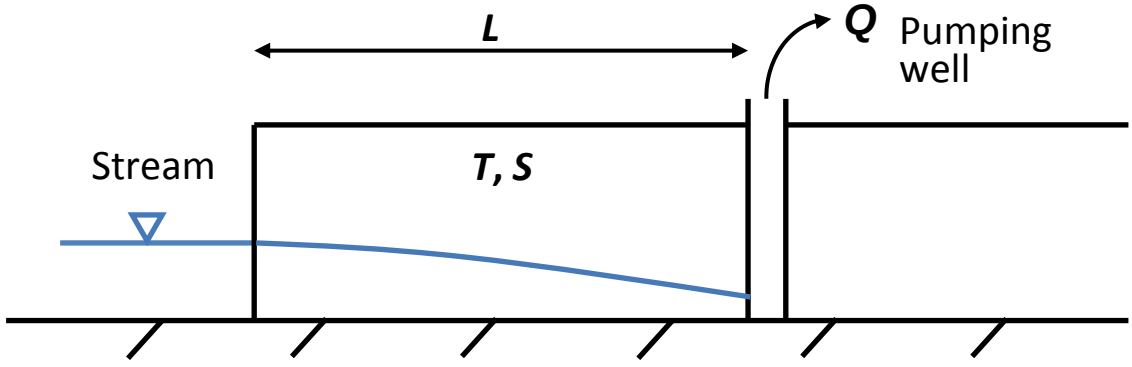

Figure 8 Analytical solution: Glover-Balmer method

5.2 Numerical models (spatial discretisation methods)

Numerical models use a time and/or spatial stepping procedure to predict groundwater behaviour over time and/or space. This is achieved by subdividing the continuum of the natural system—and hence, the governing equations—into discrete time or space parcels or blocks within which the system state is easily calculated using various assumptions. The procedure permits solution of more complex, heterogeneous problems than analytical methods. Appendix B outlines some specific model functionality such as the capacity of a

model to represent dual phase flow, which requires both data, understanding and more complex numerical algorithm.

The solution of the governing equations for numerical models involves solving a large number of differential equations: one set of governing equations for each time and/or space parcel, forming a matrix to be solved. This is done using approximating techniques that operate on the mathematical model to change it to a form that can be readily solved in a reasonable time. The most widely used approximating techniques are finite difference and finite element approximations; these are discussed further below. Examples of models applied at the regional scale to mining proposal assessments can be found in Appendix C.

5.2.1 Finite element and finite difference methods

Numerical groundwater flow models may adopt a finite difference, finite element or finite volume approach. The differences between these methods are mathematical. The most widely used approximation methods are the finite difference and finite element methods. Examples of model types and numerical algorithm applied are at Appendix B.

Multiple bores may allow the effects of coal seam gas extraction to be communicated to the overlying groundwater system.

Finite element models consider the spatial domain to be divided into polygons (commonly triangles) that are typically referred to as elements. Nodes are located at the intersection of elements. The elements and nodes are collectively referred to as the finite element mesh. Mathematical flow equations are solved to predict unknowns at the nodes, and unknown values—such as groundwater head—across an individual element, or polygon, are calculated by interpolating between the values at each of that element's nodes. A finite element mesh is shown in Figure 9b.

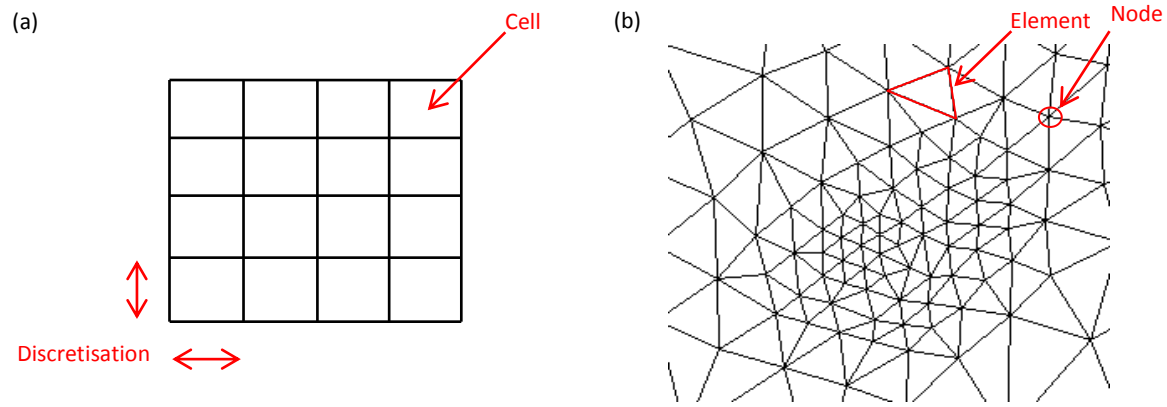

Figure 9 (a) Finite difference grid and (b) Finite element mesh

Finite element models are generally considered to yield more accurate results when handling moving boundaries, such as a transient watertable; or coupled problems, such as surface water–groundwater interaction or contaminant transport (Fetter 2001). Due to the nature of their mesh construction, finite element models can also represent complex geological geometries better than the finite difference method. Unlike the finite difference approximation, where a groundwater head is calculated for an entire cell, the finite element

approximation defines the variation in groundwater head over an element using interpolation functions.

The finite volume method uses a volume integral formulation for the system, with a finite partitioning set of volumes to discretise the equations. Although this method is not commonly used in groundwater simulation, it is often used for numerical solution of fluid dynamics equations.

Both finite difference and finite element methods are suitable for regional groundwater modelling. However, finite element approaches offer the possibility to more accurately represent irregularly shaped geological structures and features, such as irregularly spaced well fields and rivers/streams/surface water bodies. Finite difference approaches are sufficient to represent more regular geometries, and are likely to provide an equally suitable approach to a finite element approach where data are limited (i.e. complex geometries are not present or are unknown).

Numerous modelling tools may be considered when using numerical models to simulate the groundwater impact from coal seam gas production. The following sections discuss axisymmetric, reservoir, and regional groundwater flow modelling tools. The different tools generally target different spatial scales, such as the well-field (or subwell-field) scale, the far-field (regional) scale, or a scale in between (see Appendix D).

5.2.2 Axisymmetric flow models

Axisymmetric flow models consider two-dimensional sections through the ground profile, about an axis around which conditions are symmetrical (e.g. around a coal seam gas well). Because symmetry is fundamental to these models, they may only be used to provide meaningful results where geological and groundwater flow conditions are relatively symmetrical. These conditions are well represented for consideration of behaviour in the vicinity of a single well within a wellfield.

GEO-SLOPE's SEEP/W and Rocscience's SLIDE are examples of modelling tools that provide axisymmetric groundwater modelling software. MODFLOW-SURFACT also includes an option for discretising the model domain using an axisymmetric geometry. This may be suitable for modelling coal seam gas well fields at the local scale. These tools are useful for modelling groundwater responses adjacent to individual wells, which can benefit assessment of test well or groundwater response within well fields.

5.2.3 Reservoir models

Reservoir models are commonly used to estimate gas production and produced water volumes. They may be analytical or numerical. The spatial scale considered by these models is generally limited to the well field.

Reservoir models typically account for the following processes:

- adsorption/desorption of gas to coal surfaces, typically using a Langmuir isotherm approach—see Section 2.1
- dual porosity of coal seams (dual porosity/dual region approach)
- diffusion of gas from the coal matrix to the fracture system, typically in accordance with Fick's Law—see Section 2.2
- flow of gas and water (i.e. multiphase flow) in the fracture system, in accordance with laminar Darcy flow where flow is treated as being proportional to head gradient

- shrinkage of the coal matrix due to gas desorption (see Section 3.4 on geomechanical effects in this document, and Coffey Geotechnics, forthcoming).

Different reservoir models may approach these processes in different ways. For example, some models use an empirical approach to gas sorption, others adopt an equilibrium (pressure-dependent) sorption approach, while still others consider non-equilibrium (pressure and time-dependent) sorption.

Examples of reservoir models include various proprietary models, such as:

- Schlumberger Inc's ECLIPSE model and its derivative, ECLIPSE H20, which provides limited regional-scale flow calculation
- Computer Modelling Group Ltd's Generalized Equation-of-State Model (GEM) Compositional Reservoir Simulator (c.f. Arenas 2004)
- Advanced Resources International Inc.'s COMET3 model
- Golder Associates Inc.'s fractured reservoir simulation tool FracMan
- RPS Energy's reservoir simulator Tech SIM
- CSIRO and University of New South Wales jointly-developed SIMEDWin (and its coupling with geomechanical software FLAC3D to form the FLAMED model)
- Various recently developed models (e.g. Guo et al. 2003; Mazumder et al. 2003; Shi & Durucan 2003c).

PFLOTRAN is a recent public domain algorithm developed by a conglomerate of United States academic and research institutions. It can simulate multiple-phase fluid flow and chemical transport, with the advantage of being able to run on multiple workstations in parallel. This has the potential to significantly reduce simulation times.

The geometry of the subsurface facies used in a reservoir model is typically adopted from a petrophysical model. A petrophysical model is a three-dimensional representation of the subsurface media volume of interest, and is generally developed using open-hole logs (geophysics, lithology, and structural comments) in conjunction with a specialist algorithm that generates the representation. The model is inert—that is, it provides a time-independent analogue of the subsurface. Its primary purpose is usually for application of flow processes for reservoir modelling. The most widely used petrophysical modelling algorithm for coal seam gas development in Australia is Petrel, which is produced by Schlumberger.

5.2.4 Regional groundwater models

General-purpose regional groundwater flow models are used to simulate the hydraulic heads and groundwater flow rates of aquifer systems over potentially large areas beyond the well field (i.e. in the far field, at a regional scale). Typically, heterogeneous ground conditions and material anisotropy are accounted for by spatially varying hydraulic properties and model layering. Widely used examples of modelling tools of this kind are discussed below.

MODFLOW is a widely used numerical groundwater flow modelling software package developed by the United States Geological Survey (McDonald & Harbaugh 2003). The software package is public domain and adopts a modular approach, in that numerous modules may be used in conjunction with the basic modelling software. It has been updated progressively since its first publication in 1983. The basic MODFLOW software package is a three-dimensional, finite difference model that considers saturated groundwater flow, and does not include multiphase, dual porosity, unsaturated flow or solute transport. Surface water interaction is represented (not coupled) through use of boundary conditions. However,

due to MODFLOW's modular nature, a number of commercially developed add-on modules have been developed to model specific processes not included within the basic MODFLOW package. These including modelling unsaturated flow (e.g. SURFACT[1]) and solute transport (e.g. MT3D[2]), variable density flow (e.g. SEAWAT[3]), and various numerical solvers. MODHMS[4] is a version of MODFLOW that incorporates coupled groundwater and surface water interaction. Several graphical user interfaces have also been commercially developed, such as Visual MODFLOW[5], PMWIN[6], Groundwater Vistas[7] and GMS[8].

FEFLOW is a numerical groundwater flow modelling software package owned by DHI-WASY GmbH. The package comprises a three-dimensional, finite element code that considers variably saturated groundwater flow. FEFLOW does not model multiphase flow, but does include reactive (solute) transport. Surface water interaction is represented (not coupled) through use of boundary conditions, but can be interfaced with the software MIKE11 to provide a coupled approach to surface water–groundwater interaction. FEFLOW can also simulate axisymmetric conceptualisations.

HydroGeoSphere (Therrien et al. 2012) is a three-dimensional, finite element software package that includes coupled and fully integrated surface and subsurface water flow, including surface water areal flow and runoff to channels. The model considers variably saturated conditions in (potentially) dual-porosity media, and migration of reactive chemical species. The model does not consider multiphase flow.

Some model codes can be extended or coupled with other models to represent other natural processes, such as geomechanical processes and/or surface water–groundwater interactions. In such cases, additional uncertainty analysis of model inputs and outputs would be required.

HYDRUS 2D/3D (Šejna & Šimůnek 2007; Šimůnek et al. 2008) is a three-dimensional, finite element software package for modelling variably saturated flow with solute transport in both the liquid and gas phase. The model includes representation of dual-porosity media but not multiphase flow.

