Background paper on produced water and solids in relation to coal seam gas production

Report prepared for the

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Introduction and overview

The purpose of this report is to review the issues, management practices, impacts and risks related to produced water and solids generated by the coal seam gas (CSG) industry. The report has been commissioned by the NSW Office of the Chief Scientist and Engineer as one of a number of independent studies to inform the NSW Government about the potential impacts of CSG exploration, extraction and related activities on human health and the environment. The content and recommendations of this report are based largely on publicly available, independent peer-reviewed literature and reports by and for government agencies.

Produced water has been defined as water that is brought to the land surface during the process of recovering methane gas. It includes water generated in CSG wells as well as flowback water that may be associated with hydraulic fracturing and other processes involved in drilling and the extraction of gas. Produced water is chemically different to freshwater and other groundwater sources, reflecting the depositional environment of the coal measure, the maturity of the coal and the flux of other groundwater sources into and out of the coal formation. Produced water is generally high in dissolved salts, metals, dissolved or dispersed oil compounds (that may include naturally occurring BTEX compounds), dissolved gases and naturally occurring radioactive materials. Additional compounds may be found in produced water as a result of chemicals used in well construction and maintenance or added to hydraulic fracturing liquids. The quantity and quality of produced water generated in wells varies, particularly between coal seams, although presently there is very little spatial and temporal data on how produced water changes in quantity and quality over the course of a CSG project.

The management of produced water must be informed by the potential impacts of accidental releases on local and regional water systems (surface and subsurface). The full range of treatment and disposal options must be considered to ensure that those used are the most appropriate for the conditions. The potential cumulative effects of a CSG project on water used in other sectors of the economy, such as for human consumption and agricultural purposes, and on environmental systems, such as natural springs and wetlands, need to be assessed at the local and catchment scales. The limited available data on groundwater and surface water systems, coupled with the short time the CSG industry has been operating in Australia, means that current hydraulic models are unable to adequately predict the subsurface and surface impacts of produced water. Impacts may arise from surface flows and inter-aquifer movements when produced water is disposed of via streams or through aquifer injection, and there may be effects on the soil if produced water is disposed of via irrigation. The disposal of concentrated salts from treatment processes will continue to be a challenge for the industry and requires further review and research.

Pollution from and the risks associated with produced water can generally be categorised into three areas: discharges from surface pipes or leaks from surface water infiltration and evaporation ponds (no longer permitted for produced water in NSW and Qld); failures related to the integrity of wells; and changes in aquifer pressure as a result of the release of gases and water from the coal seam or from the injection of produced water.

Failures in surface operations are more likely to be identified and subsequently disclosed to regulatory agencies because they are more visible. Aquifer contamination is more likely to result from well failure. Leaks from wells may increase as the wells age and degrade, although ongoing improvements in well construction, maintenance and capping should lessen this risk. A longer-term risk that requires ongoing attention is the effect of changes to the natural hydrostatic pressures within aquifers as a result of extracting gas and water or injecting produced water as a disposal option. A lack of baseline data, limited industry and independent monitoring, and a paucity of independent analysis of the results of such monitoring are key areas of concern. Similar concerns have been raised in areas of unconventional gas production in the United States (Osborn et al. 2011). Hydraulic fracturing, defined as the specific process of fracturing rock formations, seems to present a lower risk than is often perceived with this practice, provided there is regulatory control on the type of chemicals that may be used and monitoring of its influence on seismic activity. Until further independent studies are concluded on this practice, including on the fate of the associated chemicals in reduced oxygen conditions, a precautionary approach should be taken on when and where hydraulic fracturing is used. The management of abandoned wells and their possible function as conduits between aquifers should be reviewed in the context of their geological settings and the risks to critical aquifers.

There appear to be few independently reviewed studies of CSG and produced water in NSW. Public access to industry and government agency monitoring and models is limited, and investigations of pollution events made by mining and environmental agencies are not as transparent and accessible as they should be. Scientific evidence to support government policy, improve industry practice and inform the community should be a priority, both for the CSG industry, which is mostly still in its infancy in NSW, and the regulatory authorities, who have been reforming regulations reactively and rapidly in the last two years.

Terms of reference

1. What is produced water in the context of Coal Seam Gas? What are the characteristic components of produced water, and the waste solids generated from produced water?
2. What are the potential issues (e.g. environmental and human health) associated with produced water and the separated solid waste from CSG activities?
3. Are there stages through the CSG phases that produced water and solids are more or less of an issue? Are there differences between the volume or composition of produced water and solids over different coal seams and basins in NSW and Australia? How are the volumes of produced water modelled or calculated at the CSG planning stage? Discuss these predictions in terms of best practice.
4. What processes and technologies are available (or are in development) for the management of produced water and separated solids (e.g. reverse osmosis, reinjection)? What are the advantages and disadvantages of these approaches and what factors influence the process chosen? Comment on international best practice.
5. What agricultural, industrial or environmental uses could produced water and solids be put to following extraction through CSG processes?
6. Discuss any known incidents related to produced water and solids in Australia and internationally (e.g. Pilliga spillage)
7. Discuss any potential 'worst case scenarios' and the likelihood/risk of the scenarios occurring with produced water and solids.
8. What risk assessment and risk management approaches should be taken for produced water and solids? What are the mechanisms or solutions that can be used to address or remediate impacts and problems related to produced water and solids, including national or international examples? Comment on international best practice in relation to risk management and remediation.
9. What are the knowledge gaps/unknowns/research gaps in relation to CSG activities and produced water and solids?
10. Any other comment you believe relevant to the understanding or management of these issues.

Disclosure

Associate Professor Gore is part of Macquarie University's Produced Water Research Centre. He is a former member of the NSW Government's Thirlmere Lakes Inquiry (2011–2013; www.environment.nsw.gov.au/water/thirlmerelakesinquiry.htm). He has provided analyses and advice in a pro bono capacity for a community group in the Gloucester (NSW) area regarding metals in domestic tank rainwater (2010–2012), including a public presentation in Gloucester (2011). He has supervised an undergraduate Honours project in stream water composition in the Gloucester Valley (2013).

Dr Davies was the Senior Manager Sustainability at the Sydney Catchment Authority in 2011–2012, with responsibility for the coordination of CSG projects within the drinking-water catchment.

In this report, all data, studies and reports related to CSG activities and produced water have been drawn from publicly available material and sources.

Glossary

Abbreviation	**Definition as used in this document**
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency.
BTEX	An acronym for the volatile aromatic compounds benzene, toluene, ethylbenzene and xylene.
CH_4	CH_4 – methane.
CSG	Coal seam gas (also known as coalbed methane).
NORM	Naturally occurring radioactive materials. TENORM is used in some studies to denote technologically enhanced NORM.
PAH	Polycyclic aromatic hydrocarbons. Carbon compounds that consist of fused rings of carbon atoms, typically with attached functional groups.
PHREEQC	Low temperature aqueous geochemical software available freely from the United States Geological Survey. Refer to: http://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phreeqc
PRB	Powder River Basin – refers to a Wyoming, United States of America coal field actively producing coal bed methane.
PW	Coal seam gas produced water (other types of produced water are spelled out).
RO	Reverse osmosis – water purification using a semi-permeable membrane.
SAR	Sodium adsorption ratio – a measure of the sodicity of water. It is the ratio of sodium to calcium + magnesium, viz: $SAR = [Na^{+}] / \{([Ca^{2+}] + [Mg^{2+}]) / 2\}^{1/2}$
TDS	Total dissolved solids (typically reported in mg/L).
Voids	Fractures, pores and other inhomogeneities in coal, in and along which methane is held.

Chapter 1. What is produced water in the context of coal seam gas? What are the characteristic components of produced water, and the waste solids generated from produced water?

Structure

- Background
- Where methane occurs in coal
- Hydraulic fracturing – the process and the chemicals
- Composition of flowback water and produced water
- Waste solids from produced water
    - Suspended solids
    - Dissolved solids
    - Precipitates and naturally occurring radioactive material
    - Evaporites
    - Biotic matter
- Suggestions arising from this chapter

Background

CSG produced water is water that is brought to the land surface during the process of recovering methane gas. Two types of water are generated in (CSG) wells: flowback water and produced water. Consideration of where methane is hosted and how it travels through coal formations will help an understanding of the characteristics of produced water.

Where methane occurs in coal

Methane is held in coal seams along naturally occurring fractures, pores and other macro- and micro-inhomogeneities (collectively termed voids in this document). The voids exhibit a bimodal size distribution (the 'dual porosity' of Jamshidi & Jessen 2012), with fractures and macro-voids defining the coal fabric and micropores characterising the matrix. The ability of the gas to move through the coal formations depends on the type, number, size, orientation and connectivity of these voids and, particularly, on the dimensions of the connections between the voids. Most of the gas in coal usually occurs adsorbed to the walls of the smaller voids. While only a small proportion of gas is typically adsorbed to the walls of the larger voids, these larger voids are essential for the flow and extraction of water and gas from the coal (Freij-Ayoub 2012, Jamshidi & Jessen 2012). The permeability of Australian coals typically ranges from 1 to 10 milliDarcys, although these estimates are based on few data, and coals in the United States reach a permeability of 35 milliDarcys (Jamshidi & Jessen 2012).

The release of gas from coal can be stimulated by the removal of water that occurs naturally in the rock formation. When the water is removed and released from hydrostatic pressure, there is a degassing of the formation and the water. The gas and water can then be removed by pumping from an extraction well. In some cases, the recovery of methane can be enhanced by the injection of gases such as nitrogen and carbon dioxide, which can reduce the amount of produced water generated (Jamshidi & Jessen 2012).

Hydraulic fracturing – the process and the chemicals

The greater the connectivity of the voids, the greater the amount of gas resource that can potentially be extracted. Void connectivity can be enhanced by hydraulic fracture stimulation (also known as hydraulic fracturing, or 'fraccing'), whereby a mixture of water, fine sand and chemicals are pumped into the formation. The pressure exerted by the pumps injecting this mixture opens cracks and increases void connectivity, and the sand acts as a 'proppant', helping to keep existing and new micro-voids open to facilitate the flow of water and gas. The use of hydraulic fracturing may be more prevalent towards the end of the effective life of a well as a means to enhance gas recovery from the coal seam as it gradually depressurises. Its efficacy is highly dependent on the characteristics of the coal seam and therefore it is difficult to generalise about when and how it is used.

Various chemicals used in hydraulic fracturing help water flow by increasing wettability, reducing biotic activity, inhibiting corrosion and the development of precipitates ('scale') and acting as pH buffers (e.g. Ahmadun et al. 2009, Batley & Kookana 2012; Table 1.1). The composition of these additives varies according to formation geology and chemistry and also to socio-legal requirements. In some cases, commercial advantage may mean that full public disclosure of the types of chemicals used is unlikely. It is estimated that 45 chemicals are used in hydraulic fracturing in Australia (APPEA 2010, cited in Batley & Kookana 2012); they perform various functional roles (Table 1.1), and the specific chemicals used may vary by hydraulic fracturing location, depending on the chemistry of the coalbed and the formation water. As a consequence, there is no definitive composition of hydraulic fracturing fluid; the chemistries discussed here, therefore, are only some of the many types used in the industry.

Table 1.1. Type and use of chemicals in hydraulic fracturing operations (Batley & Kookana 2012).

Additive type	Chemicals used*	Action
Proppant	Sand, silica, ceramic particles	To wedge seams open
Viscosity modifiers	Guar gum, hydroxypropyl guar, hydroxyethyl cellulose, gelatine	Gelling agents (including food additives) to increase viscosity
Gel crosslinkers	Borate salts, monoethanolamine, ethylene glycol	To maintain gel stability
Gel breakers	Sodium persulfate, hemicellulase enzyme, t-butylhydroperoxide	To break down gel for return to surface
Mineral dissolution	Hydrochloric acid	To dissolve clay minerals
Iron complexation	Citric acid	To prevent iron precipitation
Biocides	Sodium hypochlorite, tetrakis (hydroxymethyl) phosphonium sulfate, glutaraldehyde	To eliminate bacteria in the water
Corrosion inhibitors	N, N-dimethylformamide, gelatine, methanol	To prevent pipe corrosion
Scale inhibitors	Ethylene glycol	To prevent scale formation
Friction reducers	2-Butoxyethanol, isopropyl alcohol, terpenes and terpenoids, sweet orange oil, polyacrylamides, anionic surfactants and petroleum products	To reduce surface tension

* APPEA (2013) also identified caustic soda, acetic acid, calcium chloride, sodium chloride and potassium chloride, MEA borate and enzymes as being used in Australian hydraulic fracturing operations but did not specify the role these reagents play.