DYNAFLOW is a three-dimensional, finite element fluid structural, solid and mechanics model developed by Prévost (2010). Strictly, it is not a general-purpose groundwater flow model, and does not include dual porosity or surface water interaction features.

SUTRA is a three-dimensional, saturated (two-dimensional unsaturated) flow and solute transport model (Voss & Prevost 2010). It does not include dual porosity or multiphase flow processes.

COSFLOW is a three-dimensional, finite element model developed by CSIRO (Adhikary & Guo 2005, 2007), in collaboration with the New Energy and Industrial Technology Development Organization and the Japan Coal Energy Centre. It is a coupled, two-phase, dual-porosity model that considers variably saturated flow through coal fractures/cleats

[1] For example, www.swstechnology.com/groundwater-software/groundwater-modeling/modflow-surfact-flow
[2] For example, <hydro.geo.ua.edu/mt3d/>
[3] For example, <www.aquaveo.com/software/gms-seawat>
[4] For example, <www.hgl.com/expertise/modeling-and-optimization/software-tools/modhms/>
[5] For example, <www.swstechnology.com/groundwater-modeling-software/visual-modflow-flex>
[6] For example, <www.pmwin.net/index.htm>
[7] For example, <www.scisoftware.com/environmental_software/product_info.php?products_id=43>
[8] For example, <www.aquaveo.com/software/gms-groundwater-modeling-system-introduction>

(Darcy flow), desorption of methane gas (modelled in accordance with Fick's Law and Langmuir isotherm), and dynamic coupling of flow and mechanical deformation. The model does not include solute transport. COSFLOW was used to model mine water inflows at Springvale Colliery, New South Wales (Guo et al. 2008). The study was reported to have achieved agreement between modelled and measured groundwater inflow to the underground mine. Wider impacts on the groundwater system were not assessed. The modelling effort was directed to the geomechanical behaviour resulting from longwall coal mining and the ensuing changes in hydraulic properties; these issues are not considered relevant to coal seam gas extraction.

FEMWATER (Lin et al. 1997) is a three-dimensional, finite-element model used to simulate density-driven coupled flow and contaminant transport in saturated and unsaturated zones. It also can simulate regional groundwater flow.

While the modelling software package MOVER (marketed by Scientific Software Group) and TOUGH2 (developed by the United States Lawrence Berkeley National Laboratory) model multiphase flow, they are focused on non-aqueous phase liquid transport; this could include liquid hydrocarbons or chlorinated solvents such as carbon tetrachloride. They do not consider gases such as methane or carbon dioxide.

Cross-sectional and axisymmetric numerical models, such as GEO-SLOPE International Ltd's software package SEEP/W (and contaminant transport package CTRAN/W), may be used to assess specific groundwater flow regimes in section at a local (or subregional scale). But, they are not suitable for simulating regional groundwater impacts in relatively complex geological settings.

5.3 Other related models

5.3.1 Solute transport models

Solute transport models are numerical models that simulate the concentrations of dissolved substances in groundwater. They are commonly used to predict contaminant migration, or to estimate the connectivity of adjacent aquifers and surface water bodies (e.g. rivers, lakes).

Solute transport models comprise 'submodels' within groundwater flow models. They may be either reactive or non-reactive—that is, the migrating chemicals may or may not react with other chemicals in solution. Examples of solute transport models include HydroGeoSphere, HYDRUS 2D/3D, MT3D, SURFACT, FEFLOW and PHT3D. Barnett et al. (2012) provide guidance on solute transport modelling.

5.3.2 Surface water–groundwater interaction (inclusive) models

5.3.2.1 Analytical models

There are numerous one and two-dimensional analytical groundwater 'stream depletion' models, each approaching the features of stream penetration, stream bed conductivity, stream geometry and flow boundaries in different ways. These models may be used to simulate the surface water impacts from groundwater pumping/drawdown. Some examples include the models developed by Theis (1941), Glover and Balmer (1954), Hantush (1965), Moench and Barlow (2000), Fox et al. (2002) and Hunt (2008).

Such models may be sufficient to represent simple geological conditions. However, more complex geological or geometrical conditions require the use of numerical models. For example, geologically dipping or laterally discontinuous geological strata typically result in groundwater flow regimes that differ from flat-bedded or laterally continuous geological

strata. The inability of analytical models to capture the effects of such geological geometries can reduce their use in simulating groundwater flow and pressure (Appendix D).

5.3.2.2 Numerical models

Regional numerical groundwater flow models include surface water processes to varying degrees of complexity. Surface waters are typically represented in numerical groundwater flow models by the use of boundary conditions that do not explicitly consider surface water behaviour. In other words, the surface water system is represented by a water head or flux boundary condition that does not account for surface water infiltration, rainfall runoff or stream flow behaviour. Groundwater flow models taking this approach include HYDRUS (Šimůnek et al. 2008), MicroFEM, DYNAFLOW, DHI WASY's FEFLOW model, and the SFR1 Stream Flow Routing Package (Prudic et al. 2008) used in the United States Geological Survey's MODFLOW model (Appendix B). As this treatment does not explicitly model the surface water system or the interaction of the surface water system with the groundwater system, it may be insufficient to capture dynamic interactions between groundwater and surface water (e.g. Swain & Wexler 1996). This can lead to inaccuracies in the simulation of groundwater flow and pressure behaviour.

In contrast, coupled surface water–groundwater modelling approaches calculate flows by either simultaneously or iteratively considering both groundwater and surface water flow processes. Coupled surface water–groundwater models can include both analytical and numerical approaches that are integrated into groundwater flow models. Modelling approaches that consider simultaneous groundwater and surface water processes, with coupling between a surface water model and the United States Geological Survey's MODFLOW, have been developed by Sophocleous and Perkins (2000), Osman and Bruen (2002), Lin and Medina Jr (2003), Feinstein et al. (2006) and the United States Geological Survey (BRANCH model). Fully integrated surface water–groundwater modelling approaches with the ability to simulate detailed groundwater flow include DHI's coupled software MIKE SHE, the (user-based) coupling of DHI WASY's FEFLOW and MIKE (Monninkhoff 2002), the United States Geological Survey's GSFLOW model (Niswonger et al. 2006), and the MODFLOW-based MODHMS developed by HydroGeologic Inc.

Surface water models that do not include groundwater modelling capability are not a focus of this report. Such models include the Integrated Quantity Quality Model developed by the New South Wales Department of Natural Resources (Centre for Natural Resources 1999), the Resource Allocation Model developed by the Victoria Government Department of Sustainability and Environment (2012), and BMT Group Ltd's TUFLOW. A detailed review of surface water–groundwater models and their suitability to Australian conditions is provided by Rassam and Werner (2008).

5.4 Summary of modelling tool features

A summary of modelling tools that can simulate the impacts of coal seam gas developments on groundwater is presented in Appendix B. The summary is not intended to indicate that these are the only modelling tools that can simulate these impacts.

The modelling capabilities of each modelling tool listed are:

- dimensionality and type of numerical technique
- dual porosity nature of coal
- multiphase flow (fluid and gas)
- (de)sorption of methane gas

- geomechanical influence on aquifer permeability
- variably saturated (water) flow or limited to saturated flow only
- solute transport
- surface water–groundwater interactions (coupled or uncoupled).

Models suitable for use at the regional scale are noted by their regional ‘model type’ in Appendix B. Examples of regional model simulations are given in Appendix C, and an evaluation of modelling approaches and scale can be found in Appendix D.

6 Groundwater modelling approaches

A 'modelling approach' is defined in this report as the action of using a specific modelling tool (an algorithm or platform) to simulate a natural system. Application of regional groundwater models, assumptions and uncertainty analysis are specified in Appendix C.

The following sections outline modelling approaches that may be used to assess the groundwater impacts from coal seam gas extraction. While a single groundwater modelling tool may be selected quite frequently the way the model is parameterised may be quite different. We consider the application of these modelling approaches to address specific modelling objectives, and provide examples of the use of specific modelling tools. These examples are summarised in Appendix C. The examples are not intended to be complete, and do not constitute recommendations, but illustrate the tools in current use.

6.1 Conceptual model development

The conceptual (hydrogeological) model is a descriptive representation of a groundwater system that incorporates an interpretation of the geological and hydrogeological conditions (Anderson & Woessner 1992). It is an essential stage in the modelling process and provides the basis for condensing data and knowledge into a simplified representation of the groundwater system to identify key features, processes, knowledge gaps and uncertainties.

There is no one perfect way to simplify a system within a conceptual model. However, it should characterise the hydrogeological conditions (including the stratigraphic units, geometries and time scales of flow components within the system) and identify the water inputs and outputs (e.g. pumping activities, rainfall recharge, surface water interaction) for the broader hydrogeological and hydrological system under study. Simplifications in the representation of the natural system are made, subject to data availability and the scale of the representation.

Alternative conceptual models should be considered to explore the significance of the uncertainty associated with different views of how the system operates (Barnett et al. 2012).

6.2 Analytical modelling

An analytical modelling approach can be useful for preliminary assessment of the potential impacts of coal seam gas developments on groundwater.

At the preliminary assessment stage, data are often limited (this issue was raised in Appendix A). Consequently, quantitative assessment of the aquifer system would be subject to a high degree of uncertainty. Analytical modelling approaches, due to their simplicity, have far fewer data requirements than numerical modelling approaches, and offer an alternative assessment approach in such data-poor cases or under relatively simple geological conditions. However, analytical models are subject to uncertainty associated with the conceptual appreciation of the conditions modelled and the limitations under which the natural system must be described.

Analytical approaches may be used to address the full range of modelling objectives. However, the usefulness of analytical approaches tends to be limited to relatively simple geological environments and hydraulic conditions, and/or data-poor assessment conditions. Numerical groundwater modelling approaches are therefore required to account for more complex geological geometry (including geological faults, intrusions, slides and other

subsurface anomalies), hydraulic connections, adopted parameters relevant to those settings, or groundwater abstraction from multiple wells in a complicated watershed.

Analytical models may be used to assess groundwater drawdown or stream flow depletion due to coal seam gas extraction. For example, groundwater drawdown was analysed using an analytical modelling approach for the Santos GLNG project's Roma coal seam gas field in the Surat and Bowen Basins, due to paucity of field data and the relatively simple geological geometry. A simple analytical method (Glover & Balmer 1954) was adopted to perform preliminary assessment of stream flow depletion due to coal seam gas production in the San Juan and Piceance Basins (S.S. Papadopulos & Associates Inc. 2006, 2007). The Glover-Balmer method assumes a linear stream fully penetrating a homogeneous, isotropic, semi-infinite aquifer with single phase (water only) horizontal flow. These limitations need to be considered in the interpretation of model results.

Hydraulic test analysis algorithms (e.g. Theis 1941; Hantush 1965) may be used, depending on the features and geometry of the area under assessment. Many of these methods can incorporate multiple media layers; however, isotropic and homogenous conditions are usually assumed within each layer. Boundary conditions may be restrictive (for example horizontal layering, or specified head boundaries that must be vertical or horizontal). A compendium of analytical methods for analysis of subsurface fluid flow is provided in Harr (1962).

6.3 Numerical modelling

Numerical modelling for coal seam gas production projects is generally undertaken to meet one of the following two categories of objectives:

- production-related objectives—modelling to predict gas and water production rates. Because water production rates are relevant to potential groundwater impacts, these models are sometimes used in concert with other models to assist in simulating potential impacts
- regional groundwater impact objectives—modelling used directly to simulate the groundwater impacts from coal seam gas extraction.

6.3.1 Production-related modelling

6.3.1.1 Reservoir models

Numerical reservoir models fall into the category of production-related models, because they are generally used to estimate gas and produced water production rates. Reservoir modelling tools (see Appendix B for examples) can model the complex physical processes that occur in the vicinity of the well field (near-field scale), such as dual-phase flow, methane gas desorption, the dual porosity nature of coal and geomechanical effects. However, due to the intensive computational requirements (i.e. processing time) of simulating these processes, it is currently impractical to use these types of models to predict impacts at the regional scale.

Reservoir models may address re-injection of produced water at the well-field scale. However, they generally do not deal with groundwater quality. They cannot model groundwater–surface water interactions, or assess cumulative impacts from other developments in the vicinity of the modelled well field.

Reservoir models are useful for assessing groundwater depressurisation and produced water volume at the near-field scale. Results from such modelling are helpful in validating the results of regional groundwater models by reviewing the consistency of groundwater

depressurisation and produced water predictions. However, this modelling approach is impractical for assessing potential impacts at the regional scale.

6.3.1.2 Axisymmetric flow models

Axisymmetric flow models may be useful when modelling ground profiles that are relatively symmetric around a vertical axis. However, where geological and hydraulic conditions are relatively asymmetrical, this approach is not suitable. It is generally restricted to estimating groundwater depressurisation, produced water volumes and produced water re-injection in the vicinity of the well field, and cannot model complex geological geometries or impacts on a regional scale. These models may be useful to understand the performance of individual wells, but is of limited value for regional assessment: except perhaps to develop input to regional groundwater models in the form of simplifications of the drawdown development at individual well fields.

Axisymmetric flow modelling tools (see Appendix B for examples) can account for some geomechanical effects (e.g. permeability changes due to ground compression, but not due to gas desorption), But, they do not account for complex physical processes that occur in the vicinity of the well field (near-well scale), such as dual-phase flow, methane gas desorption or the dual porosity nature of coal. Reservoir models therefore offer significant advantages over axisymmetric flow models.

6.3.2 Regional groundwater modelling

Regional groundwater models are most suitable for modelling potential impacts at the regional scale. They are the most suitable model for assessing cumulative impacts.

Regional groundwater modelling tools (see Appendix B) provide a useful platform for the development of regional models to simulate potential groundwater impacts. The deficiencies typical of these tools relate to their:

- representation of near-field flow regimes, such as dual-phase flow and impacts of flow induced by gas desorption
- representation of the dual porosity nature of coal
- ability to model coal permeability changes (geomechanical effects) due to depressurisation and gas desorption
- treatment of surface water–groundwater interaction.

Explicit modelling of these processes and features is required to accurately simulate potential groundwater impacts in the vicinity of the near-field.

Some tools (e.g. DYNAFLOW, HST3D, SWIFT) offer limited or no ability to model unsaturated flow or solute transport, or to represent coal anisotropy. Some regional groundwater modelling tools can model these processes and features (see Appendix B). However, most cannot explicitly include dual porosity, dual-phase flow or geomechanical effects. The extent to which those phenomena influence groundwater depressurisation—and thus, potential impacts—at the regional scale has not been significantly researched, and information relating to their influence is not publicly available.

In cases where a phenomenon is assessed to be significant, it may be possible to indirectly account for its influence using standard regional groundwater modelling tools. For example, the modelling tools FEFLOW and MODFLOW-SURFACT may implicitly account for the geomechanically induced effects of depressurisation on coal seam permeability, by adopting time-varying permeability changes to the coal during a model simulation. However, it is important to ensure that implicitly modelled effects are consistent with other processes. In the

previous example, changes in coal seam permeability are dependent on groundwater depressurisation, which is dependent on the permeability of the coal. Because these processes are coupled, it can be difficult to ensure that modelled conditions are consistent when implicitly modelling a process in isolation. This represents a challenge to implicitly modelling phenomena in regional groundwater flow models.

6.4 Multiple approaches

A single modelling approach may not fully capture all processes and phenomena that influence impacts, because few single platforms can simulate all possible processes. For example, some modelling approaches and their associated tools are more suitable to assessing the near-field scale, while others are more appropriate for the regional scale. Appendix D outlines the advantages and disadvantages of different groundwater modelling approaches and the appropriate application for the different model types.

Multiple approaches may therefore be adopted to cover a broad range of processes. For example, analytical modelling approaches and/or reservoir modelling approaches may be used in tandem with a regional modelling approach until the consequences of omitting multiphase flow from regional simulations are adequately understood. The predictions made using each individual approach are then used as checks or to test the validity of assumptions used in other approaches.

6.5 Testing assumptions

The extent to which phenomena such as groundwater flow behaviour, geomechanical effects and surface water–groundwater interactions affect the simulation of potential water-related impacts is dependent on the conditions specific to the well field and wider geological environment. The significance of such phenomena on groundwater flow in a regional setting is not always well established.

Multiple approaches may therefore be used to address all phenomena of significance. The assumptions inherent in adopting a particular modelling approach should be tested, and the use of multiple approaches can be used to confirm the assumptions made in other approaches. It is often not possible to assess the contribution of individual phenomena without first conducting modelling, and an iterative approach may be required.

The most appropriate tool(s) to be used will be influenced by assumptions associated with the particular processes and properties. In practice, modelling practitioners are strongly influenced by their modelling experience and the levels of familiarity with and availability of different modelling tools can be a dominating factor in modelling tool selection. While this may not appear to be ideal, the use of modelling tools is complex and lack of familiarity can lead to error.

Appendix C provides examples of modelling simplifications and assumptions utilised for proposed coal seam gas developments in Australia (and one in the United States). The table lists the modelling approaches, tools adopted, and simplifications and assumptions made. The regional modelling tool MODFLOW is typically used, with FEFLOW used for one development and an analytical model used in one instance. The MODFLOW and FEFLOW approaches generally involved modelling of multiple geological units over a wide area. None of the methods explicitly addressed dual-phase flow, geomechanical effects, or anisotropy or dual porosity of the coal seams. It is possible that these effects were secondary or insignificant from a regional modelling context. No clear guidelines are available for identifying the significance of these mechanisms on regional groundwater flow modelling. Reservoir models are not included, because there are few examples in the public domain,

and regional modelling is currently developed and commonly used to simulate the groundwater impacts from coal seam gas extraction.

7 Issues to consider for groundwater modelling

This section identifies issues to consider when modelling potential groundwater impacts from coal seam gas production, as well as more broad considerations for groundwater modelling. Coal seam gas-specific issues are either unique to, or assume an increased importance for, modelling the impacts on groundwater from coal seam gas extraction, or other multiphase extraction. This discussion is intended to assist in selecting modelling strategies likely to reduce uncertainty created by groundwater simulation of coal seam gas extraction. The coal seam gas-specific issues to consider include:

1. Near-field flow processes (multiphase fluid flow, coal dual porosity, gas liberation)
2. Model representation of coal seams and layered strata
3. Accounting for modified hydraulic conditions caused by hydraulic fracturing
4. Accounting for modified hydraulic conditions caused by coal seam gas production
5. Accounting for coal anisotropy

Note: Issues 1 to 5 are all features to include in a coal seam gas-specific groundwater model.

More general groundwater modelling considerations that are important for simulating the potential groundwater impacts coal seam gas production include:

1. Interaction of surface water and ground water
2. Modelling of cumulative impacts
3. Assessment of impacts on water quality
4. Assessment and quantifying uncertainty in modelling
5. Reporting of modelling studies.

Note: Issue 1 is a feature to include in a groundwater model where required; issues 2 and 3 are common purposes for developing a groundwater model, which may dictate the need for including particular features; and issues 4 and 5 are selected important stages of modelling projects.

These issues are discussed below. All groundwater modelling should be conducted in accordance with the general guidance provided in the Australian Groundwater Modelling Guidelines (Barnett et al. 2012).

7.1 Coal seam gas-specific issues

7.1.1 Near-field flow processes

Groundwater flow within, and proximal to, a coal seam gas well field is known to be strongly influenced by multiphase fluid flow, coal dual porosity and gas liberation from coal.

- Multi-phase fluid flow:
  - Three distinct fluid flow processes, experienced in stages, occur during coal seam gas extraction. Each stage propagating spatially from the well into the coal seam.

  - The stages are (i) saturated single-phase water flow, (ii) unsaturated single-phase water flow, and (iii) dual-phase (water and gas) flow.
- Dual porosity of coal seams:
  - Coal seams have a 'dual porosity' nature in which the coal has both micropores (primary porosity, within the coal matrix) and macropores (secondary, fracture porosity; comprising the coal cleats).
  - These types of porosity affect fluid flow in different ways.
  - The dual porosity nature of the system imparts a similar bimodal nature to the hydraulic conductivity distribution of the system.
- Gas liberation from the coal:
  - For many decades, the petroleum industry has applied reservoir models with multiphase flow and dual porosity in characterising the financial viability of a reservoir.
  - The particular use of the results (profitability of the resource) naturally required that significant effort be expended in attempting to replicate all important natural processes.
  - Reservoir models used for coal seam gas development are developed from existing reservoir models for petroleum. However, scrutiny of, and groundwater impact assessment for, coal seam gas developments in Australia is relatively new, and to date, conventional regional groundwater flow models, which ignore multiphase flow and gas liberation, have been used for impact assessment.
  - Investigation into the significance of near-field coal seam gas extraction processes on regional hydraulic heads has only recently been undertaken.

Recent research addressing the significance of these processes in a regional context is presented by De Vertuil et al. (2013). This work describes development of a regional, dual-phase flow model for assessment of far-field impacts. Initial results suggest that gas liberation plays a significant role in controlling drawdown in the liquid groundwater phase at large distances. Development of these hybrid models is at an early stage. However, the results are encouraging, and may provide a more reliable platform for coal seam gas impact assessment. This work suggests that it is preferable to use a multiphase flow modelling platform for coal seam gas development. Apart from the research effort of De Vertuil et al. (2013), there does not appear to be any other available regional impact assessment tool that considers multiphase flow and/or gas liberation.

Where multiphase algorithms are implemented, it is possible to represent the well field as specified extractions of water and gas. This information is usually readily available from field studies undertaken by the proponent when assessing the economic potential and energy production of the well field. This representation removes the necessity of estimating the hydraulic head in close proximity to the well field.

The extent to which near-field coal seam gas extraction processes influence hydraulic heads in the far field depends on the conditions specific to the well field and wider geological environment. To accurately model potential impacts, the influence of these phenomena should be considered. This implies that the results of reservoir modelling of the coal seam gas well field should be accessed, if available, to account for dual porosity effects, dual-

phase flow and gas liberation. Guidance on identifying the conditions under which these factors are relevant to regional groundwater modelling would be a useful area of research.

7.1.1.1 Representation of coal seam gas well fields with regional (single-fluid phase) models

Regional groundwater models used to assess the potential groundwater impacts from coal seam gas development on a regional scale, which are unable to simulate multiphase flow, may represent groundwater depressurisation induced by a coal seam gas well field in two main ways.

- Observed groundwater extraction rates are specified for wells in the well field, and depressurisation is calculated by the model according to specified extraction. This approach avoids the use of water level measurements from extraction wells, which are not representative of the hydraulic head field just outside the well casing. Modelled hydraulic heads within the well field may not be comparable to observed heads, and estimation of far-field heads becomes a quasi-empirical exercise.
- Groundwater levels in the well field (based on results of reservoir modelling, or on well field design expectations) can be used as the basis for a boundary condition for the well field in the regional model. This approach has the advantage of using a boundary condition, which incorporates the effects of multiphase flow and gas desorption without explicitly modelling these processes using a regional model. This approach is expected to be more effective in simulating regional impacts on groundwater head, but simulation of produced water would be uncertain.

Where a single-phase algorithm is implemented, there is no opportunity to include both extracted fluids (water and gas). Representation of well-field operation using only imposed groundwater extraction does not correctly simulate the total fluid extraction. Hence, calibration of media hydraulic parameters becomes confounded by the absence of gas extraction.

In such cases, it is preferable to impose a transient hydraulic-head condition from a reservoir model, if available. Fluid extraction rates calculated by the model can be used as a semi-quantitative calibration target. Single-phase flow models should be used with caution, since calibrated parameter estimates are subject to the absence of additional flow phases, such as gas desorption. To assess regional impacts, the major uncertainty introduced into the model is therefore the calibration of parameters—typically to near-field information—and application of these parameters to the far field.

Where reservoir model results are not available, or are considered to have an unacceptable uncertainty, then the only available relevant information may be measured water levels in extraction bores. This situation is problematic: individual wells have significant well loss, and hydraulic heads immediately outside the well casing are likely to differ significantly from the water level in the well. In addition, the hydraulic head field proximal to the well field is most likely to exhibit significant vertical head gradients. Hydraulic head measurements throughout the vertical profile in the vicinity of the well field would be required for this approach to be viable; however, this information is rarely known to the required level.

The combination of reservoir and regional models—where the parameter and potential field of the subsurface volume represented by the reservoir model replaces the same fields in the same volume in the regional model—creates a difficulty at the boundary where the regional governing equations take over. If head and flow were matched at that boundary, the dual-phase flow processes relevant to reservoir behaviour might be accounted for in the regional model, provided various conditions were met.