Composition of flowback water and produced water

Following hydraulic fracturing, the water that had been pumped in is allowed to flow back to the surface – this water is termed 'flowback water'. Flowback water is a mixture of hydraulic fracturing fluid and formation water, making it physically and chemically different to produced water. After the flowback water is removed, the 'formation water' that continues to be co-produced with the gas is termed produced water. The amount of produced water taken from a well depends on the natural water content of the rock formation and the time since the initiation of pumping. If the formation is sufficiently permeable, produced water may be generated over the entire lifetime of the well, although the volume will generally decrease over time.

The composition of produced water varies according to the depositional environment of the coal, the rank (thermal maturity) of the coal, and the flux of fresh water into the coal formation from surrounding formations. The depositional environment has either saltwater or fresh/brackish characteristics and changing major and trace element characteristics. The rank of the coal affects some of its physical characteristics, including voids and water content. These first two parameters (i.e. the depositional environment and the rank of the coal) also determine whether the methane generation pathway is dominated by thermogenic or biotic (sulfate-reducing) processes. The permeability of the formation, and the availability and nature of water in surrounding formations, may dilute or concentrate various constituents in the produced water. The chemistry of the broader geology also affects the formation water. Formations draining volcanics rich in magnesium- and iron-bearing minerals, or granites rich in quartz, for example, will have very different chemistries of trace metals or naturally occurring radioactive materials (NORMs). Finally, the length of time that the coal, bedrock and aquifer water have to react will also affect the chemistry of the water (Nghiem et al. 2011). Understanding the hydrogeology and surrounding geology is a fundamental part of predicting the composition of produced water.

Produced water is typically rich in cations such as Na^+, K^+, Ca^{2+}, Mg^{2+}, Ba^{2+}, Sr^{2+} and Fe^{2+} and anions such as Cl^-, SO_4^{2-}, CO_3^{2-} and HCO^{3-}, reflecting the brackish marine depositional environment of coal measures. From these marine origins, the chemistry of the water in the coal is modified by geological influences so that the water can become unique to an area. We know of no Australian studies that have synthesised the available chemistry data across Australia's geological basins, across NSW or even within a basin or gas-producing field. It is possible, however, that such a study lies within unpublished company reports or the records of Geoscience Australia's groundwater group. So it remains that the overall pattern of ionic composition of produced water in Australia is poorly constrained.

Table 1.2 presents data on the chemical composition of some NSW, Qld and international produced water. Apparent is the large range in the data, both within sites and between sites. For example, the Surat Basin produced water exhibits as much variability in total dissolved solids (TDS) as all other sites do collectively. This variability is not just a consequence of the dilution or concentration of formation water, since parameters do not vary synchronously. For example, Table 1.2 shows that the Powder River Basin (USA) analyses have among the lowest TDS in the table but amongst the highest sulfate of produced waters in both Australia and the United States. Additional data are required in order to explore and understand these apparent patterns. Many more data are available in consulting and operator reports, but they are not readily viewed or collated (see section on data accessibility in Chapter 9).

Produced-water constituents of concern may include:

- the chemicals used in hydraulic fracturing; and
- waste solids, including suspended particulate solids (from the formation, corrosion/scale products and bacteria), dissolved solids from the formation water, precipitates (including

NORMs) along the flowpath of the produced water from the coalbed to the surface discharge point, evaporites at the earth's surface, and biotic materials.

Waste solids from produced water

Suspended solids

Suspended solids occur as fragments from the coal seam and intercalated and surrounding silicate rocks, and as precipitates such as scale, that break off and are transported in the produced water to the surface. If coarse enough, these waste solids may be removed in settling ponds; if they are finer-grained, filtration may be required to remove them.

Dissolved solids

In most coalbed produced water, dissolved solids are dominated by sodium cations and by anions of chloride and bicarbonate. The sodium adsorption ratio (SAR) is a measure of the sodicity of water. A SAR >9 in non-saline soils is potentially damaging for irrigation-based agriculture (Table 1.3; Healy et al. 2011). SAR is discussed further in Chapter 5. A typical upper limit for the concentration of TDS in seawater is about 40,000 mg/L; in extreme cases, however, brines may have a TDS concentration of up to 300,000 mg/L (Ahmadun et al. 2009). Brackish produced water is in the minority, however. A literature survey of 377 published analyses in the United States found that less than 3% of produced water samples were brackish to hypersaline (i.e. >5,000 mg/L; Alley et al. 2011). High concentrations of TDS, increased further at the surface by evaporation or reverse osmosis, may create liquid and solid waste that can exceed drinking, livestock and irrigation limits for TDS, sodium adsorption ratio, iron, fluoride and other elements. Organic compounds, including aromatics, have been reported in produced water in the United States. However, literature pertaining to the organic components of Australian produced water is scarce, with a few reports noting the association of elevated benzene, toluene, ethylbenzene and xylene ('BTEX') chemicals with CSG and coal gasification in Qld (Volk et al. 2011, p. 57). In one case in the northern Bowen Basin in Qld, traces of benzene were present at 1–3 µg/L (Volk et al. 2011, p. 56), which is above the 1 µg/L Australian Drinking Water Guideline (NHMRC 2004). The few reports of BTEX analyses in wells in NSW reveal concentrations below the limits of reporting at Wyong, north of Sydney (Parsons Brinckerhoff 2005, Volk et al. 2011, p. 57), and Broke in the Hunter Valley (Parsons Brinckerhoff 2010, Volk et al. 2011, p. 57).

Precipitates and naturally occurring radioactive material

Precipitates occur notably as scale in production-line wells and pipes. Isotopes of radium, which are generated from the decay of uranium and thorium, are slightly soluble and may be present in produced water. These naturally occurring radioactive materials ("NORM"), particularly ^{226}Ra and ^{228}Ra, co-precipitate in scale, which in many places is dominantly composed of calcium carbonates. Scale precipitates lines wells and pipes and reduces the cross-sectional area available for flow, ultimately clogging them. There is a strong correlation between Ba and Ra concentrations. ^{226}Ra has been found in produced water in concentrations of 0.3 – 1.3 Bq/L and ^{228}Ra in concentrations of 16–21 Bq/L (Ahmadun et al. 2009), with total radiation ranging from 0.004 – 333 Bq/L (USEPA 2013a). This range in ^{226}Ra is on the low end of the range for natural waters reported elsewhere (0.8 – 75 Bq/L in Spain; Soto et al. 1988). Of course the problem is not so much one of the radioactivity of the produced water itself, but the radioactivity of the scale in the pipes which can contain concentrated amounts of these radionuclides and their daughter products ^{210}Pb, ^{210}Bi and ^{210}Po. The relatively complex decay chain containing these isotopes contains alpha, beta and gamma emitters, and these can be hazardous particularly where dust is inhaled so respiratory protection is an important aspect of risk management. In the United States, ~100 tons of scale per oil well (note: not gas well) are generated per year (US EPA 2013b), with pipe /tank scale ranging in total radioactivity from <9 – 3.7 x 10^7 Bq/kg which is 4-5 orders of magnitude greater than background soils (USEPA 2013a).

Evaporites

Salt precipitation can also occur via the evaporative concentration of produced water at the ground surface. While the use of evaporation basins is rare and now largely discontinued, there is fundamentally little difference between this and the disposal of produced water by spray irrigation, as has occurred in NSW (e.g. the Gloucester Valley) with the approval of the NSW Environmental Protection Authority. Spray irrigation distributes the produced water onto waste rocks or onto paddocks (often when growing young fodder crops), and the water is lost through evaporation from the air or the plant or soil surface, transpiration, and deep discharge and aquifer recharge. However, the solutes in the produced water are not lost to the atmosphere. Instead, they are left behind in the soil environment, where a small amount will be taken up by the crops and the remainder will either be lost to deeper aquifers and local streams or remain in the soil. As soils, streams and shallow aquifers dry up, salts may precipitate. These solutes will be sorbed onto soil particles only loosely and, on rewetting, they may move vertically or laterally, depending on the flow direction of the water. The ‘distribution’ approach to managing produced water can be environmentally damaging in an insidious way, with the aphorism ‘dilution is not the solution to pollution’ being appropriate. The effects of disposal of produced water by distribution are difficult to predict because of site-specific characteristics such as: the water budget; soil antecedent moisture, soil depth, soil permeability and ion exchange behaviour; surface aquifer characteristics; and topography and the proximity to streams.

Biotic matter

Produced water may contain biological components at concentrations of 50–100 cells/mL (Ahmadun et al. 2009), although the genesis of these cells (or cell fragments) remains unclear. Biological material will be remnant from the coal measures (Klein et al. 2008), particularly if they are low rank. Some of these cells may even be viable; several studies report active cultures from Eocene to Oligocene (35–25 Ma) and Cretaceous (120 Ma) ambers, and Permian (250 Ma) halite crystals (Lambert et al. 1998, Greenblatt et al. 1999, Satterfield et al. 2005). Of greater concern, perhaps, are viable cells introduced during drilling or hydraulic fracturing, which have the potential to grow within the formations, wells and production lines. Biocides are added to hydraulic fracturing fluids to suppress bacterial growth, but if such growth occurs, biofilms and other biological materials will contribute to the waste solids contained in produced water.

Suggestions arising from this chapter

- That produced water be analysed more frequently than at present, which in many wells is a grab sample quarterly, with some analytes measured annually. At present, we know very little of the spatial and temporal variability of the composition of produced water.
- That a centralised and publicly accessible database of the composition of Australian produced water be created, particularly regarding organic components, for which there are few analyses.

- That an agreed and consistent set of analytes be measured at a minimum. Most reports are good at elemental data and some petroleum hydrocarbon fractions because commercial laboratories are experienced at these measurements and, partly as a consequence, they are relatively inexpensive. Other parameters could be measured in addition to the minimum agreed set. The parameters in that set could be decided once a compendium of data of produced water was compiled and examined – parameters exceeding Guidelines, those with predicted ecotoxicological or environmental significance, and those exhibiting substantial variability would be of interest.
- That a centralised and publicly accessible database of the composition of hydraulic fracturing fluids be created.

Table 1.2. Representative values of water quality parameters for selected basins in Australia, USA and South Africa. (after Nghiem et al. 2011, METGASCO 2012, AGL 2013).

Country	**Australia (NSW)**	**Australia (NSW)**	**Australia (Qld)**	**Australia (Qld)**	**USA**	**USA**	**USA**	**South Africa**
Parameter	**Camden** (AGL well 15/SL03, 4th Q FY13)	**METGASCO** (PW in storage)	**Surat Basin** (basin wide)	**Surat Basin** (Tipton)	**PRB** (47 samples)	**PRB** (Mitchell Draw)	**Walsenburg**	**Waterberg**
pH		8.81	8–9	7.6–8.9		8.2	8.41–8.52	7.8
TDS	7790	3070	1200–4300	4500–6000	370–1940	3460	588–722	5125
SAR			107–116			25		85.4
Boron	0.06	313				0.2	0.21–0.26	
Fluoride	1.3	0.78		0.77–1.00		1.0		4
Sodium	3030	557	300–1700	1840–3461	130–800	880	250–314	2023
Magnesium	4	11				14.6	0.01	10.4
Silica	9.6					12		
Sulfate	<1	15	5–10	2	0–12	1.0		418
Chloride	287	1430	590–1900	2060	6.3–64	28.4		287.1
Potassium	10	777				35.2	1.2–1.3	16.5
Calcium	4	13			5.9–57	28.0	1.7–2.4	25.1
Manganese	0.007	0.9		0.07–0.10				0.3
Iron	0.13	7		0.07–4.50				0.99
Bicarbonate (as $CaCO_3$)	6540	236	580–950	1030	290–2320	2416		4712

* PRB = Powder River Basin, USA. Empty cells = no data. Measurements in mg/L except for SAR, which is measured in $meq^{-0.5}$.

Table 1.3 Tolerance of various crops to SAR under non-saline conditions (after ANZECC 2000, p. 4.2–11).

SAR of irrigation water	SAR Hazard	Crop
2–8	<3.0 No hazard 3.0–8.0 Slight to moderate	Extremely sensitive – avocado, citrus, fruits, nuts
8–18	8.0-9.0 Moderate >9.0 Acute	Sensitive – beans
18–46	Acute	Moderately tolerant – clover, oats, rice, tall fescue, dallis grass
46–102	Acute	Highly tolerant – wheat, cotton, lucerne, barley, beets, rhodes grass

Chapter 2. What are the potential issues (e.g. environmental and human health) associated with produced water and the separated solid waste from CSG activities?

Structure

- Potential problems associated with produced water and separated solid waste
  - Environmental health
  - Human health

Potential problems associated with produced water and separated solid waste

Physical problems associated with produced water include water balance, changed surface water and aquifer conditions, erosion and sedimentation, and water quality.

Much of NSW has a negative water budget, where water loss due to evapotranspiration and vertical infiltration exceed water supply. Where this occurs, streams may be referred to as ‘losing streams’ because the amount of flow in the channel decreases down-valley. This is typical of all streams and rivers draining westward from the Great Dividing Range, and which, mostly, form part of the Murray-Darling Basin (exceptions exist, usually in the form of internally draining basins in the far northwest of the state). The Gunnedah Basin typically has these environments. The corollary is that there are also ‘gaining streams’, which are more typical of streams draining coastward to the east of the Great Dividing Range (such as those found in the Sydney and Gloucester basins).