Ultimately, the choice of representation will depend on whether the adopted modelling code simulates a single fluid phase or multiple phases. This is because gas extraction bears directly on the depressurisation of groundwater. The choice of modelling code may also depend on the risks faced by the model client (the coal seam gas proponent or regulator) and whether the uncertainty inherent in the model outputs is acceptable for decision making.

Herckenrath et al. (2013) provide results relating to compensation for modelling errors incurred by up-scaling and neglecting dual-phase flow, and assessment of physical resemblance of parameters in up-scaled models of the impact of coal seam gas on groundwater. Doherty and Herckenrath (2013) discuss the use of a single-phase flow model to simulate multiphase flow.

Predictions of produced water volumes are important for water management, but are of secondary importance for regional impacts to groundwater — unless the model results are used to inform allocation or licensing decisions. In either case, the simulated degree of depressurisation and produced water flow rates for the well field should be consistent with observations. The imposed conditions and predictions being simulated should compare favourably with estimates made by the coal seam gas proponent's multiphase reservoir model, if available.

Modelling the development of the well field over time (that is, considering evolving hydraulic heads) is important. The crude assumption that the well field is fully developed from the outset would overestimate inflow and groundwater drawdown impacts.

> ***Summary:*** Models should accurately represent groundwater depressurisation and produced water flow rates of coal seam gas well fields. The decision to use a model code that can simulate multiphase flow and gas liberation will depend on the location and nature of regional groundwater and whether the uncertainty in model outputs is acceptable for decision making. Should a model be used that cannot simulate these processes, the model's representation of the applied stress (gas and water extraction) should be carefully assessed. In these cases, observations of hydraulic head and water extraction will be important in assisting calibration. Realistic assumptions of the timing of well-field development (growth in size and rate of water extraction) should be employed.

7.1.2 Model representation of coal seams and layered strata

Geological conditions in Australian sedimentary geological basins in which coal seam gas developments are located typically comprise consolidated sedimentary geological units, such as sandstone, siltstone and mudstone. Target coal seams are interbedded within the sedimentary units at depths typically greater than 200 m below ground surface, and surficial alluvial aquifer systems (such as in sands or clays) are associated with creeks and rivers. The target coal seams in basin environments across Australia vary in their lateral continuity and thickness.

The continuity and geometry of target coal seams can significantly influence the extent of groundwater drawdown induced by coal seam gas production. Groundwater models must therefore capture these coal seam characteristics adequately.

In many cases, coal seam gas is extracted from multiple coal seams. Depending on the vertical distance between these seams, it may not be practical to model each seam individually. In such cases, it may be necessary to combine multiple physical layers into a single composite layer for the purpose of modelling. Similar simplifications may be required for the strata above or below the coal-bearing formation. In these cases, it is essential to have due regard to the layered structure of the geology and to adopt model parameters

representative of the layered system modelled. Using such simplified methods will impart a degree of uncertainty to model results. The degree of uncertainty will be related to the difference created by the simplification in the functioning of the model algorithm.

Where a coal seam and surrounding layers have been inappropriately characterised as a single model layer, a specified discharge from that single layer will create less drawdown than if the discharge was applied only to the coal seam, in a three-layer case with vertical anisotropy.

Where laterally continuous coal seams have been modelled as discontinuous, model-predicted groundwater drawdown may be underestimated at a distance from the well field. Where a number of horizontally bedded layers are combined for modelling, the vertical hydraulic conductivity should be modelled as the thickness-weighted, harmonic mean hydraulic conductivity of the combined layers. The horizontal hydraulic conductivity should be modelled as the thickness-weighted, arithmetic mean hydraulic conductivity of the combined layers.

Hydraulic conductivity measurements used for modelling will require scaling to transform hydraulic test results from the scale of the hydraulic tests to the scale of the model discretisation. This will introduce additional uncertainty, unless conditioned by hydraulic tests conducted in the same medium and location at different scales. Typical methods used in the natural sciences are described in Bierkens et al. (2000). Jackson et al. (2003) analyse scaling as applied to sandstone, which is a common component of Permian coal measures in Australia and worldwide.

Layering in a numerical model involves simplification of the lithological variation within a modelled layer. The layering is developed based on consideration of lithological contrasts and the hydraulic communication between lithological units, to define hydrostratigraphic units. Lithological variations can be incorporated by applying hydraulic property contrasts throughout the layer. However, it is important to ensure that the appropriate flux exchange direction (vertical or horizontal) between lithological units, as would occur in the natural system, is maintained. Hydrostratigraphic units defined in a model are therefore approximations of the natural system. A modelled hydrostratigraphic unit may contain small-scale, high-permeability zones that may range in geometry (from a maximum contrast viewpoint), from thin and laterally extensive to thick and discontinuous.

> ***Summary:*** The number and geometry of model layers should adequately represent the geological conditions of the coal seams, as well as the overlying and underlying strata, and geological features (such as faults, folds, intrusions, slides and other subsurface anomalies). Where horizontally bedded geological layers are combined for modelling, the properties of the composite layer must take the properties of the component layers into proper account.

7.1.3 Accounting for modified hydraulic conditions caused by hydraulic fracturing

Hydraulic fracturing is sometimes undertaken to increase the permeability of the coal seam, thereby potentially increasing the gas yield and/or production rate. The permeability of overlying or underlying strata may also be increased. Added uncertainty for groundwater modelling is created by the difficulty of measuring permeability changes caused by hydraulic fracturing (Nelson 2003).

Groundwater models that do not account for the increased permeability of geological materials that have been hydraulically fractured may underestimate produced water volumes

and/or regional groundwater drawdown. Therefore, it is important that where hydraulic fracturing has been undertaken, or is proposed, the influence of hydraulic fracturing on the permeability of the coal seam(s) and the overlying and underlying units is assessed. Where changes to the hydraulic properties of these materials may result in a significant change in the vertical hydraulic conductivity of geologic units—either above or below the coal measures over the capture zone of an extraction well—these should be accounted for. The outcome and assumptions in this assessment should be included in the groundwater modelling report.

The possibility that fracturing could cross more than one model layer should also be taken into account. Changes induced by hydraulic fracturing may only influence those model cells or elements used for representation of the well field. If hydraulic fracturing is expected to increase vertical conductivity, this should be included in the base-case analysis. For lesser changes, the potential effects could be considered using sensitivity analysis.

> ***Summary:*** Where hydraulic fracturing has been undertaken or is proposed, the change in hydraulic conductivity of geological materials (including the coal seams and the overlying and underlying units) resulting from the hydraulic fracturing should be assessed. Where increases in the effective vertical hydraulic conductivity of the geological unit above, within or below the target horizon are identified, the groundwater model should take the effects of fracturing into account: either within the base-case model or via a sensitivity analysis.

7.1.4 Accounting for modified hydraulic conditions caused by coal seam gas production

During coal seam gas production, coal permeability typically reduces during the early stages of production, due to reduced water pressure and consequent closure of matrix fractures. During later stages of production, coal permeability increases, due to gas desorption and consequent shrinkage of the coal matrix. Coal porosity may also be modified. The permeability changes may be small relative to the range of permeability values of the coal, or the uncertainty in the range of those values. Nevertheless, the significance of potential changes in hydraulic properties of the coal due to coal seam gas production should be assessed. Models such as those developed by Seidle and Huitt (1995), Palmer and Mansoori (1998), Pekot and Reeves (2002, 2003), Shi and Durucan (2003a, 2003b, 2003c, 2004, 2005a, 2005b), Robertson and Christiansen (2006) and Palmer (2008), may be used to estimate the coal seam gas production-induced changes to coal permeability and porosity. Groundwater modelling should account for any significant changes in coal hydraulic properties due to coal seam gas production.

Pan and Connell (2012) report the effect of coal shrinkage after gas desorption, which leads to a geomechanical response that changes the effective stress and thus the permeability. They review coal permeability and the approaches to modelling its behaviour.

The extent to which these processes influence groundwater flow, and thus groundwater drawdown and produced water volumes, depends on the conditions specific to the well field and wider geological environment. As such, a case-by-case assessment will be required.

> ***Summary:*** The significance of potential changes in hydraulic properties of the coal due to coal seam gas production should be assessed. Estimates of changes in coal permeability should be based on coal permeability/porosity–pressure models (such as the Palmer-Mansoori, Shi-Durucan, and Robertson-Christiansen models listed above), and the proposed depressurisation of the coal seams. The impact of the expected changes in coal permeability on groundwater flow, drawdown and produced water volumes should then be investigated although at the regional scale some parameters

may be unknown. Since depressurisation and changes in permeability are coupled, this assessment may require iterative groundwater modelling.

7.1.5 Accounting for coal anisotropy

Coal seams, like all fractured media, have spatially anisotropic hydraulic parameters. The most important of these—from a fluid modelling perspective—is the hydraulic conductivity (K). This anisotropy creates a parameter field that varies in three dimensions, and is known as a tensor. Most modelling platforms allow for an approximated tensor using only three elements (one for the vertical direction, and two principle orthogonal directions for the horizontal plane), which is sufficient for the vast majority of models. The ratio of vertical K to horizontal K (Kv/Kh) is known as the vertical anisotropy; the ratio of K in the two principle orthogonal direction (K1/K2) is known as the lateral anisotropy. With the discretisation available in numerical models, the lateral and vertical anisotropies can be easily incorporated in the vertical and lateral directions.

Coal exhibits both horizontal and vertical permeability anisotropy. The permeabilities in horizontal directions (parallel to bedding plane) typically differ, and the permeability in the vertical direction (perpendicular to bedding plane) differs from the permeability in the horizontal directions. This can affect groundwater flow significantly, resulting in potentially different drawdown in different directions.

For a typical undisturbed, layered, sedimentary-fractured medium (i.e. ignoring major structural features or induced deformation), vertical anisotrophy Kv/Kh is the most important. It characterises the degree to which depressurisation at depth is transmitted to the surface, and the amount of fluid flow occurring in the coal seam, or other layer, of interest. A reasonable estimate of this anisotropy will be required for numerical simulation. It is a critical variable in petroleum reservoir analysis, because it defines the cost associated with removal of hydrocarbons, due to dilution of the hydrocarbon by water from vertical leakage. Ayan et al. (2001) (adapted from Lake 1988) provides a useful discussion on vertical anisotropy. Figure 10 illustrates the concept of vertical anisotropy, which is usually incorporated into model calibration, but requires a reasonable estimation of spatially distributed flow observations. A reasonable estimate of Kv/Kh should also be incorporated into a model.

Anisotropy can be assessed from hydraulic tests conducted in the field, where observations that are some distance apart are available. It can also be estimated from fracture populations or geophysical surveys. Vertical anisotropy is routinely measured in the petroleum industry when characterising the production of the reservoir, using specialist, downhole vertical interference testing tools. However, these measurements are often not publicly available, or depths are kept confidential. Strong horizontal anisotropy in coal seam hydraulic conductivity is a ratio greater than 10 between the major and minor principal hydraulic conductivity values. This information would be useful for better parameterisation of hydraulic conductivity in regional groundwater models.

Inappropriate representation of coal anisotropy within models may result in the incorrect prediction of areas of groundwater drawdown and impact.

Summary: Horizontal permeability anisotropy of the coal should be represented in regional groundwater modelling where production trials have indicated strong horizontal anisotropy in coal seam hydraulic conductivity

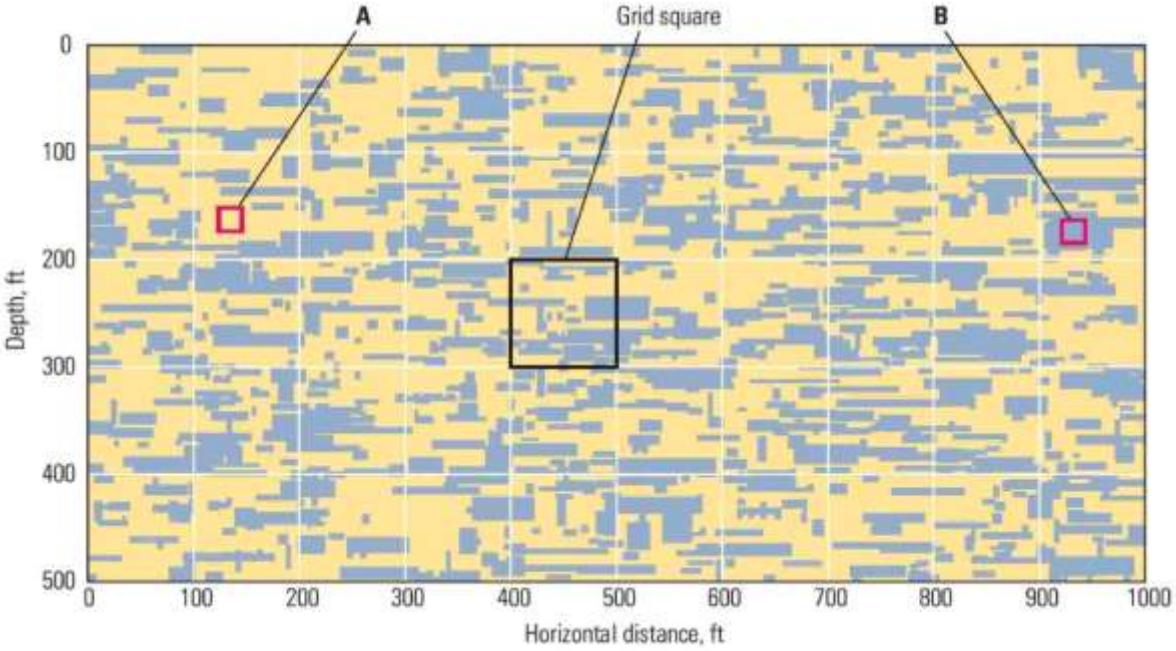

Figure 10 A cross-section of an idealised reservoir that exhibits large-scale anisotropy caused by local heterogeneity. The sandstone (yellow—A) contains randomly distributed shales (gray—B). Kv/Kh for the total volume is about 1 x 10^{-4}; however, the grid square, which may represent a reservoir simulation block, has a higher value of Kv/Kh

7.2 General issues

7.2.1 Model representation of surface water–groundwater interactions

The groundwater drawdown induced by coal seam gas production can affect surface water by modifying the groundwater pressures that govern the interaction between surface waters and groundwater. Surface water bodies can also influence groundwater flow behaviour. For example, water from a river or stream may contribute to an underlying aquifer; alternatively, shallow aquifers may contribute groundwater to deeply incised streams. Interaction between surface water and groundwater involves interaction between the groundwater system and rivers, streams, lakes, seas, wetlands, marshes, swamps or estuaries.

To adequately assess the potential impacts of coal seam gas operations on both groundwater and surface water, groundwater models must include the processes that govern the interaction between groundwater and surface water. Inaccurate representation of surface water–groundwater interaction will result in potentially inaccurate model predictions of water losses/gains from/of streams, rivers and lakes, and/or groundwater flows in the vicinity of surface water features.

When surface waters are not significantly affected by groundwater flow exchange, models that represent surface waters by standard model boundary conditions are expected to adequately model behaviour. However, to support this approach sufficient evidence would need to be provided to assume that there is no interaction between surface and groundwater. When surface waters are significantly affected by groundwater flow exchange, such as when coal seam gas extraction changes a stream from gaining to losing, a coupled surface water–groundwater modelling approach may be required.

Oversimplification of groundwater–surface water interaction in models may result in underestimation of the impact of coal seam gas production on losing streams.

Existing guidance for modelling groundwater–surface water interaction is provided by Barnett et al. (2012), Rassam et al. (2012), Rassam and Werner (2008) and Rassam et al. (2008).

> ***Summary:*** To effectively assess the potential impacts of coal seam gas developments on surface water, and to accurately model groundwater flow behaviour, models should include processes that adequately account for groundwater–surface water interaction. Where this interaction is dealt with by commonly used groundwater modelling tools, coal seam gas proponents should be required to objectively demonstrate that surface water impacts are adequately assessed. Barnett et al. (2012) provide guidance on suitable modelling approaches for surface water–groundwater interaction.

7.2.2 Modelling of cumulative coal seam gas impacts

The 'Methodology for bioregional assessment of the impacts of coal seam gas and coal mining developments on water resources' Barrett et al (2013) summarises cumulative impacts as:

> '*the aggregate, successive and incremental impacts on receptors, distributed in time and space, that occur in addition to the direct and indirect impacts of coal seam gas and coal mining development*'.

The United States *National Environmental Policy Act of 1969* defines cumulative impact as:

> *'the impact on the environment, which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (Federal or non-Federal) or person undertakes such other actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time'.*

Groundwater abstraction for purposes unrelated to coal seam gas production, such as irrigation, stock watering, industry and mining, is common in the existing and proposed coal seam gas-producing regions of Australia. Further, numerous coal seam gas developments may be present in the region, each inducing some groundwater depressurisation. The groundwater depressurisation impacts from all abstraction sources, whether from coal seam gas production or other uses, can be cumulative.

In addition to modelling the potential impacts induced by the proposed project, the impacts due to neighbouring coal seam gas production and other groundwater users (e.g. agriculture, industry, domestic use) should be assessed in concert with the impacts of the proponent's development. To accurately assess potential impacts, all contributing abstraction sources must be captured as accurately as possible.

The potential impacts of the coal seam gas extraction under study should be simulated using groundwater modelling to predict the incremental effects of the proposed development, and to recognise the combined effects of all developments in the region. However, it can be difficult to accurately quantify the activities of adjacent developments, if groundwater abstraction activities in the region are not publically available.

To provide a general initial understanding of the potential contribution of a particular coal seam gas development to potential impacts, it is good practice to model:

1. the proposed development in addition to all other groundwater abstraction sources

2. all other groundwater abstraction sources, but not the particular (proposed) coal seam gas development under study.

Subtracting the results of (2) from (1) then provides an initial indication of the contributing impact of the particular development under study.

The combined impacts of multiple developments may be modelled by:

- explicitly considering all impacts in concert within the same simulation, or
- combining the individual contribution of different impacts (from different simulations or estimates), using the principle of superposition to predict a total cumulative impact.

Care must be taken in superimposing the separately simulated impacts from adjacent developments that include mine dewatering or coal seam gas extraction. This can overestimate groundwater extraction volumes, because the objective of these activities is to achieve a target groundwater level or pressure reduction, rather than a required supply of groundwater.

The timing of individual activities is an important aspect of consideration of cumulative effects. When considering the contribution of a particular development to cumulative impacts, it is critical to understand the timing of the development and the timing of other groundwater-related activities in the vicinity. Because coal seam gas extraction can influence groundwater levels well after extraction has ceased, it is important to take account of the gradual nature of groundwater recovery in considering cumulative effects.

In some cases, due to the long history of development and complexity of earlier activities affecting groundwater levels, simulation of the complete history of a region may be difficult. The following approach could then be applied:

- The proposed development is modelled to provide predictions of drawdown extent.
- The predicted zone of influence is compared with the positions of existing and proposed activities in the area, and their potential zones of influence, to identify a potential zone of overlap.
- If the degree of drawdown from the proposed development is small where it coincides with that from other developments, the principal of superposition can be used to assess the incremental effect of the proposed development on the pre-development groundwater levels.
- If there is considerable overlap, modelling of the combined effects may be needed along the lines described above.

Summary: Cumulative impacts on groundwater should be modelled in a way that considers the coal seam gas development under assessment, as well as groundwater abstraction by all other groundwater users (including other coal seam gas well fields and abstraction from all other sources, which are used for activities such as irrigation, stock watering, industry and mining). Where analysis reveals that the predicted impacts of the proposed development on groundwater levels are small, and is well supported by evidence in the vicinity of surrounding and proposed activities, then the principal of superposition can be used to assess the incremental effect of the proposed development. Otherwise, combined modelling of the various activities should be included explicitly.

7.2.3 Assessment of impacts on water quality

The depressurisation associated with coal seam gas production may change groundwater flow conditions by mixing groundwaters of differing water quality from different groundwater horizons. Impact assessments should therefore consider the potential for water quality to be affected by the coal seam gas development. In cases where there is potential for the water quality of either shallow or deep aquifers to be affected by coal seam gas depressurisation, modelling should quantify the extent of that impact.

The following staged approach should be followed to address groundwater quality:

- A qualitative assessment should estimate likely groundwater flow paths and compare the water quality of the groundwaters of interest.
- If this reveals potential for significant impacts on water quality, then a semi-quantitative assessment of the time for an impact to be realised could be carried out. Travel times for potential impacts to develop can be calculated using particle tracking methods and concentration changes can be assessed using water balance models (simple mixing formulae).
- If the above assessments reveal water quality impacts of environmental significance, then numerical solute transport modelling might be needed to:
  - refine the nature and extent of predicted water quality impacts
  - develop management strategies
  - design mitigation measures.

Assessment of the effects on groundwater quality caused by coal seam gas-induced depressurisation should consider connectivity between hydrogeological units. The degree of disconnectivity between hydrogeological units should be explicitly assessed based on field data.

> ***Summary:*** The impact of coal seam gas developments on water quality should be assessed using qualitative and semi-quantitative methods, where quantitative methods are not possible. Should this qualitative or semi-quantitative assessment require refinement to characterise water quality impacts, and to develop management strategies or design mitigation measures, then groundwater quality (e.g. solute transport) should be modelled.

7.2.4 Assessing uncertainty in modelling

As discussed in Section 4.5, uncertainty is primarily a function of poor data and poor representation of hydrogeological relationships. However, uncertainty may also arise due to either a lack of knowledge (e.g. unknown hydraulic properties of a geological unit) or discrepancies/variance in knowledge (e.g. wide variation in the permeability of a particular geological unit). Even where extensive data are available, uncertainties may be associated with simplifications or approximations adopted to facilitate modelling.

Uncertainty may have a variety of sources, including:

- field data measurements and interpretation
- conceptual model structure, such as geological geometries and boundary conditions

- adopted model input parameter values, such as the hydraulic properties (e.g. permeability) of geological units.

Different combinations of model input parameters can also produce equivalent results, leading to uncertainty over which combination is more accurate. For example, simultaneous decreases (or increases) in hydraulic conductivity and recharge may lead to similar predicted hydraulic heads, Note that in this situation, observed flows would be used to help overcome the correlation in these parameters.

Conceptual model uncertainty can contribute a greater degree of uncertainty to model predictions than hydraulic parameters (e.g. Ye et al. 2009). Groundwater abstraction and recharge may contribute most significantly to uncertainty in regional groundwater modelling studies (e.g. Moore et al. 2011). The specific contribution to uncertainty in modelling outputs will largely depend on the specific model and data available. However, assessment of uncertainty should consider all these factors.

Uncertainty in relation to parameter selection may be reduced—or at least, better understood—during model calibration by using automated calibration techniques (e.g. tools such as PEST or UCODE).

The uncertainty associated with model inputs means that a degree of uncertainty is associated with model results (predictions). For this reason, it is wise for modelling studies to analyse the uncertainty inherent within the results. Assessing this uncertainty permits a more informed approach to management decisions. In cases where significant datasets are available, a stochastic uncertainty analysis (e.g. Monte Carlo) can quantify the uncertainty in model results. In cases where data are limited, extensive sensitivity analysis can provide an indication of how data limitations affect the results, as well as the uncertainty associated with those data limitations.

The sources of uncertainty (i.e. the details of the conceptual model and the specific parameter values that are not confidently characterised) should be identified. Knowledge of which sources may contribute most significantly to uncertainty in model predictions is useful when developing management strategies for the design of subsequent field studies.

7.2.4.1 Model calibration

The intentional matching of model parameters and outputs to measured parameters and observations conditions the model, to some degree, to these measurements and observations. The calibration process may reduce the uncertainty in model output. Parameter estimation tools such as PEST (Scientific Software Group 2012) or UCODE (Integrated GroundWater Modelling Centre 2012) may be used to constrain model inputs during the model calibration stage and improve model robustness and accuracy (e.g. Doherty et al. 2010). This approach requires a high degree of experience and discernment by the model user for final parameters to be appropriate. Where the initial parameter set of a model undergoing a parameter estimation run is at some distance from the global minimum for the parameter system, the calculated confidence limits for parameters subject to estimation may be useful for identifying poorly resolved parameters and guiding an uncertainty analysis of model predictions.