Geomorphic observations from the United States indicate that stream cross-sectional areas typically increase through erosion so that the channel can accommodate a 1–2 year recurrence interval flood peak. In general in NSW, smaller, more common floods are accommodated within stream channels, and the channels can recover from larger, less frequent floods. If produced water creates a new base-flow level in these streams, however, floods will become larger and the channel will erode to accommodate the additional flow. The extent to which the channel will erode depends on the initial size of the channel and the volume of the produced water discharge.

There appears to be no systematic pattern to the location of CSG well heads in landscapes in Australia. However, many well heads are found in small headwater areas, which are referred to as low stream order networks. These small sub-catchments typically have intermittent surface flow, and may have small and poorly defined channels, or in some cases the channel may be absent. Should treatment and discharge of produced water to the environment occur at these locations, then substantial erosion of the channels might occur. The counterpoint to soil and sediment erosion is deposition, and this would also need to be considered for its potential to clog channels downstream and for its impacts on flora and fauna.

Unconfined aquifers form the margins of many channels flowing in sedimentary valley fills (typically occurring as floodplains). The additional height and volume of water flowing in channels will lead to a greater height of water in these aquifers. This might be problematic if the aquifer water is saline, causing a problem akin to irrigation salinity, whereby naturally occurring salts are brought into the root zones of plants by a high watertable. The risk of this occurring due to CSG produced water is probably relatively low, but it does require further consideration in modelled discharges and in particular field situations.

Chemical problems associated with produced water include sodicity, salinity, turbidity and toxicity due to salt, trace elements, organic components and radioactivity. All these problems can have implications for environmental health if produced water is discharged into sensitive environments at sufficient quantities, and for human health through direct (e.g. if produced water is discharged in drinking-water catchments) and indirect contact (if chemicals in produced water bio-accumulate in crops and stock that ultimately are ingested by humans).

Produced water is typically rich in cations such as sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), barium (Ba^{2+}), strontium (Sr^{2+}) and iron (Fe^{2+}) and anions such as chloride (Cl^-), sulfate (SO_4^{2-}), carbonate (CO_3^{2-}) and bicarbonate (HCO^{3-}) (Chapter 1, Ahmadun et al. 2009). The most common cation associated with produced water is Na^+, and it occurs in concentrations ranging from <150 mg/L to >34,000 mg/L (the latter value is around the sodicity of seawater). Cl^- overwhelmingly dominates the anions, with concentrations ranging from <1 to >70,000 mg/L (the latter being about three times the concentration of Cl^- in seawater). It is no surprise that salt toxicity is probably the greatest environmental threat posed by produced water and separated solid waste. The pH of produced water is typically strongly alkaline, with ranges of 8–9 being common; such a high pH is highly unusual in Australian streams and would likely have detrimental effects on their biota. Minor and trace elements pose the next greatest threat, with the analytes of concern depending on the formation from which the produced water is derived. The elements magnesium, aluminium, iron, strontium and barium can also pose significant threats in places. NORMs may be a problem in produced water derived from some coal formations, but this requires additional investigation.

Such physical and chemical problems rarely occur in isolation. What may first appear to be minor problems could concatenate, resulting in unacceptable environmental or human health outcomes. Other aspects of CSG extraction may also create problems, such as the management of liquid fuels to operate wells, pumps and treatment facilities (such as reverse osmosis) if the operation is not connected to the electricity grid. The disposal of reverse osmosis treatment brines and consumables associated with drilling may create other problems associated with produced water and the solid waste that is generated from it.

Chapter 3. Are there stages through the CSG phases that produced water and solids are more or less of an issue? Are there differences between the volume or composition of produced water and solids over different coal seams and basins in NSW and Australia? How are the volumes of produced water modelled or calculated at the CSG planning stage? Discuss these predictions in terms of best practice.

Structure

- Phases of CSG extraction
- Timing of the phases of CSG extraction
- Suggestions arising from this chapter

Phases of CSG extraction

CSG operations fall into three phases which align with the exploration licence and production approval: phase 1 – exploration; phase 2 – production; and phase 3 – remediation. We consider the production phase in further detail here and recognise three sub-phases quantifiable by the amount of produced water generated: 2a – pre-extraction; 2b – testing and initial extraction; and 2c – operation. Each sub-phase has different implications for produced water.

The pre-extraction phase comprises planning, surveying, exploration, drilling and well installation. The use of drilling chemicals ('drilling muds'), combined with water imported to the site for drilling and exploratory hydraulic fracturing, creates the potential for aquifer perforation and the leakage of drilling chemicals, hydraulic fracturing water and chemicals, and formation waters. The potential for this leakage depends on the number of holes drilled, the design of the well installation, the experience and competence of the drillers (what could be termed their level of professionalism), the volume of pumped water, the corrosiveness of the waters and the time since installation (which has implications for the possible collapse of the steel casings that form the well liners and of the concrete that forms the collars and hydraulic seals around the pipes). In some places in NSW, exploratory drill holes to prove either the geology, the coal resource or the gas resource have been drilled at a spacing of less than 60 m (Figure 3.1; Merrick & Alkhatib 2012, p. 174). If the potential for leakage increases with metres drilled, then a high density of drill holes increases the risks involved in the operation.

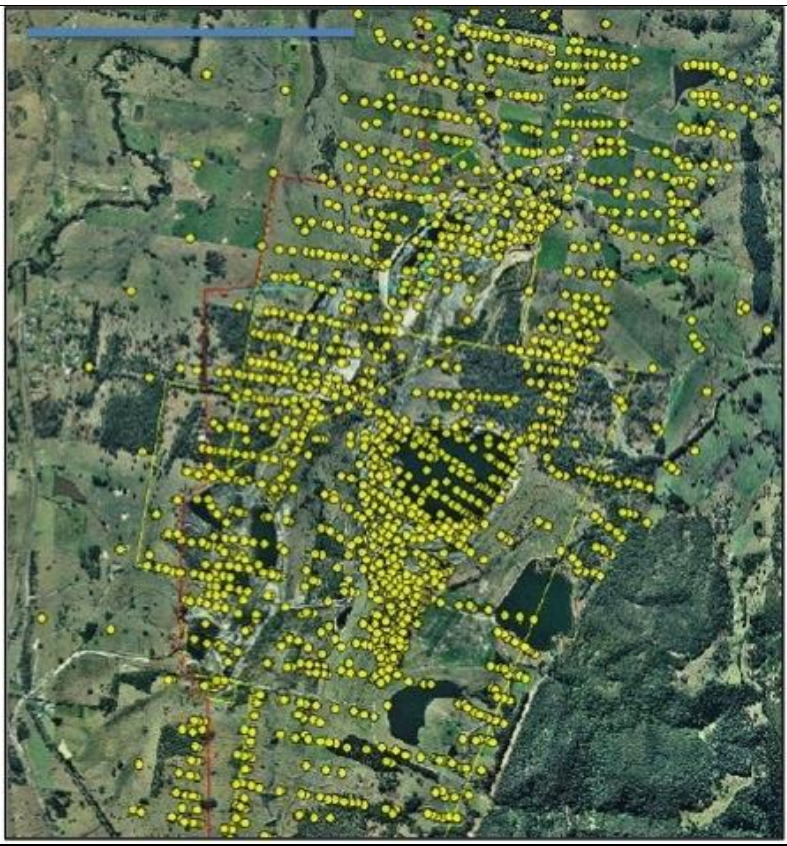

Fig. 3.1. Detail of part of the Gloucester Valley (NSW) showing the locations of all holes >10 m depth drilled within exploration leases.

Scale bar at upper left is 3 km. (After Merrick & Alkhatib 2012, p. 174).

Testing and initial extraction consists of assessing site hydrogeology: i.e. the amount and type of formation water and its chemistry and formation permeability, and whether hydraulic fracturing is required (and, if so, the extent to which it is required and the number of repetitions). The initial extraction of water creates the flowback water described in Chapter 1.

Production is usually the phase of longest duration and consequently the phase in which most of the produced water is generated. Exceptions to this are where the gas flow is short-lived and the well is deemed sub-economic, and where there are economic or other operational reasons for closing the wells prematurely. The amount of produced water is typically greatest in the first month to one year of operation, with a subsequent asymptotic decline to a steady-state extraction rate. This is characteristic of aquifer depressurisation and a change to a permeability-limited flux of water and is different between and within coal measures (noting that individual wells within the same CSG operation will have different produced-water flow profiles).

Well shutdown and remediation does not generally generate produced water, but there remains a residual risk of aquifer contamination as a consequence of failure of the hydraulic seals around casings.

Timing of the phases of CSG extraction

The gas yield from production wells persists for varying periods, depending on the initial content of gas, coal permeability, treatment of the coal (e.g. through hydraulic fracturing), the efficacy of the chemicals used during hydraulic fracturing, and the chemistry of the produced water. For example, the development of precipitates (‘scale’) during production may constrain the volume of fluid that can be pumped along a well. In general terms, however, wells will be productive for several years after the initial perturbations related to hydraulic fracturing, with declining gas yields over time.

Model simulations for scenarios in the United States suggest that the rate of gas yield will decline to less than 20% of the initial yield within ~2500 days (Fig. 3.2, Jamshidi & Jessen 2012). Whether a well actually reaches that relatively low yield depends on the continued economic viability of the well as yields decline, with the possibility that the operator decides to terminate the operation. As the volume of gas declines, so too might the volume of produced water, depending on the permeability of the formation (Fig. 3.3).

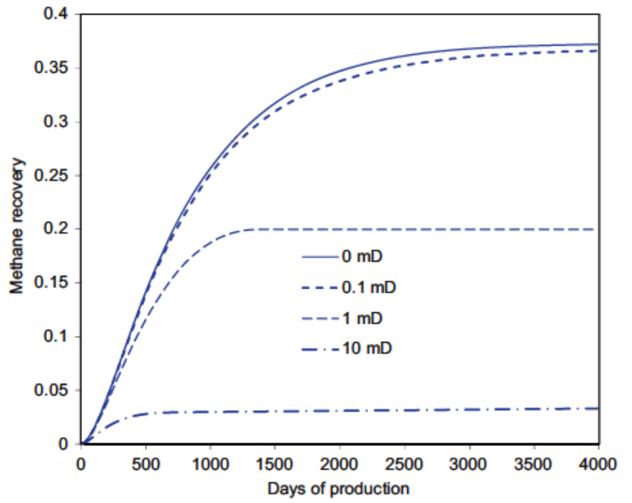

Fig. 3.2. Modelled methane recovery vs time for permeabilities in the range 0–10 milliDarcys. (From Jamshidi & Jessen, 2012).

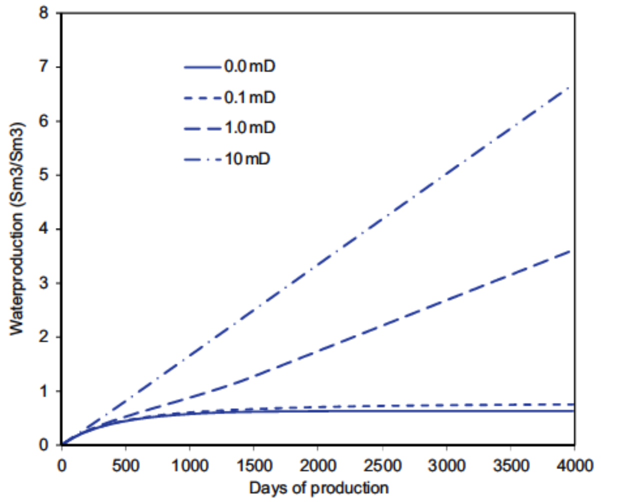

Fig. 3.3. Modelled water production vs time for permeabilities in the range 0–10 milliDarcys. Larger permeabilities allow greater steady-state pumping rates from the surrounding aquifer. (From Jamshidi & Jessen, 2012).

There are substantial differences in the moisture contents of coal formations in NSW, and, in turn, significant differences between coalfields in NSW and the ‘wet’ Qld coalfields. For example, the southern coalfields of the Sydney Basin are widely regarded as ‘dry’ (although this is a relative term, and underground mines in those areas require dewatering operations, just as elsewhere). Northward, formation waters increase in volume, and the volume of produced water per unit of gas will also increase. As a consequence, the amount of produced water will vary from well to well and regionally from coalfield to coalfield. As an indication of potential differences in produced-water yield, in the first year of operation, the Gloucester and Hunter coalfields yield 1.2 to 1.5 the amount of produced water yielded in the southern coalfields, while the coalfields in Qld’s Surat Basin yield about 25 times as much produced water as the NSW coalfields. The Qld coalfields not only yield more water per well, it also takes longer for their yields to decline to an asymptotic value. In NSW, the period in which the yield declines to an asymptotic value is typically less than three years, whereas in some Qld fields the yield is still declining significantly after four years, and the asymptotic values are typically above the initial produced-water yield of NSW wells. The low produced-water yield creates its own environmental problems because, in ‘dry’ wells, additional water will be needed at the well head for hydraulic fracturing operations, should they be required.