There are two main parameter estimation methods: gradient-based and non-gradient-based optimisation. Tools such as PEST and UCODE use the former method. Methods in the latter category are less prevalent in commercial tools; typical examples include genetic algorithms (multistart Simplex, Wang 1991), simulated annealing (Thyer et al. 1999), and the shuffled complex evolution algorithm (Duan et al. 1992, 1993). Many of these methods suffer from the problem of usually only finding a local system minimum, rather than the global minimum. This

is a continual problem in parameter estimation, and initial conditions significantly influence estimation performance. Tolson and Shoemaker (2007) present the use of an additional method: the dynamically dimensioned search algorithm. This is a non-gradient method applied to a watershed model and is described as a simple, stochastic, single-solution-based, heuristic global search algorithm. It was developed to find good global system solutions within a specified maximum function (or model) evaluation limit, and is designed to scale the search to the user-specified number of maximum function evaluations. It has a novel approach, in which it searches globally at the start, and searches more locally as the number of iterations approaches the maximum allowable number of function evaluations.

7.2.4.2 Uncertainty analysis

Barnett et al. (2012) discuss the assessment of uncertainty in model parameters and predictions. Uncertainty assessment can involve linear or non-linear methods. They provide the following useful references for further reading:

> *'Descriptions of uncertainty, as well as specific uncertainty tools, methods and mathematical foundations include, but are not limited to, the following: Beven (1993; 2009), Beven and Binley (1992), Moore and Doherty (2006), Hunt and Welter (2010), and Doherty (2011). Detailed description of guidelines and software tools currently available for groundwater uncertainty analysis are given by Doherty et al. (2010). Description of the highly parameterised approach for maximising information extracted from field data and minimising model structural error during groundwater model calibration is given by Hunt et al. (2007) and Doherty and Hunt (2010). A detailed example of the use of models for assessing the worth of data collection for reducing model uncertainty, and the importance of avoiding model oversimplification, is given by Fienen et al. (2010) and Fienen et al. (2011). Detailed description of the theoretical basis of an uncertainty approach to groundwater modelling can be found in Moore and Doherty (2005), Christensen and Doherty (2008), Tonkin et al. (2007), Tonkin and Doherty (2009), Doherty and Hunt (2009a;b), Doherty and Hunt (2010), Doherty and Welter (2010), Moore et al. (2010), and Appendix 4 of Doherty et al. (2010).'*

Simple assessments of the uncertainty of model predictions generally use direct approaches, which predict model outcomes based on a limited number of discrete scenarios that have been subjectively selected by the modeller. Perhaps the most common direct approach is sensitivity analysis, which quantifies the influence of incrementally varied model parameters on model predictions.

Sensitivity analysis usually comprises small changes in input parameters. The full range of uncertainty in these parameters is not usually explored when assessing the impacts on model outputs. However, the procedure is simple and is commonly used to explore potential scenarios, highlight the model input parameters to which the model predictions are most sensitive, or assess how data limitations affect predictions. By accounting for a range of model input parameter values in the sensitivity analysis, the range in potential model predictions can also be presented. This information can be useful for decision makers—for example, in reviewing the range of possible groundwater drawdown or produced water volumes that might be expected from a coal seam gas development, or in identifying which data can be obtained through field investigation to reduce model uncertainty. However, for complex models with many model parameters, a thorough sensitivity analysis of most/all parameters is computationally intensive, and may require problem simulation on several processors in parallel.

Sensitivity analysis may be conducted manually by the modeller, or tools may be used (e.g. MOD-PREDICT; Tonkin et al. 2003) to improve the efficiency of the process. Deterministic methods do not consider the probabilistic structures of inputs, such as subsurface physical heterogeneity (e.g. variability in aquifer parameters), and cannot quantify the probability of model outcomes (e.g. the likelihood of a particular design failing). To achieve this, stochastic approaches are used (Li et al. 2004). These approaches provide a broader coverage of the parameter spaces associated with a mathematical representation of a natural system. They also provide lower levels of significance (i.e. higher levels of confidence for parameter ranges) for outputs than do typical sensitivity analyses.

Stochastic (or probabilistic) analysis involves the use of statistical methods to predict a probabilistic distribution of potential model results/outcomes. This approach can incorporate information relating to uncertainty, identify which parameters are associated with the greatest uncertainty, and provide a range of possible outcomes (with presentation of the probability of each possible outcome). Numerous stochastic approaches may be used to estimate uncertainties in model predictions, including first-order analysis, perturbation analysis, and various kinds of Monte Carlo analysis (e.g. Markov chain, Null-space).

Monte Carlo simulation can assess probabilistic outcomes from models. This approach involves many individual simulations, each of which has input parameter values randomly selected from a probability distribution of potential values for each parameter. Combining the modelling outcomes permits assessment of the probability (likelihood) of model outcomes. However, use of this approach is constrained by the fact that each input parameter must be assigned a probability distribution of values. Development of probability density functions requires large amounts of data that, depending on the model parameter, are often not available. In such circumstances, the probability density function for a parameter can be estimated from measurements made for similar subsurface media at other locations. Other uncertainty analysis considers the total bounds (or probability distribution) of prediction based on the total uncertainty (bounds or probability distribution) of the input parameters.

The choice of method for sensitivity testing to assess uncertainty in model output depends upon the complexity of the model and the understanding of the uncertainty of the input parameters. It is infeasible to carry out a sensitivity test of every model input. Therefore, sound judgement—combined with an understanding of the groundwater system—is essential in selecting the approach and detail of sensitivity testing. These approaches also contain the implicit assumption that the basic structure of the model (e.g. geometry, extent of aquifers, nature of boundaries) is correct. The uncertainty associated with model structure is commonly overlooked.

For example, in practical terms, uncertainty can be addressed by comparing results with the groundwater responses of nearby developments and by interpreting pilot-scale trials. These provide measurements of extracted fluid volumes and subsequent drawdown over a large scale, and may also allow assessment of large-scale hydraulic parameters. This can reduce the level of uncertainty in model predictions. The uncertainty in relation to groundwater impacts can also be addressed through development of a response plan to address the possibility of unfavourable outcomes during operation. Such measures may include injecting water (subject to quality considerations) to mitigate effects of drawdown of shallow aquifers, or modifying the operation of the coal seam gas extraction wells.

> ***Summary***: Assessment of potential impacts should acknowledge uncertainty in modelling. Where possible, it should also quantify the uncertainty and identify contributing sources of uncertainty, with consideration of structural/conceptual and parameter uncertainty. Reporting should discuss the uncertainty associated with the

model predictions. Barnett et al. (2012) provide guidance on uncertainty and reporting. Consideration could also be given to acceptable levels of uncertainty.

7.2.5 Reporting of modelling studies

The development and results of models must be communicated effectively, and with sufficient detail. A modelling report is considered to have provided sufficient information if the model can be reproduced and similar results obtained.

Report discussion should address the key issues related to modelling groundwater impacts due to coal seam gas production, as listed above. Further, reporting of coal seam gas groundwater modelling studies should:

- follow existing guidelines (e.g. Barnett et al. 2012)
- provide sufficient information to allow reproduction/duplication of the modelling, including
  - definition of the base and thickness of units modelled
  - definition of the way coal seam gas extraction is modelled over time
  - material properties adopted for modelling and how these vary over the model domain
  - clear definition of the nature and location of model boundaries
  - treatment of recharge and evaporation/transpiration
  - treatment of other groundwater activities (e.g. irrigation, groundwater extraction, mining)
  - initial conditions adopted
  - clear definition of the treatment of surface water features (e.g. creeks, rivers, lakes, wetlands)
- provide a clear statement, including justification, of the assumptions employed in developing the model parameters
- present modelling results that include both groundwater drawdown and fluxes
- partition depleted water source volumes for licensing purposes
- discuss uncertainty associated with model development and predictions
- provide results and discussion of cumulative impacts.

Groundwater modelling studies should recognise existing water resource management plans and policies, such as the New South Wales Water Sharing Plans, Queensland Water Resource Plans and Resource Operations Plans, and New South Wales Aquifer Interference Policy. Modelling results could be presented in the context of such plans and policies. For example, the volumes of water extracted under coal seam gas production could be compared with water budgets nominated in water resource management plans for the area(s) under study. Groundwater extraction from coal seam gas production may draw significantly on groundwater resources. This will need to be consistent with the requirements of individual jurisdictional water management plans and other policies.

Impact assessment modelling studies for proposed coal seam gas developments may involve the collection and review of significant hydrogeological and hydrological data. This data may be used to amend interpretations of sustainable groundwater extraction limits,

particularly where new geological and hydraulic connectivity data have been obtained, and to update water management plans. To facilitate use of the data, the modelling report should reference the material collated. Modelled impacts should be presented in a way that can be usefully interpreted in terms of the prevailing water sharing plans or water resource plans.

Summary: Reporting should follow national guidelines, be sufficiently detailed to allow reproduction of modelling undertaken, and present the modelling results in a manner that is consistent with regulatory requirements. Modelled impacts should be presented in a way that can be usefully interpreted in terms of the prevailing water sharing plans or water resource plans, and known concerns associated with the local area and proposed development.

8 Further knowledge requirements

This section discusses knowledge gaps associated with modelling the groundwater impacts from coal seam gas production. In addition to these, there will inevitably be knowledge gaps for particular developments in relation to the hydraulic parameters applying to the various potentially affected geological horizons, and in the understanding of the detailed geological profile in the area of interest. There will also often be uncertainties in the use of groundwater by others, and background groundwater levels and quality. Knowledge gaps of this kind are commonplace for regional groundwater modelling, and are not specific to modelling impacts of coal seam gas extraction. Appropriate data collection and analysis undertaken before modelling minimises the uncertainty of model inputs, and therefore outputs.

8.1 Influence of flow phenomena and geomechanical effects

As discussed in Section 3.3, three main flow and geomechanical phenomena influence the groundwater flow regime within the immediate vicinity of the well field:

- dual-phase flow is typically induced within the well field during coal seam gas production
- coal has a dual porosity structure that can affect fluid movement
- gas liberation from coal and general groundwater depressurisation can affect fluid flow by changing coal permeability.

While available reservoir modelling tools (e.g. ECLIPSE and GEM) can represent the above phenomena, and account for impacts beyond the immediate vicinity of the well field, their use at the regional scale is impractical due to the intensive computational requirements. The base components of modelling tools commonly used for regional groundwater modelling studies (e.g. MODFLOW and FEFLOW) are not capable of modelling dual-phase flow, the dual porosity nature of coal, or geomechanical effects without modifications. Appendix B lists models that include these functions that include models such as COMET 3, COSFLOW and GEM; however, these are not often applied at the regional scale. Past modelling studies for proposed coal seam gas developments in Australia that used regional groundwater modelling tools have assumed the effect of dual phase, dual porosity and gas liberation-affected flow phenomena and geomechanical changes to hydraulic properties to be negligible. In Appendix C the effects of these processes are often not represented in the regional groundwater models and listed as a model assumption and simplification.

There is limited data on the influence of dual phase or dual porosity flow or geomechanical phenomena beyond the vicinity of individual well fields. Few studies available in the public domain explore the influence of dual phase or dual porosity flow, or geomechanical phenomena, on the predictions of regional groundwater modelling for coal seam gas production. However, to take in account near well-field processes like coalbed desaturation, current efforts by Herckenrath, Doherty and Moore (2013) aim to combine traditional groundwater simulation tools with coal seam gas reservoir models. While it is still unclear how to combine coal seam gas reservoir models with standard groundwater modelling tools their research paper explores how to 1) to quantify and compensate for modelling errors incurred by up-scaling and neglecting dual-phase flow and 2) to describe the physical resemblance of parameters in up-scaled CSG groundwater impact models.

Without more detailed knowledge of the degree to which dual-phase flow and coal dual porosity flow occur, the conditions under which they occur, and the degree to which

geomechanical effects may influence groundwater flow behaviour beyond the well field, uncertainty will remain in simulations of coal seam gas production-induced impacts on groundwater.

Further research could aim to:

- assess the extent to which these factors influence the results of regional modelling and predict the volumes of produced water
- develop relationships to identify the areas/environments and times for which these factors are important for regional groundwater modelling
- identify methods for representing these processes in a simplified way for regional modelling and estimating the magnitude of the errors introduced by using such methods.