There is as yet no regional compilation of the physical and chemical characteristics of produced water across NSW. Nor have we found records of how the volume of produced water is modelled or calculated at the planning stage, although this information may be available within company records.

Suggestions arising from this chapter

The ratio of methane recovery to produced water generated is optimised when gases such as nitrogen and carbon dioxide are used in hydraulic fracturing. It would be innovative to investigate the efficacy and economics of the use of such gases in NSW coalfields. Flue gas from power stations might usefully be deployed for this purpose and, because carbon dioxide has a strong affinity for the coal surface (Jamshidi & Jessen 2012, p. 59), the process may result in some sequestration of carbon from the injected carbon dioxide, offsetting (to some extent) the greenhouse gas emissions involved in the production of coalbed methane. The location of power stations adjacent to coalfields would affect positively the economics of this scenario.

Chapter 4. What processes and technologies are available (or are in development) for the management of produced water and separated solids (e.g. reverse osmosis, reinjection)? What are the advantages and disadvantages of these approaches and what factors influence the process chosen? Comment on international best practice.

Structure

- Background
- Management of produced water and solids
    - Infiltration/evaporation basins
    - Aquifer reinjection
    - Reuse for industrial purposes
    - Reuse for agriculture
- Treatment methods
    - Hydrocarbon droplets
    - Suspended solids
    - Dissolved hydrocarbons
    - Dissolved solids
    - Alkalinity
    - Disinfection
    - Degasification
    - Wetlands – an example of a 'treatment train' approach
- Suggestions arising from this chapter

Background

The treatment of produced water is complex due to the diversity of issues it can present, but in general there are five possible management strategies:

1) avoid the generation of the produced water;
2) inject the produced water back into the same formation or other suitable formation, typically below a relatively impermeable barrier at depth. This may require transport of the produced water from the well head to a suitable reinjection point. Some treatment may be required to reduce biofouling and scaling and thereby to ensure that the injected water does not reduce the permeability of the receiving formation;
3) reuse the produced water for hydraulic fracturing operations or other industrial use. The produced water would need to be treated before use to ensure it is fit for purpose. In particular, treatment may be required to remove suspended solids or TDS;
4) use the produced water for livestock watering, crop irrigation or some other agricultural purpose; and
5) discharge the produced water to the receiving environment, typically as environmental flows.

Of these options, treatment may be required for all but option 1. In some cases, hydraulic fracturing water can be modified with carbon dioxide or nitrogen to enhance methane recovery, use less water for hydraulic fracturing and create less produced water pumped from the formation (Chapter 4). As described in Chapter 1, the parameters to be managed in produced water include oils, suspended solids, dissolved hydrocarbons, dissolved solids, alkalinity, disinfection and degasification.

Management of produced water and solids

Infiltration/evaporation basins

Produced water has been disposed of in unlined earthen basins, with water losses by vertical infiltration and evaporation. The ongoing addition of saline water to an evaporation basin, however, would result in increasing concentration of solutes, which in some cases can lead to exceedence of water-quality guidelines. For example, Sowder et al. (2010) found that arsenic became concentrated in a Wyoming evaporation basin beyond drinking-water standards. A geophysical study of conductivity around infiltration basins has shown divergent responses, depending on site conditions. In one case, infiltrating water from a basin was thought to have dissolved soil salts, increasing plume conductivity (Lipinski 2007, Lipinski et al. 2008). In other cases, aquifer water was enriched in salt, but in one case it was diluted by the infiltration basin water (Lipinski et al. 2008). Despite the complex response at the site described by Lipinski, what is clear from a mass balance approach is that additional salt released into the Australian environment is undesirable, particularly if the solute chemistry is unusual. This potential management method – the disposal of produced water in infiltration/evaporation basins – is mentioned here for the sake of completeness, but it is no longer permitted in either NSW or Qld.

Aquifer reinjection

The most common technique used for the disposal of produced water in the United States is reinjection into underground aquifers. The advantages of this technique are that it requires minimal treatment and it is able to dispose of a significant volume of water at or near the well head. In 2007 it was estimated that 98% of on-shore produced water in the United States was injected underground, with 59% used to maintain formation pressure and increase the output of oil and gas production (including by hydraulic fracturing) and 40% disposed of into nonproducing formations. The remaining 2% was managed through evaporation ponds (which are not permitted in NSW), off-site commercial disposal, beneficial reuse (such as in irrigation) and other purposes (Clark & Veil 2009).

Reuse for industrial purposes

Produced water presents opportunities for resource recovery, but the complexity and diversity of the water chemistry create formidable challenges. Potential uses include the production of sodium bicarbonate and bromine, pumped hydroelectric storage and the cooling of thermal power stations (Chapter 5).

Reuse for agriculture

The use of produced water for agricultural purposes is a form of disposal to the environment, with the potential to generate commercial benefits for gas producers, farmers and graziers.

Treatment methods

Hydrocarbon droplets

Oil particles can be removed by a range of methods, the choice of which depends on the size of the droplets. Larger (>40 µm diameter) droplets can be removed by skimming, gravity separators and corrugated plates. Droplets with a diameter of 3–25+ µm can be removed by filters, meshes, hydrocyclones and gas (including air) flotation. Finer droplets (0.01–2 µm in diameter) can be removed by membrane filters and centrifuges. Each of these methods has its own efficacies and costs.

Suspended solids

Suspended solids are removed by filtration or centrifuge. The latter differs from the former by setting the water in a spinning motion, which has an impact on cost, but the treatment outcomes of the two techniques are similar. Micro- and ultra-filtration are effective at removing suspended matter, including inorganics and hydrocarbon droplets (Mueller et al. 1997, Cumming et al. 2000, Leiknes & Semmens 2000, Visvanathan et al. 2000), but they will not remove salts, meaning that further treatment of the produced water will most likely be required. Nanofiltration is an alternative filtration method (Mondal & Wickramasinghe 2008), but fouling with hydrocarbons remains a problem. Some nanofiltration membranes respond well to flushing with clean, lukewarm water to remove foulants (Mondal & Wickramasinghe 2012).

Dissolved hydrocarbons

Soluble organics can be removed from produced water by sorption onto media held in columns. Activated carbon and zeolites (with or without surfactant modification) work efficiently, although a range of other natural and synthetic media may also be used. Consideration of sorption as a method and the media to be chosen will depend on the type of organics contained in the produced water, the rate at which the columns become saturated (i.e. achieve 'breakthrough'), and how much water can be passed through the columns – because residence time in the column affects the amount of analyte removed.

Membrane bioreactors may also be used. A bench-scale submerged hollow-fibre membrane bioreactor removed 99% of total petroleum hydrocarbons from salty, oily produced water from Turkey within 245 days. The influent water consisted of 2210 mg/L hydrocarbons in the range n-C9 to n-C40. A comparison of chromatograms showed that all of the light (n-C9 to n-C13) hydrocarbons were degraded, with substantial reductions up to n-C40, including a reduction in the unresolved complex mixture (Kose et al. 2012, their Fig. 4). Since the unresolved complex mixture can consist of highly recalcitrant compounds, the performance of similar membrane bioreactors offers substantial potential for the treatment of Australian produced water.

Dissolved solids

Where the concentration of TDS is low, ion exchange can work efficiently for the selective removal of Na+ ions from produced water (Kargbo et al. 2010). Reverse osmosis works effectively for TDS concentrations of up to 20,000 mg/L. For higher concentrations, from 40,000 to 100,000 mg/L, thermal distillation and evaporation are effective.

Salts/minerals are removed efficiently by reverse osmosis (Xu & Drewes 2006, Qian et al. 2012), although evaporation, distillation and membrane filtration have also been used to good effect. Each of these methods has benefits and costs, but most operators use reverse osmosis. Fouling due to hydrocarbons in produced water occurs readily with the commonly used polymeric reverse osmosis membranes; however, zeolite-based membranes show great potential for separating organics from the water with a reduced propensity for fouling (Liu et al. 2008).

Water-softening can occur via the selective removal of calcium and magnesium ions, typically using ion exchange resins. Ion exchange resins have limited capacity for water treatment and are best-suited to low concentrations of the analyte of concern in the feed water. Ion exchange resins can be regenerated readily, reducing their cost of operation. A benefit of ion exchange resins is that they can be engineered to be very specific for the ions of concern. For example, arsenic and mercury have been removed successfully from produced water using ion exchange resins (Lothongkum et al. 2011). Electrodialysis reversal has been tested successfully on produced water, showing the removal of (in order of fastest to slowest): $Ca^{2+} \approx Mg^{2+} > K^{+} > Na^{+}$ and $SO_4^{2-} > HCO_3^{-} > Cl^{-}$ (Sirivedhin et al. 2004).

The disposal of brine generated by reverse osmosis, nanofiltration and ion exchange remains a key area of concern due to its high concentration of salts and other chemicals, particularly where high volumes of produced water are generated in wet coalfields (Chapter 3).

Alkalinity

Produced waters are typically alkaline. If the alkalinity needs to be reduced, and other means of removing bicarbonate ions are not required, the addition of an acid could reduce pH. The kinetics of the sulfuric acid–sodium bicarbonate reaction has been constrained as a prelude to the treatment of produced water (Tuwati et al. 2011).

Disinfection

Produced water can be disinfected to kill bacteria and algae by either chemicals or radiation. Chemicals are typically strong oxidisers, such as ozone and hydrogen peroxide, which act to degrade organic matter. Radiation by ultraviolet light is commonly and effectively used as well. Both types of disinfection offer simple off-the-shelf solutions, but both are reduced in their efficacy by the presence of suspended solids and some dissolved constituents, which may also become degraded. For example, the oxidation state of some compounds may increase (nitrites become nitrates), and others (e.g. cyanides, PAH) may break down.

Degasification

Gases can be removed from produced water via a range of methods, which may include pressure reduction, ultrafiltration and heating. Specific target gases (e.g. carbon dioxide) can be removed by air stripping, whereby a fine stream of air or nitrogen is bubbled through the produced water.

Wetlands – an example of a ‘treatment train’ approach

A treatment train consists of a sequenced approach to the management of water contaminants. The most upstream treatment deals with the most tractable problems and typically consists of a detention basin that removes coarse particles by sedimentation. Dispersed oil on the surface of the water may be skimmed off. Some organics will be lost by evaporation in the detention pond, although this depends on the nature of the organics and the environmental temperatures. The treatments that follow are arranged in a sequence designed for the identified contaminants and to best suit the treatment technologies proposed, typically involving microbes that degrade hydrocarbons and redox manipulation to facilitate the precipitation of metals. Adsorption of contaminants onto flora is also common (ALL Consulting 2006). The following section describes one such pilot treatment train, which is here called a ‘wetland system’, although, strictly, wetlands form only part of this treatment train.

A sequenced, pilot-scale wetland system was designed and tested (Kanagy et al. 2008). The United States has guidelines for the minimum quality of water discharged to receiving waters, with standards specified by National Pollutant Discharge Elimination System (NPDE) permits under the Clean Water Act administered by the United States Environmental Protection Agency (Kanagy et al. 2008). The pilot-scale wetland system was designed to clean water to this minimum NPDE standard. The sequence consisted of three detention basins, an oil/water separator, two saltwater wetland cells, a reverse osmosis unit, and two series of four freshwater wetland cells (Fig. 4.1), which provided both reducing and oxidizing environments to help precipitate metals and degrade hydrocarbons. Produced-water compositions were synthesised from approximately 4,000 records of produced-water compositions, and water-quality targets were set by compiling approximately 50 NPDE permits in the United States (Kanagy et al. 2008). Efficacy was determined using inorganic chemical analyses compared against the water-quality targets and by ecotoxicological tests using the water flea *Ceriodaphnia dubia* Richard. The system performed better for saline and hypersaline water than it did for brackish water and freshwater because of the enhanced reducing conditions in the final sets of cells caused by higher saline inflow conditions.

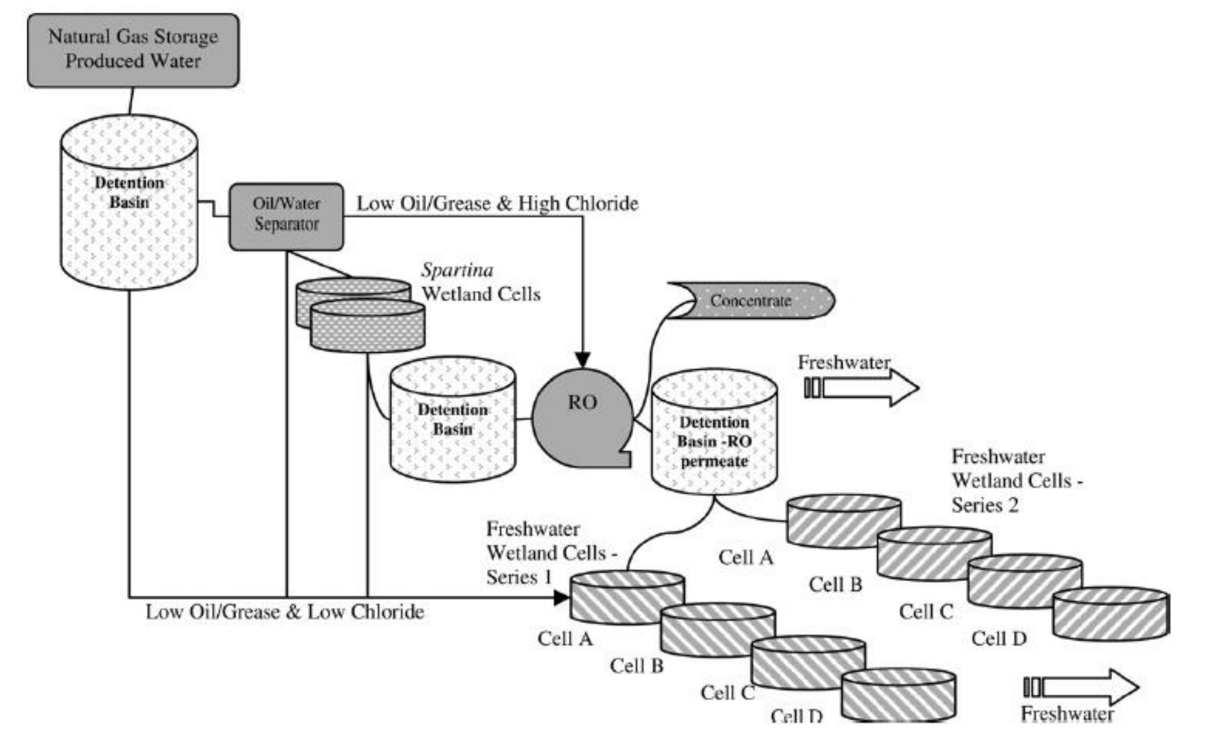

Figure 4.1. A pilot-scale wetland system designed to allow the discharge of produced water to the aquatic environment. This system removed copper, zinc, cadmium and lead effectively. (From Kanagy et al. 2008).

Suggestions arising from this chapter

There has been at least one case of an industry body processing produced water through a regional sewage treatment plant. We understand that this action was legal and we do not intend to enter that debate (see ABC 2012, for example). However, as a general principle, municipal wastewater treatment plants, although robust, are not designed to treat large volumes of oily, saline produced water, possibly with unusual chemistries. If municipal sewage treatment plants are to be used for this purpose, then the plant operators need to ensure and be prepared to justify the decision that doing so will not harm the basic functionality of the plant – processing sewage and other domestic waste water.

Chapter 5. What agricultural, industrial or environmental uses could produced water and solids be put to following extraction through CSG processes?

Structure

- Uses at the gas field
- Cropping applications
- Stock watering
- Other environmental uses for, and options for the disposal of, produced water
- Industrial applications of produced water and solids
- Suggestions arising from this chapter

Produced water has various potential uses, depending on requirements and the treatment of the water.

Uses at the gas field

Produced water can be reinjected for aquifer repressurisation, or simply for disposal. Produced water can also be reused at the gas field for hydraulic fracturing, following some treatment (refer to Chapter 4). In parts of NSW, open-pit coal mine produced water is disposed of by spray irrigation, either of waste rock piles or of alfalfa grown specifically for the purpose. In the irrigation disposal strategy, water is removed mostly by evaporation, transpiration and vertical infiltration. Although the irrigation helps suppress dust from waste rock piles, the disadvantage is that the chemical components of the water are simply redistributed onto and into the landscape, which will inevitably lead to saline discharge in local streams, either following rainfall or as a result of increased base flows in local streams.

Cropping applications

Agricultural uses of produced water can include irrigation and livestock watering. Spray irrigation using treated produced water can be used to grow crops as the primary objective. The salt tolerance of a range of crop species is well known and reported, so the matching of water quality and crop type can be readily managed. To achieve sufficient coverage of a field, centre-pivot (comprising a boom rotating about a fixed radius) or linear-move (comprising a traversing boom with rotating spray heads) spray irrigation systems are typically used.

Because produced water is usually high in sodium and bicarbonate, it is possible that its use for irrigation will lead to problems of soil salinity and sodicity (Ganjegunte et al. 2005, 2008, Johnston et al. 2008). The sodicity of water and soil water extracts can be expressed as the sodium adsorption ratio (SAR), which is defined as the sodium to calcium + magnesium ratio (see glossary). A high SAR may have substantial implications for agricultural soils. Excess Na^+ satisfies charge sites in soil minerals, particularly clays, leading to a net loss of attraction between soil particles. Under these conditions, soil dispersibility is enhanced, leading to the collapse of soil structure and decreased infiltration, with the effect of increasing erosion and stream turbidity (e.g. Abu-Sharar et al. 1987, Ganjegunte & Vance 2006, Johnston et al. 2008). Increased SAR values, and the sodicity of agricultural land, coupled with chloride toxicity, are major limiting factors in the use of untreated or insufficiently treated produced water for agricultural purposes.

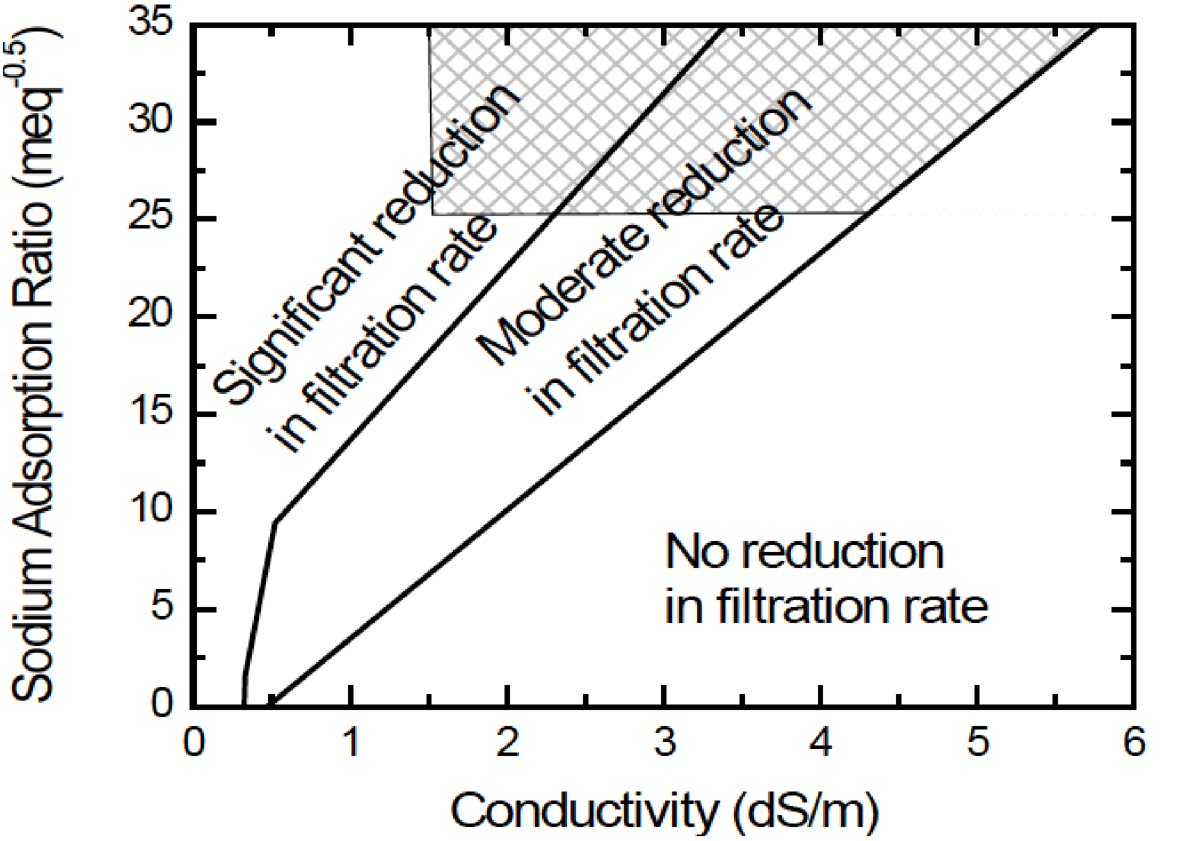

Figure 5.1. Relationship between soil degradation, conductivity (representing salinity) and SAR value (representing sodicity). The shaded area shows the region of typical SAR and salinity values of untreated CSG produced water (From Nghiem et al. 2011).

Subsurface drip irrigation systems trialled in the United States for the disposal of produced water yielded equivocal results. Although drip-lines were placed at 0.9 m depth so that the produced water would move downward into unconfined aquifers, water also moved upward into the root zone. As a result, soluble salts concentrated in the root zone.

There is some promise in the application of amendments to produced water used for irrigation (sensu Johnston et al. 2008), although the outcomes of irrigation with these amendments would be specific to the combination of produced-water chemistry, soil type and the crop being irrigated. If irrigation with water with an undesirable SAR is likely, two strategies can be considered (Johnston et al. 2008) to modify the SAR. The first is to pre-treat the produced water to reduce the SAR using ion exchangers such as zeolites (Zhao et al. 2008, 2009). Zeolites are open-framework silicates with numerous sites where cations can sorb loosely. Exposure of the zeolite to high-molality solutions allows saturation of the crystal lattice with selected cations. For example, zeolite grains washed in a calcium- or potassium-rich solution would displace sodium ions from the crystal lattice. That Ca-zeolite, exposed to sodium cations in produced water, would desorb calcium in exchange for sodium. Preparation of the zeolites can also be achieved using a range of acids (Wang et al. 2012), allowing for the inexpensive treatment of produced water.

A second approach is to treat the soil or irrigation water with powdered sulfur or gypsum ($CaSO_4.2H_2O$). The gypsum dissolves, releasing calcium and sulfur ions into the soil solution. The divalent calcium replaces some of the monovalent sodium on the surface of clays, leaving occasional surface charge sites unsatisfied and resulting in greater electrostatic attraction between clay particles. Sulfur decreases soil pH, enhancing the dissolution of calcite ($CaCO_3$), which frees Ca^{2+} ions to enter the soil solution and react with soil minerals such as clays.

Neither of these approaches is innovative; chemical engineers use the ion exchange capability of zeolites routinely, and most farmers know that dispersive soils in earthen dam walls are best amended with gypsum in order to prevent tunnelling by water and premature failure. A shortcoming of the first approach is that ion exchangers become exhausted, and while crushed zeolite is readily available and relatively inexpensive, freight of the new material to the treatment site, and freight for removal and disposal of the exhausted zeolite (or renewal by reflushing with a calcium solution), can be expensive. The second approach has the problem that while water and soil amendments modify and ameliorate the SAR ratio, the amount of salt increases and can continue to impact the environment. Neither approach is optimal; a combined approach to ameliorate the impact of sodic produced water may be the best strategy.

Stock watering

Stock watering shows promise as an option for the use of produced water, although there is a limit to the volume of water required by stock in all agricultural contexts, and pumping or freighting the water to other stock locations would have significant implications for the economics of produced-water management. Animals show varying tolerance to salinity in their drinking water; some stock, such as sheep, are relatively robust and others, such as pigs, are much less tolerant (Table 5.1).

Table 5.1. Salinity tolerances of livestock (mg/L of soluble salts). (From PIRSA 2006)

Animal	Maximum concentration for healthy growth	Maximum concentration to maintain condition	Maximum concentration tolerated
Sheep	6,000	13,000	***
Beef cattle	4,000	5,000	10,000
Dairy cattle	3,000	4,000	6,000
Horses	4,000	6,000	7,000
Pigs	2,000	3,000	4,000
Poultry	2,000	3,000	3,500

*** Maximum level depends on the salt content of the feed available. For example, stock grazing on chenopods such as saltbush would have a greater body burden of salt and would need to drink more frequently, and would therefore tolerate less salt content in the water. Seawater has a reference value of approximately 35,000 mg/L.

Other environmental uses for, and options for the disposal of, produced water

Environmental applications of produced water typically involve surface discharge for environmental flows. This could generate substantial benefits in NSW, where environmental flows are often low, especially west of the Great Dividing Range, but aspects of the chemistry and thermal properties of the produced water, and of the naturally occurring flood heights and flow regimes of streams, would need to be considered carefully. An additional use of produced water might be for groundwater recharge to offset extraction by the CSG industry or to replace groundwater extracted by agricultural applications.