In assessing the significance of errors introduced by modelling simplifications, it is important to acknowledge the underlying uncertainty in the knowledge of aquifer properties and the geological conditions over the regional areas modelled.

8.2 Surface water–groundwater interaction

Although the depths from which coal seam gas is extracted are generally relatively remote from surface water processes, the potential impacts on flows in surface streams and rivers are of great community interest. Changes in river flow associated with groundwater impacts could influence water sharing processes. In Australian groundwater assessments of coal seam gas extraction, the effects on surface water flows are typically addressed by nominating water levels in rivers and lakes based on historical records, and using the groundwater model to predict changes in the rate of seepage between groundwater and rivers.

Surface water interaction is often represented (not coupled) through use of boundary conditions within the groundwater model. However, groundwater models can be interfaced with surface water modelling software to provide a coupled approach to surface water–groundwater interaction. For example, FEFLOW can be coupled with MIKE11 to model groundwater interaction with surface water bodies. This provides a more complete treatment of the surface water impacts of coal seam gas extraction, but in some cases, the additional value of this approach may be limited.

Research directed at providing an understanding about *when* explicit modelling of coupled surface water–groundwater flow is needed to simulate the connectivity between surface water and groundwater systems in the vicinity of coal seam gas reserves is required.

The following specific areas of research would be of benefit:

- to identify when to model surface and groundwater interaction beyond the traditional methods would be beneficial
- identify the significance of groundwater recharge during flood events for major alluvial systems near existing or proposed coal seam gas operations
- quantify seepage relationships between groundwater and surface water bodies (especially wetlands and rivers).

8.3 Monitoring datasets

Records of the fluid extraction and groundwater drawdown for coal seam gas operations are limited, and may not be immediately accessible to researchers as industry generally releases data according to regulatory timeframes.

The following points illustrate the current situation in Queensland regarding release of this information into the public domain:

- Queensland geology and reservoir data are confidential for two to five years, but is available in the public domain thereafter.
- Water production data are available six monthly after the two-year confidentiality period is over.
- Monitoring data (e.g. groundwater levels) is largely available publically.
- Production profile data are available publically through state regulatory authorities, tenure holders, environmental impact assessment reports, or business plans, although the granularity needed for some purposes may be insufficient.
- The Queensland Office of Groundwater Impact Assessment can access data directly from coal seam gas companies through separate agreements.

Collated results from coal seam gas exploration, and monitoring groundwater responses from coal seam gas extraction, would be most valuable in reducing uncertainty and for supporting further research: including evaluation of the performance of models of various kinds. Case study reports would be most useful if they clearly identify the geological setting for individual developments, have detailed records of the rate of groundwater and gas extraction from individual bores, and record groundwater heads, including clear definition of the location of the monitoring points (including the geological horizon monitored, and location in relation to pumping bores).

8.4 Improved representation of hydrogeological features

The influence of major hydrogeological features, such as aquitards (i.e. flow-impeding layers), spatial variability of hydraulic conductivity and fracturing and fault zones, on groundwater flow and pressure transmission is not well understood, and is not well represented in most groundwater models. Future research could identify appropriate assessment methods for these features, their range of properties and influence on groundwater flow and how best to represent them in numerical models of regional groundwater flow. Sensitivity analysis of the groundwater simulations, uncertainty analysis and regional significance of the results would need to be considered.

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Appendix A - Coal seam gas workshop

On 24 August 2012, Coffey Geotechnics Pty Ltd held a workshop on the modelling and impacts of coal seam gas on water resources and ground subsidence. The workshop was attended by groundwater modelling specialists and representatives from the coal seam gas industry, thereby providing an opportunity for industry and expert opinion to be considered in the development of this report. The attendees are listed below, followed by a summary of their comments.

Projects:

CSG Comparison of Groundwater Modelling Approaches and Subsidence Impacts from CSG Extraction

Meeting time and venue:

10:00 to 16:00, 24 August 2012, Coffey Chatswood (Sydney) Office

Attendees:

- Office of Water Science: Dr Geraldine Cusack, Mr Bruce Gray
- Qld Water Resources Commission: Mr Sanjeev Pandey
- AGL Energy: Mr John Ross
- Arrow Energy: Mr St. John Herbert, Mr Simon Gossmann
- QGC: Mr John Grounds, Mr Daniel de Verteuil
- Santos: Mr Glenn Toogood, Mr Todd Gilmer, Dr Kumar Narayan
- Kalf and Associates: Dr Frans Kalf
- Heritage Computing: Dr Noel Merrick
- Strata Control Technology: Dr Ken Mills, Dr Winton Gale
- Coffey Environments: Mr Michael Blackam
- Coffey Geotechnics: Mr Ross Best, Mr Paul Tammetta, Dr Ben Rotter

Meeting subject:

Gathering input from industry and specialist experts on issues relevant to subsidence impacts from coal seam gas and modelling the potential groundwater impacts from coal seam gas extraction.

Chairperson:

Mr Ross Best

Item	Discussion
Characteristics of coal	• Characteristics of coal vary, including anisotropy and direction. Strong horizontal anisotropy has been observed at one location in the Bowen Basin. • Cleats are part of the coal fabric and are an intrinsic property of the coal.

Item	Discussion
	Increase in depth and the rank of coal is usually associated with smaller cleats. • Coal exhibits a full range of porosity (dependent on rank). • If significant carbon dioxide is present, cleats can become clogged with calcite. • Typically, (reservoir) models consider that the matrix has no pore volume (no water storage). In reality, there may be contributing water within the matrix. • How the coal is distributed in the coal bearing formation is important (in Surat coal is only 10% of thickness). • Representation of coal properties is scale dependent, and can be a function of micro-level molecular pore investigations through to macro-level regional reservoir analyses.
Sorption behaviour	• Data for Australian coals in the context of CSG are not in the public domain. • It may be prudent to assess sorption behaviour separately for each development. • Gas carrying capacity of water is not sufficient to carry useful gas volumes. • Reservoir history matching can be useful for assessment of permeability changes due to gas desorption.
Stress-related changes	• Parameters are generally derived from laboratory scale tests (typically conducted on matrix to assess permeability, porosity, modulus, etc). Work conducted by Dr John Seidel (USA) may be of use. • Industry's derived parameters are generally not in the public domain, but parameter values may be found in Society of Petroleum Engineers Journal and similar publications. • Permeability reduces with depth. Increase in depth and increase in temperature both increase capacity to store methane.
Hydraulic fracturing	• As natural horizontal stresses in the coal seam are lower than in the overlying and underlying units, fracturing tends to be vertical and to propagate horizontally parallel to the principal stress directions within the coal. • Hydraulic fraccing is required in Camden, but not generally required in Surat (about 10–15% of wells are fracced in parts of the Surat). • Assessment of fracture propagation may be undertaken using micro-seismic sensors, and/or the inclusion of a radioactive isotope within the proppant fluid. • Micro-seismic monitoring can provide a useful tool for identifying the position and depth of fracturing. • Tilt meters are commonly used to assess the direction of fractures in coal mining. Back analysis can indicate how fracture is growing. • Groundwater temperature profiling may be used to assess aquifer connectivity (between two wells). • Useful data may be found in Powder River study by Mark Zoback and from the University of Wollongong's research on fracture flow.
Flow processes near wells and well	• High pressure stream of gas and water (mixed) is present—gas and water are not spatially separated.

Item	Discussion
operation	• There is a timelag for water (i.e. water continues to be released after initial depressurisation). • Depressurisation potentially propagates up through the overlying strata and such effects are more likely to be witnessed in the vicinity of localised features (such as where a low hydraulic conductivity unit pinches out). • A single well in Surat/Bowen Basin has an average working lifespan of about 5 or 6 years, whereas the well field has a lifespan of about 30 or more years. • Gas and water are at the same pressure. Gas concentration dictates the type of flow (bubbles/slugs/etc). Gas bubbles up but meets capillary resistance. • Gas flows in the gas phase and is not significantly spatially separated from the liquid (water) phase. • Gas field operators manage the well field system to avoid dead spots between wells. In the Powder River Basin, additional wells were installed during production to reduce well spacing to eliminate dead spots formed by the intersection of the cones of depression from each bore. • Horizontal wells are not used at present in the Surat and Bowen Basins—the coal seams not thick enough for them there—but they are used in the Southern Sydney Basin. • QLD Water Resources intend to obtain vertical groundwater pressure profile measurements from CSG wellfields. Results available 2013/2014.
Settlement considerations	• It is useful to consider cumulative impacts (including impacts from other CSG operations and irrigation). Presence of disturbed ground (e.g. in vicinity of previous long wall mining) should also be noted. • Subsidence expression at the surface depends on the directional pressure distribution and ground deformation/deflection. • Accurate baseline measurements are helpful. • Multiple groundwater pressure monitoring points (in coal measures, coal matrix, aquifers and aquitards) within the well field would allow better understanding of the vertical propagation of pore pressure changes. • It is useful to conduct assessments in the context of what magnitudes are critical in different environments and whether settlement is differential/localised or widespread and uniform. • Differential settlement can be induced by geological features (e.g. dykes). None of the attendees reported differential settlement associated with groundwater level reduction near faults. • Different measurement techniques may predict differential settlement with varying adequacy. • Accurate baseline data is required to determine what is causing subsidence and to quantify the changes. • Need to distinguish between uniform subsidence and non-uniform subsidence.
Settlement monitoring and measurements	• Australian developments have proposed monitoring but currently there is no/very limited data available. • The San Juan Basin and Powder River Basin developments may provide useful overseas data. Nelson (2007) may provide useful data for international cases of general (non-CSG related) subsidence. • InSAR is an effective technique for measuring large settlements over

Item	Discussion
	large areas, but may be confounded by (and analysis may require correction for) vegetation, ploughed fields, shrink/swell responses and movements greater than one satellite signal wavelength between satellite pass-overs. • Monitoring is considered desirable when significant subsidence is expected. • Seismic methods for sensing changes in stress with depth may have significant limitations. • Potential impacts to swamps and wetlands may be worthy of consideration.
Modelling approaches: purpose of modelling	• It is useful to consider cumulative impacts (including impacts from other CSG operations and irrigation). The presence of disturbed ground (e.g. in vicinity of previous long wall mining) can be important. • Substitution (mitigation) by using production water for irrigation is relevant in the context of beneficial use. • Modelling can be used to drive groundwater monitoring choices that reduce model uncertainty. • Modelling can be used to assess the significance of ground disturbance associated with hydraulic fracturing. • Different models may be helpful in undertaking different impact assessments (e.g. assessment of regional groundwater impact may use different model to assessment of impact to springs).
Modelling approaches: considerations	• Biggest constraint is the lack of appropriate data. • There are scale issues with modelling in both time and space. • The full recovery period may be important (potentially hundreds of years). • Reservoir models can be split into single-phase flow models and dual-phase flow models. • Re-injection can be to the coal seam, deeper underlying aquifers, or to shallower overlying aquifers. • Data on aquitards is very important and is typically very limited. • Flow under re-injection of viscous brines may not obey Darcy's law—cement grout may be a more relevant surrogate. • The potential presence of poorly constructed bores (that potentially hydraulically connect aquifers) may be relevant. Bore integrity and connectivity could be important. • It would be useful for comparison of modelling approaches to review how different models communicate with each other (e.g. surface water models coupled with groundwater models). • Discretisation/resolution is relevant to the context of modelling purpose. • Density-dependent flow may be relevant (e.g. where injection of low saline production water is of lower density than native groundwater). • Types of models: conceptual, analytical, sectional, regional, parameter estimation, numeric.
Modelling approaches adopted by industry	• QGC are developing a coupled reservoir and regional groundwater model. This is at a research level and is some time off being used for design or impact assessment. • QGC are working with the CSIRO and John Doherty on upscaling of reservoir models in ECLIPSE to regional groundwater flow models in

Item	Discussion
	MODFLOW. • Santos conducted 2D analytical modelling for the Surat for assessing volumes of produced water.
Modelling approaches: guidelines	• Highly prescriptive guidelines would tend to suppress creativity and dynamic exploration of new modelling tools. • Fit-for-purpose modelling is essential. • Ground and surface water models (and how they link) are required. • Repeatable, transparent and well-documented models are required. • Assumptions need to be comprehensive and clear. • Errors need to be estimated. • Chemistry of water and mixing would be useful. • Long-term modelling to assist monitoring and evaluation. • Existing guidelines cover a wide range of modelling issues relevant to CSG. • It would be useful for any development of new CSG modelling guidelines to cover topics that existing guidelines do not address in relation to CSG-specific issues. • Factors considered relevant include – distinguishing between operating sites and 'greenfield' sites – degree of model parameterisation – complexity of model vs stage of project/complexity of task – different versions of the one model—for example, do different versions of MODFLOW affect the comparison of results.
Uncertainty in modelling	• Factors considered relevant include – data limitations and data availability – conceptual models – parameters for field validation – pareto analysis in assessing uncertainty – likelihood analysis – cluster analysis – Bayesian and Monte Carlo analysis – validation.