Industrial applications of produced water and solids

Brines formed by the reverse osmosis concentration of the solutes in produced water have potential industrial applications. Electrolysis using graphite electrodes has been used to recover bromine from flowback and produced water without liberating chlorine or oxygen (Sun et al. 2013). Perhaps the greatest promise for the industrial use of produced-water brines is the creation of sodium bicarbonate ($NaHCO_3$) through the reaction of carbon dioxide in the presence of ammonia (a modified Solvay process). The resultant solid product, sodium bicarbonate, can be used in a wide range of medical, dietary and industrial applications. An attendant benefit of this process is that it reduces the salinity and pH of the remaining brine. Reverse osmosis plants can be designed to have zero liquid waste discharge by coupling reverse osmosis with ultra(nano)filtration. Final polishing of the treated brine typically uses ion exchangers to achieve zero liquid waste. The cost of brine disposal is presently up to one-third of the cost of desalination, so the development of beneficial uses of produced-water brine should be a priority.

In the United States, Levine and Barnes (2010) advocate the use of treated produced water for pumped hydroelectric storage, with subsequent release for environmental flows. This proposal is more feasible in areas with high terrain relief, but it offers a mechanism whereby the carbon costs of CSG extraction might be partially offset.

Produced water in the northern Sydney Basin might be employed in the cooling systems of thermal coal-fired power stations. In times of drought, the Hunter River and tributaries act as a water supply for these power stations. Inter-basin transfer from the Manning River headwaters, whereby water is piped into the upper Hunter catchment, ensures adequate supply for the power stations. Produced water could potentially help alleviate some of the water stress on the Hunter River, and increased environmental flows would help dilute some of the more saline discharges released into the Hunter River from open-cut coal mines.

NORM elements (radium, radon) typically co-precipitate in the formation of scale minerals in pipes. NORMs are predominantly alpha particle emitters and when concentrated in scale precipitates or in other solids they can present a substantial hazard for gas-field employees. There are no proposed uses for NORM solids, but their safe disposal needs to be addressed. Suggestions have been made to dispose of NORMs in old wells and to distribute them across the land surface. There are no known uses for this material, and disposal or other management of NORMs should be considered in consultation with the Australian Radiation Protection and Nuclear Safety Agency.

Suggestions arising from this chapter

The calculation of salt budgets should be a compulsory part of any activity in which salt is discharged into the environment. In NSW, most of the Sydney and Gunnedah basins have net moisture deficits, so that water released into the environment concentrates salt in either the stream or soil environments before it can discharge into the sea. This is particularly the case for streams in the Murray-Darling Basin. Although not all produced water is salty or even brackish, the effect of evaporative concentration means that even low-salt produced water can potentially contribute significant amounts of salt or other contaminants to the environment. Salt budgeting is one way of determining whether the discharge of this material will have more than a minor or transient impact on the environment.

The fate of salt ions in produced water discharged into the environment is little understood. The chemistry of produced water is usually dissimilar to that of the soil water in the near-surface environment, and, because produced water concentrates by evaporation, unusual minerals may precipitate. While the types of minerals can be predicted by thermodynamic chemical models such as PHREEQC (USGS 2013d), it is possible that different minerals may form as a consequence of slow reaction kinetics and non-equilibrium conditions. Empirical experiments in a variety of field soils that apply produced water with subsequent desiccation and examine the evaporate mineralogy may be instructive as to the diversity of mineral types that may form.

Chapter 6. Discuss any known incidents related to produced water and solids in Australia and internationally

Structure
- Background
- Australia
  - Pilliga State Forest, Narrabri, NSW
  - Talinga, Condamine River, Qld
  - Wieambilla Estate, Tara, Qld
  - Moranbah (Mackay) and Dalby, Qld
- International
  - Dimock, Pennsylvania USA
  - Pavillion, Wyoming, USA
  - Grande Prairie, Alberta, Canada

Background

This review of reported pollution incidents relies on investigations undertaken and statements made by the relevant federal and state environmental protection agencies in addition to peer-reviewed literature on the incidents. This approach has identified three important findings: discovery and reporting of pollution events is often initiated by environmental groups; the mainstream media report events in advance of any regulatory investigation; and reports on investigations by environmental regulators, if they exist, are not readily accessible to the public. In NSW, findings are often summarised in brief media statements that tend to focus on those events that have resulted in fines or other regulatory action. The situation is similar in Qld, where most pollution incidents are reported only by the media. While there is now greater onus on industry to notify the environmental regulator about pollution incidents (refer to the NSW Protection of the Environment Legislation Amendment Act 2011), the findings of the NSW Environment Protection Authority about pollution incidents should be more accessible, including via the Authority's pollution-reporting webpage.

Australia

Pilliga State Forest, Narrabri, NSW

The Eastern Star Gas produced water spillage in the Pilliga State Forest in NSW is perhaps Australia's best known CSG water pollution incident. Santos Ltd purchased Eastern Star Gas in November 2011 and subsequently self-reported on the former company's environmental impacts, including accidental discharges of produced water into Bohena Creek. These resulted from the intermittent failure of a water treatment facility, which operated from 2009 to December 2011. It is unclear how much water was discharged in these events, or indeed how many events occurred. A subsequent investigation by the NSW EPA resulted in the issuing of two penalty notices of $1500 each to Eastern Star Gas for the overflow from a storage pond in March 2010 and December 2010 following heavy rain.

On 25 June 2011 another event was reported by Santos Ltd to the NSW EPA where approximately 10 kL of water with TDS of ~16,000 mg/L and high ammonia levels escaped from a ruptured pipe between pond 1 and the water treatment plant and flowed for 420 m across the surface into Bohena Creek. In a report prepared for Santos Ltd by Golder Associates (2012) on the incident the consultants concluded that the black residue found on the ground surface was likely to be attributable to biogenic interference from natural sources rather than to a petroleum hydrocarbons. The vegetation stress observed in the spill area was likely the result of elevated salts affecting the shallow soil zone, with the characteristics of the salts and substances generally consistent with produced water from CSG.

Santos Ltd was issued with a Formal Warning by the NSW EPA for a discharge in December 2011 that contained high levels of ammonia, although the NSW EPA has stated that this event did not result in environmental harm.

A number of other smaller incidents and inconsistencies have also been reported at the former Eastern Star Gas operation.

Talinga, Condamine River, Queensland

The Australian Pacific Liquid Natural Gas (LNG) project approval permits the discharge of treated CSG water from the project's Talinga water treatment facility into the Condamine River. A condition of approval is that the treated water meets the ANZECC[1] water quality standards before it is discharged into the receiving water body. Water quality monitoring undertaken in 2011 reported high levels of boron and cadmium in the treated water. Elevated levels for boron was foreshadowed in the Talinga CSG Water Management Plan due to the technological limitations of reverse osmosis membranes to reduce boron (Australian Pacific LNG 2011 at section p9.9.9). The Qld Department of Environment stated that it would amend the operating licence to allow the discharge of elevated levels presumably to be consistent with current discharges as sought by Australian Pacific LNG (2011). Under the terms of the operating licence, Australian Pacific LNG must also undertake seasonal environmental monitoring, with initial sampling suggesting that the discharges have not had any ecological impacts.

Wieambilla Estate, Tara, Queensland

In March 2013, the Qld Government released a report on the likely impacts of the CSG industry in the Tara region (Queensland Health 2013). This followed complaints by residents related to CSG activities in the Wieambilla Estate in Tara, Qld, in 2012. The investigation concluded that no clinical or environmental monitoring data were able to demonstrate a link between the reported health complaints and the impacts of the local CSG industry on air, water and soil quality.

Samples were taken from roof-harvested potable water supplies, on-site ponds and other surface water supplies and were assessed against the Australian Drinking Water Guidelines (ADWG) (NHMRC & NRMMC 2011). Four exceedences – for pH, aluminium, cadmium and zinc – were reported for potable water harvested from roofs. According to the report, the exceedences for these 'aesthetic parameters' were, with the exception of cadmium, only slightly outside the ADWG values and would not represent an immediate or long-term health risk. In the case of the two elevated cadmium samples, the values were only 'marginally' above the ADWG guideline and below the less-conservative value specified by the World Health Organization. The elevated values were 'likely attributed to the impurities in the zinc of galvanized pipes or in solders used in plumbing fittings' (p. 11).

An analysis of pond and surface water identified exceedences for TDS, aluminum, iron, total silica and microbial activity (coliform units). Apart from the microbial activity, however, the ponds were generally fit for purpose. The elevated coliform counts were thought to be a result of human or animal faeces rather than contamination by CSG water or other CSG emissions. An ionic profile of

[1] Australian and New Zealand Environment and Conservation Council.

the surface water was undertaken using Schoeller diagrams. The ponds and surface waters reported distinctly different profiles to CSG water, which usually reports low concentrations of sulfate, calcium and magnesium, and high bicarbonate (Van Voast 2003).

Moranbah (Mackay) and Dalby, Qld

The Arrow Energy CSG projects at Moranbah and Dalby reported BTEX chemicals in groundwater. Arrow Energy stated that it has not and does not use BTEX chemicals in its operations.[2] BTEX chemicals are found naturally in coal and petroleum reserves and may be brought to the surface with produced water as part of exploration and production activities. These chemicals are harmful to human health. The environmental and health concerns relate to the use of BTEX chemicals that can be (and have been in the past) used in hydraulic fracturing activities elsewhere. The Qld Government placed a ban on the use of BTEX chemicals in hydraulic fracturing in 2010 (Qld Natural Resources and Other Legislation Amendment Act (no 2) 2010).

International

Table 6.1 presents the conclusions of an analysis of 43 widely reported incidents related to on-shore gas well drilling between 2005 and 2009 in the United States (MIT 2011). In summary, almost half the reported cases of pollution concerned the contamination of shallow water zones by natural gas. The most frequent cause of this contamination was the inadequate concreting of casings in wellbores, which allowed natural gas to migrate from lower formations to the upper groundwater layers. Other pollution incidences were attributed to off-site surface spills, typically the result of failures or leaks in open storage pits. Notably, the MIT (2011) review found no incidents that conclusively demonstrated the contamination of shallow water by produced water, including the contamination of groundwater at Pavillion, Wyoming (see below). On the basis of three reports on the Pavillion, Wyoming, incident dated between 2009 and 2010, the MIT review concluded that there was no clear link between the drilling activity and the contamination (refer to Appendix 2E in MIT 2011).

Table 6.1 Widely reported incidents involving gas well drilling in the United States, 2005–2009 (MIT 2011, p. 39)

Type of incident	Number reported
Groundwater contamination by natural gas or drilling fluid	20
On-site surface spills	14
Off-site disposal issues	4
Water withdrawal issues	2
Air quality	1
Blowouts	2

Dimock, Pennsylvania, USA

In 2009, a methane explosion occurred in a drinking-water well within the Marcellus shale play at Dimock, Pennslylvania. An investigation of the incident by the Pennsylvania Department of Environmental Protection (DEP) found that 18 drinking-water wells were contaminated with methane (PA DEP 2010), due, among other things, to insufficient casing of the boreholes and excessive borehole pressure. The company responsible, Cabot Oil and Gas, has been ordered to cease drilling in the area and has been banned from developing new or existing hydraulic fracturing wells until authorized by DEP. In December 2011, the United States Environmental Protection

[2] BTEX chemicals have also been reported at other CSG sites in Queensland, such as the Surat Basin (www.originenergy.com.au/news/article/asxmedia-releases/1231 Accessed 12 Sep 2013).

Agency announced that the contaminated water was safe "to drink", but subsequent sampling by residents identified ongoing pollution (McAllister & Gardner 2012). This pollution was later also detected by the United States Environmental Protection Agency as part of a revised sampling program (US EPA 2012b).

The Dimock case highlights how important it is for the regulator to require operators to undertake rigorous monitoring and reporting and, in the event of a contamination event, to put in place robust and comprehensive monitoring programs that determine the extent of contamination prior to the issuance of any declarations of safety (Cooley & Donnelly 2012). In particular, the case shows that there are reputational risks for regulators if they are perceived by the community to provide hasty and scientifically deficient decisions that can lead to compromised environmental and health outcomes.

Pavillion, Wyoming, USA

In 2011, the United States Environmental Protection Agency issued a draft report on groundwater contamination at Pavillion. This followed reports by residents in 2009 of changes to the taste and odour of water in their drinking wells. The draft report concluded that hydraulic fracturing was the likely cause of the groundwater contamination (US EPA 2011). This conclusion was based on monitoring undertaken by the United States Environmental Protection Agency between March 2009 and April 2011, and it drew on multiple lines of evidence to infer the possible cause of the contamination of near-surface groundwater. The conclusion that hydraulic fracturing was the likely cause was based largely on poor well integrity, which suggested that a number of bores may have permitted the vertical movement of contaminants from deeper shale reserves that would not have been expected to occur otherwise, given the geology.

Since the release of the draft report, however, the United States Environmental Protection Agency has handed the investigation of the contamination to the Wyoming Department of Environmental Quality and the Wyoming Oil and Gas Conservation Commission, with the national agency taking on a supportive role (US EPA Newsroom Verity View 2013). The final report on the contamination of groundwater at Pavillion is expected in September 2014, with the terms of the investigation focused primarily on well integrity (Anon. 2013). Any conclusions on the most likely cause(s) of the contamination would best be based on a more detailed monitoring program rather than on the 2011 draft report.

Grande Prairie, Alberta, Canada

On 22 September 2011, a hydraulic fracturing operation at Grande Prairie, Canada, inadvertently perforated the base of a groundwater aquifer. Hydraulic fracturing was to have occurred at a depth of 1500 m. Due to human error, however, the hydraulic fracturing fluids, consisting of 130 m^3 of gelled propane and 10.07 tonnes of sand, were injected directly into the sandstone layer at 136 m. Environmental monitoring of the groundwater 12 months after the incident found that the groundwater composition continued to be impacted by the hydraulic fracturing fluids. The concentration of chloride was lower in the December 2012 sample than in the February 2012 sample, but remained elevated. Benzene, toluene, ethylbenzene, and xylene (BTEX) concentrations were unchanged between the February and September 2012 sampling events. Overall, the concentrations of petroleum hydrocarbon fractions F2 through F4 decreased between the two sampling events (Energy Resources Conservation Board 2012, section 4.1.2, p. 8).

Chapter 7. Discuss any potential 'worst case scenarios' and the likelihood/risk of the scenarios occurring with produced water and solids.

Structure

- Background
- Environmental risks
  - Surface water pollution
  - Groundwater contamination
  - Groundwater security
- Health risks
- Economic risks
- Political risks
- Technical risks
- Industry risks

Background

Defining what is 'worst case' is difficult and open to interpretation. For the purpose of this discussion, various scenarios or events are suggested that may inform decision-making processes in a policy and regulatory setting. We do not consider multiple or cumulative events that, when combined, have the potential to magnify environmental, social and economic impacts.

For the sake of simplicity, scenarios have been separated into five areas of risk: environmental, health, political, technical and industrial. Many of the scenarios will have an impact on more than one risk area – as might be expected when dealing with complex and interdependent issues. Given the unpredictable nature of forecasting, let alone the prediction of worst-case scenarios, care needs to be taken with the interpretation of the likelihood of impacts.

Environmental risks

a. Surface water pollution

Spills from pipes and containment structures are a key risk for the CSG industry. Depending on its location and magnitude, a produced water spill has the potential to sterilise soil and affect vegetation (such as occurred in the Pilliga incidents, as reported by Golder Associates 2012 – refer to Chapter 6); if the spilled produced water enters a watercourse it may have ecological impacts on downstream aquatic systems. The high salt and metal concentrations of produced water may result in ecotoxic responses. While ecotoxicity may not have occurred in the Talinga incident in the Condamine River (refer to Chapter 6) it may be possible through recurring or larger spills. Soil contamination may persist for many years, and watercourse contamination may persist for months.

For CSG projects that rely on the surface disposal (e.g. through irrigation) of their produced water, the resultant increase in salinity and impacts caused by other contaminants may lead to the impairment or complete breakdown of ecosystem function. From an agricultural perspective, such an impairment or breakdown could affect the long-term capacity of the soil to sustain productivity.

b. Groundwater contamination

The contamination of aquifers from produced water is one of the greatest long-term concerns associated with CSG and shale gas projects. The risk is real for shale gas, as shown by the contamination of groundwater, including drinking-water supplies, in Dimock, Pennsylvania, and Pavillion, Wyoming. The shale gas reserves in the United States are typically deeper and harder than the coal seams under exploration and production in NSW, requiring greater amounts of water and pressure to hydraulically fracture the shale seam. The shallower depths between the coal seams and aquifers used for drinking and agriculture in NSW may mean there is greater potential for the vertical migration of produced water through cracks, faults and wells, notwithstanding water and energy requirements for hydraulic fracturing, and consequently a higher risk of contamination.

As reported in Chapter 6, naturally occurring BTEX chemicals were found in groundwater aquifers at the Moranbah and Dalby CSG operations in Qld, highlighting the need to consider ‘natural’ pollution and the possible contamination that may occur if such groundwater is released.

Change in near-surface aquifer water chemistry as a consequence of contamination by gases and produced water derived from deeper strata can also affect groundwater systems. For example, methane has low solubility (26 mg/L at 1 atm, 20 °C) and can seep through cracks, faults and wells into groundwater systems. It can be oxidized by bacteria, resulting in anoxic conditions that, in turn, can increase the solubility of arsenic and iron and reduce sulfate to sulfide, causing water-quality problems. In extreme cases, the methane can explode if concentrations exceed 10 mg/L (Révész et al. 2010). The fate of chemicals used in well construction and maintenance and in hydraulic fracturing may also have environmental consequences (refer to Chapter 8).

c. Groundwater security

Uncertainties about groundwater plumes dynamics (Chadwick et al. 2005) and their contribution to the contamination of aquifers is an important consideration in CSG projects, particularly where the injection of produced water is proposed as a disposal option. Environmentally, long-term changes may affect the quality and quantity of groundwater aquifers, springs, hanging swamps and surfacewater systems.

For regions and activities that rely on groundwater as their principal water source or as a back-up during drought, the additional impacts of water extraction and injection due to CSG may have broader and longer-term consequences. Such consequences can affect the security and reliability of water supply for drinking water, agriculture and other energy and mining projects, including electricity generation, open-cut and underground coal mining and other mineral extraction.

CSG is an emerging industry that has also been identified as playing a key role in the state’s energy security. Therefore, aquifer security, both spatially (local and regional) and temporally (years to hundreds of years), must be a foremost consideration in strategic planning, approval and monitoring.

Health risks

Produced water contains a range of chemicals that can have health consequences if they contaminate drinking-water supplies. Once a groundwater aquifer is contaminated, it can be many years before a safety declaration can be made based on intense monitoring and evaluation by an independent regulator. In the meantime, a back-up water supply must be provided for drinking or agricultural purposes. The presence of elevated methane and other fugitive gases in drinking-water wells within 1 km of gas wells (Jackson et al. 2013b) or in the atmosphere within several kilometres of gas wells (Tait et al. 2013) is evidence of contamination. Whether the presence of water-borne gases is a precursor to other water contaminants remains uncertain. From a worst-case and risk perspective, this is an aspect of the unconventional gas sector (both on shale and coal) that demands close monitoring.

Where produced water is used for irrigation, there exists a risk of the bioaccumulation of certain contaminants in cereal crops and stock, which may affect human health. Characterising the chemical composition of produced water, and how this may change during treatment and disposal, will assist the assessment of risk.

A variety of chemicals have been used in hydraulic fracturing, many with known health risks. Of 353 chemicals used in the United States for hydraulic fracturing, 75% could affect human skin, eyes and other sensory organs and the respiratory and gastrointestinal systems, 40–50% could affect the brain/nervous system, immune and cardiovascular systems and kidneys, 37% could affect the endocrine system, and 25% could cause cancer and mutations (Colborn et al. 2011).

Economic risks

Uncertainty in the capacity of a polluter to pay for the remediation of a contamination event represents a major risk to the sector and government. This is particularly pertinent for groundwater pollution, where the discovery of the pollution could be measured in decades and the cost of remediation and the interim provision of water services would be expensive. An additional risk is the chance that a pollution incident could instigate a class action to remedy an environmental or health impact, with the potential to exceed the financial resources of the polluter. While the lodgement of pollution bonds may be a requirement of the approval to operate, setting an amount that does not affect the commercial viability of a project but also provides sufficient security against the likelihood of worst-case events is an issue for government and the industry.

Linked to the financial capacity of the CSG operator to honour remediation costs is the commercial viability of the operator in a given gas market. Should the price of the gas product fall to a level at which operators are forced to abandon (temporarily or permanently) their activities, bonds and other regulatory requirements must be sufficient to enable interim measures to be deployed to manage pollution risks, particularly those related to well integrity.

Political risks

The 1998 ‘outbreak’ of *Cryptosporidium* in Sydney’s water supply showed the vulnerability of government processes and monitoring to a loss of public confidence. Transparent decision-making processes, supported by the open and independent review and analysis of the impacts of CSG, particularly concerning produced water and fugitive gases, is a critical risk to the integrity and capability of policy and regulation to manage this activity. The contamination of an aquifer used for drinking water or an important agricultural activity will no doubt result in considerable media coverage and community protest. Decisions by government to approve CSG projects, and the conditions attached to those approvals, must have rigour, be based on best available science, and be able to be modified as new technologies, processes and discoveries are made. This does not necessarily mean that government should adopt a highly risk-averse approach; rather, the risk assessment process needs to be robust, transparent, informed by national and international precedents and based on sustainability principles.

Technical risks

The integrity of wells has been identified as the main cause of groundwater contamination (as discussed in Chapter 8). Given that CSG projects require many wells, the risk of failure of casings or concrete sealing is a key concern and is likely to be a fundamental contributing factor in any worst-case scenario. There remains a requirement for detailed standards (including codes of practice), skilled operators (to construct, operate and seal the wells) and ongoing testing and validation. While failures due to human error have and will occur (such as in the Grand Prairie incident), management systems developed by industry, their independent auditing, and review by regulators should collectively minimise systemic failures that could result in pollution.

The impact of hydraulic fracturing on the integrity of wells and beyond the targeted coal seam may lead to the unintended contamination of groundwater systems. Where hydraulic fracturing is required to liberate gas in a coal seam that is close to a groundwater aquifer, projects should be carefully reviewed by the determining authority based on the likelihood of the risk of groundwater contamination. Similar concerns relate to the potential for increased seismic risks arising from changes in pressure caused by hydraulic fracturing and how these might affect well integrity and in turn the potential for produced water to migrate to other aquifers.

Industry risks

The community is taking a very close interest in the activities of the CSG industry, and this has informed the current policy and regulatory response of government. Whether this interest and the response to it are proportionate to the known environmental risks and impacts, especially compared with those of other mining activities, is a ‘whole of mining industry’ concern. As noted in the review by Krogh (2007) and in the strategic review of underground coal mining on natural features in the southern coalfields (NSW Government 2013), underground coal mining and the related subsidence is having a direct impact on threatened ecological communities and surface water flows and possibly on the security of Sydney’s water-supply system. Community concerns related to these issues, coupled with the contaminations that have occurred in shale gas extraction in North America, have no doubt influenced the current decline in investment in new CSG projects in NSW. If gas is to be a critical energy resource in NSW, the industry must engage proactively in developing worst-case scenarios and in showing how they intend to manage risks to avoid such scenarios (House 2013). As found in this review and by others, there is limited evidence to dismiss outright many risks that may contribute to a worst-case contamination event.

Chapter 8. What risk assessment and risk management approaches should be taken for produced water and solids? What are the mechanisms or solutions that can be used to address or remediate impacts and problems related to produced water and solids, including national or international examples? Comment on international best practice in relation to risk management and remediation.

Structure

- Background
- Well integrity
- Abandoned wells
- Hydraulic fracturing
- Seismic and subsidence risks
- Surface operations and infiltration
- Groundwater hydrology
- Cumulative impacts
- Reuse and disposal
- Cost of cleanup
- Hydrology
- Suggestions arising from this chapter

Background

The management of risks can follow a goal-based approach or a prescriptive approach relying on regulation. The former is generally more flexible and places the onus on industry to update procedures and standards, and the latter relies on government to update standards and regulations and enforce these though licensing and approvals.

The United Kingdom generally follows a goal-based approach, as prescribed in the Offshore Installation and Wells (Design and Construction etc.) Regulation 1996. This regulation specifies (in parts 2 and 4) that wells should be designed and constructed so that, as far as reasonably practicable, there can be no unplanned escapes of fluids, and so that the risks to the health and safety of persons from it or anything in it, or in strata to which it is connected, are as low as reasonably practicable. The basis of this approach is to place the onus on the operator to continuously understand and manage their activity based on risks in the context of what is 'foreseeable'. The approach infers that, as new technologies or discoveries are made with respect to environmental and industry practice, or as incidences occur that result from poor practice or understanding, the operator continually modifies and updates their practice. This approach is distinct from the prescriptive approach, where regulators set standards to which the activity must comply, and these standards form the basis of the approval-to-operate conditions.

The prescriptive approach is employed in NSW through various codes of practice (such as for well integrity (NSW Trade and Investment 2012), and in most jurisdictions in the United States. Government agencies are typically charged with responsibility for developing and updating standards and performance criteria, more recently with industry and expert input and public consultation processes.