Appendix B - Numerical modelling software and base functionality

Model name[a]	Model type[b]	Proprietary/ public domain[c]	Dimensions, numerical technique[c]	Dual porosity	Multi-phase flow (liquid + gas)	Methane sorption	Geomechani-cal effects	Unsaturated flow	Solute transport	Surface water–groundwater interaction
COMET3	S	C	3D, FD	Y	Y	Y	Y	N?	Y (limited)	N
COSFLOW	S	C	3D, FE	Y	Y	Y	Y	Y	N	N
DYNAFLOW	R	C	3D, FE	N	N	N	N	N	N	Dynamic coupling (DYNRIVER)
ECLIPSE	S	C	3D, FE	Y	Y	Y	Y	Y	N	N
FEFLOW	R	C	3D, FE	N	N	N	N	Y	Y	Implicit, subreach scale; or coupled with MIKE11
GEM	S	C	3D, FE	Y	Y	Y	Y	N?	Y (limited)	N
HST3D (A public domain version of SWIFT)	R	P	3D, FD	N	N	Y (single species linear equilibrium sorption)	N	N	Y	N
HydroGeo-	R	C	3D, FV	Y	Gas phase	Non-gas	N	Y	Y	Dynamic

Model name[a]	Model type[b]	Proprietary/ public domain[c]	Dimensions, numerical technique[c]	Dual porosity	Multi-phase flow (liquid + gas)	Methane sorption	Geomechani-cal effects	Unsaturated flow	Solute transport	Surface water–groundwater interaction
Sphere			(alternate FE solver also provided)		is 'air'	sorption				coupling
HYDRUS-2D/3D	R	C	2D/3D, FE	Y	N	N	N	Y	Y	Non-coupled, subreach scale
MIKE SHE	R	C	1D/2D (surface), 3D (groundwater)	N	N	N	N	Y	N	Dynamic coupling
MODFLOW	R	P (C for many add-on modules)	3D, FD	With add-on module (e.g. SURFACT)	N	N	N	With add-on module (e.g. SURFACT)	With add-on module (e.g. MT3D, MODPATH or PHT3D)	Non-coupled, regional scale MODHMS add-on provides coupled treatment
SEEP/W	O	C	2D, FE	N	N	N	N	Y	Y (CTRAN/W)	N
SLIDE	O	C	2D, FE	N	N	N	Y	Y (steady state only)	N	N
SUTRA	R	P	3D, FE	N	N	N	N	Y	Y	N
SWIFT	R	C	3D, FD	Y	N	Y	N	N	Y	Non-coupled

Model name[a]	Model type[b]	Proprietary/ public domain[c]	Dimensions, numerical technique[c]	Dual porosity	Multi-phase flow (liquid + gas)	Methane sorption	Geomechani-cal effects	Unsaturated flow	Solute transport	Surface water–groundwater interaction
TechSIM	S	C	2D, FD	Y	Y	Y	N	Y	Y	N
TOUGH2	S	C	3D, FD	Y	N	Solid phase only	N	Y	N	N

[a] Potential usage in relation to coal seam gas production indicated against each programme

[b] Model type: R = regional model; S = reservoir model; O = other local/subregional scale modelling

[c] C = proprietary; P = public domain; FD = finite difference; FE = finite element; FV = finite volume. Y = model feature included; N = model feature not included; C = Maximum dimension shown.

Note: some models (such as FEFLOW) can be modified with custom computer code to simulate additional processes such as surface water–groundwater interaction.

Appendix C - Examples of modelling for regional impact simulations

Coal seam gas development project	Modelling tool(s) adopted	Modelling approach type adopted and processes included	Simplifications and assumptions	Uncertainty analysis	Reference(s)
Arrow Energy Surat Gas Project, Australia	MODFLOW	Regional groundwater model (120,000 km^2 model domain) Well field represented by individual abstraction wells Cumulative impacts assessed (including other CSG developments)	Dual-phase and unsaturated flow, geomechanical effects, and dual porosity nature of coal all assumed insignificant Assessed to be limited groundwater–surface water interaction – simple (non-coupled) approach to groundwater–surface water interaction adopted Coal horizontal anisotropy not modelled Coal seams not modelled independently of coal measures Hydraulic connectivity of geologic structural features ignored (Hydraulic fracturing not proposed to be undertaken by Arrow, thus its potential impact was not required to be assessed)	Deterministic uncertainty analysis only: Sensitivity analysis for specific aquifer parameters and multiple aquifers. Effect of sensitivity-adopted parameter values on calibration performance discussed Indicated significance of hydraulic parameters and range of drawdown magnitudes	Arrow Energy Pty Ltd (2012c)
Australia Pacific LNG Project, Australia	FEFLOW	Regional groundwater model (172,740 km^2 model domain) Finite element method (FEFLOW) allows	Geomechanical effects, and dual porosity nature of coal all assumed insignificant Simple (non-coupled) approach to groundwater–surface water interaction adopted Coal horizontal anisotropy not modelled Coal seams not modelled independently of coal	Deterministic uncertainty analysis only: Sensitivity analysis (two extreme cases only) for aquifer, recharge and stream conductance parameters. Effect of	Australia Pacific LNG (2010), Geoscience Australia and Habermehl (2010)

Coal seam gas development project	Modelling tool(s) adopted	Modelling approach type adopted and processes included	Simplifications and assumptions	Uncertainty analysis	Reference(s)
		improved definition of complex geology Dual-phase flow implicitly accounted for by reducing coal seam permeability Cumulative impacts assessed (including other CSG developments)	measures CSG well field represented by constant pressure head (rather than pumping flow rates) Hydraulic connectivity of geologic structural features ignored Discussion of hydraulic fracturing severely limited Hydraulic parameters assumed for most model layers due to limited data Simplified hydrogeological model, which may only reflect a partial understanding of the Surat Basin Connectivity between aquifers uncertain as geological structure poorly understood Upward propagation of depressurisation from Permian-age coal deposits in the Bowen Basin not included	sensitivity-adopted parameter values on calibration performance discussed Indicated significance of hydraulic parameters and range of drawdown magnitudes	
Santos Gladstone LNG Project, Australia	Analytical model (Roma field), MODFLOW (Comet Ridge field)	Regional groundwater model Model domain limited to project area Time-varying constant head boundary condition used to represent well field (rather than pumping/flow rates) for MODFLOW model; constant pumping rate used to represent well field in analytical model	Model not calibrated Dual-phase flow, coal dual porosity and anisotropy, and geomechanical effects not included Coal seams not modelled independently of coal measures Vertical movement of groundwater not well constrained Aquifer confinement and interconnection simplified Effects of geological faults assumed insignificant Analytical modelling did not account for size of well field Apparently no accounting of groundwater–surface water interaction	Limited deterministic uncertainty analysis: Sensitivity analysis (four cases) for specific aquifer parameters and recharge for the MODFLOW model, and for storativity for the analytical model CSG well fields were modelled separately and cumulative impacts associated with other	Santos (2009a), Santos (2009b)

Coal seam gas development project	Modelling tool(s) adopted	Modelling approach type adopted and processes included	Simplifications and assumptions	Uncertainty analysis	Reference(s)
				developments assessed on a qualitative basis	
Surat Basin	MODFLOW	Regional groundwater model – CSG region divided into three subdomains (hydraulic compartmentalisation assumed) Time-varying constant head boundary condition used to represent well field (rather than pumping/flow rates)	Dual-phase flow, coal dual porosity and anisotropy, and geomechanical effects not included Coal seams not modelled independently of coal measures No consideration of rainfall recharge Simplified geology, homogeneous isotropic conditions Cumulative impacts not assessed Apparently no accounting of groundwater–surface water interaction	None	QGC (2009)
Queensland Water Resources	MODFLOW	Regional groundwater model (300,000 km^2 model domain)	Modelling of historical CSG operation in Queensland (Surat and Bowen Basins) was undertaken Modelling included simulation of multiple CSG operations and was used to develop and assessment of cumulative impacts and aggregate groundwater extraction associated with CSG extraction	Uncertainty analysis was carried out using multiple simulations incorporating changes to the model. The results of this analysis were used to assess uncertainty in the predicted impacts	Queensland Water Commission (2012)
Namoi Catchment	MODFLOW	Regional groundwater model (30,000 km^2 model domain) CSG well fields modelled using a specified extraction rate over each	Separate model of surface water system Multi-layered model to address future CSG and coal mine development. Modelling of existing, planned and possible development Cumulative effects assessed through multiple model analyses by comparing the results for a range of	Sensitivity analyses carried out to assess uncertainty associated with rock permeability and recharge values adopted	Schlumberger Water Services (2012)

Coal seam gas development project	Modelling tool(s) adopted	Modelling approach type adopted and processes included	Simplifications and assumptions	Uncertainty analysis	Reference(s)
		well field modelled Cumulative impacts (including existing and proposed developments)	alternate development scenarios with a base case of limited development Groundwater impacts on surface water obtained using nominated head boundaries to represent permanent water courses		
Powder River Basin, Montana, US	MODFLOW	Regional groundwater model (1240 km^2 model domain) Subregional constant head boundary condition used to represent CSG well field	Dual-phase flow, coal dual porosity and anisotropy not included. Geomechanical effects assumed to have no impact Coal seams not modelled independently of coal measures Cumulative impacts not assessed Implicit (uncoupled) groundwater–surface water interaction	None	Myers (2009)

Appendix D - Evaluation of modelling approaches

Modelling approach/ purpose	Advantages	Disadvantages	Appropriate application
Analytical	Efficient and simplified analysis of all potential impacts to groundwater resources Useful when data is limited and/or geological and hydraulic conditions are relatively simple	Unable to capture complex geologic geometries (e.g. non-uniformly layered geology) or hydraulic conditions (e.g. coal anisotropy) May oversimplify hydraulic processes	Screening or preliminary assessment (particularly where data is severely limited) Can be a valuable tool for modelling flow in the vicinity of individual wells
Axisymmetric	Useful for modelling relatively symmetric conditions (e.g. in vicinity of coal seam gas wells where geological conditions are axisymmetric)	Not suitable for regional scale assessment Available tools do not consider gas desorption and migration, dual phase flow or coal dual porosity, which may pose inaccuracies in predicting impacts Not capable of assessing cumulative impacts	Assessment of impacts in the near-well (or near-field) under axisymmetric conditions Can be a valuable tool for modelling flow in the vicinity of individual wells
Reservoir assessment	Designed (and therefore best suited) to predict produced water volumes and depressurisation and in the near-field Can model near-field produced water re-injection Tools do not consider groundwater–surface water interaction Most tools account for geomechanical processes, gas desorption and migration, dual phase flow and coal dual porosity, as well as complex geological conditions	Tools not practicable for regional scale assessment due to intensive computational requirements Typically treatment is limited to the gas-bearing horizon, and overlying and underlying strata are disregarded or dealt with in a simplified way	Assessment of impacts to groundwater (not surface water) in the near-field (but not water quality) Used for design of coal seam gas well networks
Regional	Tools practicable for regional scale impact	Generally ignores geomechanical processes,	Regional-scale assessment of impacts,

Modelling approach/ purpose	Advantages	Disadvantages	Appropriate application
groundwater impact assessment	assessment Capable of representing complex geology, assessing cumulative impacts and changes to groundwater quality	gas desorption and migration, dual phase flow and coal dual porosity; this may create inaccuracies	water quality, re-injection and cumulative impacts