A report by the United Kingdom's House of Lords (House of Lords 2006) noted that risk management can contain ill-defined and ambiguous terms that may 'induce an excessively cautious attitude to risk' (para 73). The report called for terms such as 'precautionary principle' to be defined more clearly or replaced with specific and unambiguous requirements and concepts. The current debate in Australia and elsewhere on the impacts of coal seam or shale gas highlights the breadth of opinion on what constitutes a risk and how risks should be considered as part of a development approval or licensing process.

In NSW, the precautionary principle has been considered and clarified by the NSW Land and Environment Court in a number of cases (see Telstra Corporation Limited v Hornsby Shire Council [2006] NSWLEC 133). The application of the precautionary principle is embedded in the definition of ecologically sustainable development in the *Environmental Planning and Assessment Act 1979* and has been interpreted by the court and others. Most recently, the precautionary principle was applied by the NSW Planning Assessment Commission in its decision to refuse a coal seam gas (CSG) exploration project within one of the five Sydney drinking water catchments.[3]

The new planning reforms proposed in NSW (NSW Government 2013) seek to change how sustainability is understood, with a greater emphasis on economic development. This may effect how risk management principles and assessments are interpreted for new and current unconventional gas projects.

As a relatively new industry, the short-term to long-term impacts of CSG produced water (PW) on the environment are not fully described or understood, although generally the research has tended to suggest that the risks of environmental contamination are low and manageable (for example refer to the review of shale gas by ALL Consulting 2012). Notwithstanding this, should a contamination event occur from an unintended release of PW into surface or groundwater systems, the consequences could be significant.

Research suggests that the major risks of environment contamination from coal seam and shale gas projects related to PW lie in a loss of integrity of the wells and with spills associated with surface operations. A lack of robust and peer-reviewed monitoring programs that have the confidence of regulators, industry and the community remains the key impediment to fully understanding and therefore managing the risks. Groat and Grimshaw (2012) concluded that surface spills of fracturing fluids are likely to pose a greater contamination risk than hydraulic fracturing, with the key risks related to the storage, treatment and transportation of PW and related waste waters.[4]

A study by the Massachusetts Institute of Technology (MIT 2011) concluded that with over 20,000 shale wells drilled in the last ten years in the United States, the environmental record of the industry ‘has for the most part been a good one’ (p. 39). In the United Kingdom, an independent review by The Royal Society and The Royal Academy of Engineering (2012) concluded that the risks associated with hydraulic fracturing (which also incorporated well integrity and related drilling activities) is ‘very low provided that the shale gas extraction takes place at depths of many hundreds of metres’ (p. 4).

[3] On 10 July 2013 the NSW Planning Assessment Commission refused Modification 2 for an extension of time for the Apex Energy NL CSG project. In its determination, the Commission outlined a number of issues but primarily noted the uncertainties surrounding the risks and potential impacts, and that policies relating to CSG are currently evolving. In its representation to the Commission, the Sydney Catchment Authority noted that boreholes such as those proposed in the Apex application have been permitted in coal mining for a very long time but that the surface impacts of CSG for operational (extraction) purposes would have greater impacts on the catchment (www.pac.nsw.gov.au/Projects/tabid/77/ctl/viewreview/mid/462/pac/279/view/readonly/myctl/rev/Default.aspx).

[4] This study was subject to an independent review by the University of Texas (2012). The review found that while the authors, Groat and Grimshaw, did not disclose their conflicts of interest, the conclusions on spills and their contributions to risk stand (p. 20–21).

As indicated earlier, the United Kingdom tends to take a goal-based approach to environmental, health and safety regulations by requiring operators to identify and assess risk in a way that fosters innovation and continual improvement. Within this framework, the notion of reducing risks to 'as low as reasonably practicable' seeks to place an additional onus on industry over and above a simple reliance on regulations and standards that may not always reflect best practice (The Royal Society and The Royal Academy of Engineers 2012). Arguably, this approach encouraged the oil and gas industry to improve its environmental, health and safety practices more readily than a prescriptive approach would have done.

In the United States, risk analysis techniques have been used to determine the probability of water contamination associated with the extraction of shale gas. Rozell and Reaven (2012) used probability bounds analysis, which takes into account natural variation (aleatory uncertainty) and lack of knowledge (epistemic uncertainty), to assess five contamination pathways: transportation, well casing leaks, leaks through fractured rock, drilling site discharge and wastewater disposal. They found that the uncertainty associated with wastewater disposal and specifically the efficacy of contaminant removal by industrial and municipal wastewater treatment facilities posed the greatest potential risk. The risk of causing fractures from wells, and the amounts of fluids that would leak from these, were comparatively small, and with higher standards of well construction and testing, this risk was likely to reduce further. In their review of this approach, Jackson et al. (2013a) noted that the wide range of probabilities used by Rozell and Reaven (2013) incorporated grey literature and newspaper reports in addition to some peer-reviewed data. This demonstrates that there is a significant gap in scientific understanding, which reduces the reliability and application of risk models.

The risk profile will change over the life of an unconventional gas project. The initial phases of exploration and construction are likely to rank spills from transportation, the handling of drilling site fluids and the storage and disposal of PW as the greatest risks. A failure from well casing would likely occur during or after the production phase. The migration of PW through fractures that may affect drinking water could occur years or decades after the well has been decommissioned. Consideration of these issues should inform how and when inspection and monitoring programs are put in place as part of licence conditions during production and following the conclusion of a gas project, should legacy pollution (i.e. leaks that occur from a well decades after it has been capped) occur. Similar attention should be paid to cases in which PW is disposed of by surface application (such as into a creek or through irrigation), with the potential to cause a reduction, or at worse complete loss, of the agricultural capacity of soil or the health of a river due to the salinity and other compounds associated with deeper groundwater formations. Longer-term impacts of water withdrawals or the injection of PW as a means of disposal can also affect local and regional groundwater resources by changing the pressure within and between aquifers, particularly where aquifers are connected – such as in many parts of the Great Artesian Basin (CSIRO 2012 and National Water Commission 2012b).

Evidence that spills and other incidences have occurred nationally and internationally clearly indicates that the industry has to improve its technical performance and systems and reduce the potential for human errors (refer to Chapter 6). Any risk management system must be able to draw on past experience: this requires that data on reported (and unreported) events, environmental monitoring and other performance data are published by the relevant regulators and are open to independent scrutiny. The following discussion focuses on specific aspects of the unconventional gas sector and how risks associated with PW can be better managed. In considering risk, the presence of drinking water catchments and aquifers, agricultural and irrigation groundwater supplies and groundwater-dependent ecosystems must be a primary matter of consideration.

Well integrity

The integrity of unconventional gas wells and their ability to prevent contamination of groundwater formations has been a key area of concern for the industry for some time (Charfin 1994). Research into the presence of stray gas from production wells in shallow aquifers has suggested that such wells may be a pathway for the vertical migration of contaminated water (Jackson et al. 2013a). A related study also concluded that natural hydraulic connections between drinking water aquifers and deeper shale formations exist and may be the cause of contamination (Warner et al. 2012).

Two possible pathways for contamination related to well integrity are an annular leak, in which there is vertical movement between casings or between a casing and the adjacent rock formation, and a radial leak, in which fluids move horizontally from a well and migrate to the surrounding rock formations – this latter kind of leak is often associated with a failure in the concrete sealing.

Inadequacies in well construction, and particularly in the type and depth of casings and supporting concrete between the casings, are a notable risk to the unconventional gas industry and the possible contamination of groundwater resources (Jackson et al. 2013a). Unintended gas migration or leaks have been found in up to 28% of well casings, however, contamination is usually attributed to surface spills rather than to the well itself.

An important factor impacting on the integrity of a well has been linked to imperfections in the concrete sealing that can allow gases from intermediate layers to flow into, up and out of the annulus, in effect enabling both vertical and horizontal movement of gases. Stray gases, including methane, ethane and propane, are likely to occur in drinking water wells within 1 km of gas wells in the Marcellus shale gas region in Pennsylvania (Jackson et al. 2013b). The shale comprising the Marcellus formation is found 1500–2500 m underground, and the typical depth of drinking water wells is 60–90 m. Jackson et al. (2013b) concluded that the pathways for gases entering groundwater systems relate to flaws in the integrity of the well, including faulty or inadequate steel casings, imperfections in the concrete sealing of the annulus, or gaps between casings and the rock strata. While this study was unable to determine the main contributors of stray gases (e.g. casing or concrete sealing), it did suggest that the nature of the failure mechanism is likely to have an effect on the risk of contamination of groundwater aquifers. The authors suggested that the large distances between shale measures and drinking water aquifers are unlikely to support the migration of produced water. This suggestion may not hold true in Australia, however, given the relatively shorter distances between the coal measures and groundwater aquifers.

Faulty or inadequate casings can be caused by a variety of factors, such as poor thread connections, corrosion and thermal stress resulting in cracking (Brufatto et al. 2003). The risk of casing failure may be exacerbated by changes in pressure between deeper gas reserves and the surface, combined with hydraulic fracturing pressures. A failure of the casings can be a pathway for PW to migrate vertically through the well, with the gases being the first indicator that previously isolated geological layers are now connected. This failure mechanism probably presents the greater risk, and it needs to be assessed through regular and ongoing monitoring.

There is only a weak correlation between the age of a well and the presence of stray gas (Jackson et al. 2013b). This suggests either that there has been a gradual improvement in the quality of well construction over time, or that there is a slow degradation of well integrity, meaning that the number of contaminated near-surface aquifers will increase over time. This is an area for ongoing research, although Brufatto et al. (2003) noted that casing failures were common in gas fields in the Gulf of Mexico, with 50–60% of wells experiencing casing pressure failure after 15 years.

An additional failure can occur from a 'blowout', which is a sudden and uncontrolled escape of fluids from an over-pressurised and highly permeable formation. The main risk of a blowout is to the safety of workers, but fluids can escape and may present a risk to nearby surface waters. A blowout can also cause an escape through the well casing, which may lead to the contamination of groundwater systems.

In a non-peer reviewed study in Pavillion in the United States, Boling (2012) suggested that a failure of well casings appeared to be the key causative factor of near-surface groundwater contamination by methane gas from deep shale reserves (Marcellus shale) (refer to Chapter 6). The key factor influencing contamination from wells is the quality of the concrete encasing the borehole, particularly as it passes through aquifers. This conclusion was supported by MIT (2011) in its review of 43 reported environmental incidents concerning the shale gas industry in the United States, which found that the most common cause of pollution was the leakage of gas or drilling fluids into shallow zones associated with poor or no well casing (refer to Chapter 6).

The adoption of higher standards and the continual review and updating of standards based on evidence is aimed at improving the performance of wells. The most recent code of practice for CSG well integrity in NSW reflects this adaptive and continuous improvement approach (NSW Parliament 2012). A key aspect to managing risk is the requirement for multiple casings, particularly near the surface and as the well passes through aquifers used, or connected to those used, for drinking, stock or irrigation. The use of multiple casings should limit the risk of failures leading to groundwater contamination, like those that have occurred in Canada (Watson & Bachu 2009) and the United States (DiGiulio et al. 2011).

From a risk management perspective, Boling (2012), MIT (2011) and Williams et al. (2012) advocate ongoing improvements to the specifications and engineering practice related to well integrity. Factors for consideration by both regulators and the industry include:

- The use of site-specific data to inform well construction standards rather than generic regulation, codes or industry best practice. This would ensure that casings and concrete are not limited to near-surface groundwater layers but would consider a variety of other factors, such as the entire depth of the drill and the permeability of various strata, and the presence of faults and areas of known vertical and horizontal movement.
- Ensuring the ongoing examination of a well's integrity by an independent person (for example, as regulated in the UK through the Offshore Installations and Wells [Design and Construction, etc] Regulations 1996 clause 18). This should extend to but not be limited to conducting pressure tests and concrete-bond logs to ensure integrity over the full life of a well, including post-production.
- Ensuring that overweight drilling muds do not leak into the groundwater as a result of poor surface management practices, such as placing storages close to wells.
- As part of the production drilling and gas extraction phase, ensuring that unexpected pockets of shallow gas do not migrate naturally or through the well into groundwater zones.
- Continuing to improve the quality and type of concrete to minimize shrinking, which can lead to cracks that serve as vertical and horizontal conduits for gas and PW (Dusseault et al. 2000, Bentz & Jensen 2004).
- Ensuring that hydraulic fracturing processes do not cause stress to the concrete sheath and in turn cause fracturing (Brufatto et al. 2003).
- Using multiple casings and concrete between the casings, particularly through and below known aquifers (API 2009, Watson & Bachu 2009).
- Ensuring that wells no longer needed for exploration or production are left in a condition such that future leaks cannot occur (for example, the United Kingdom follows the guideline given in Oil and Gas UK 2012).

Abandoned wells

Abandoned and improperly plugged wells used for oil and gas extraction could become a pathway through which gases and fluids contaminate shallow groundwater aquifers if they become repressurised (Jackson et al. 2013). Repressurisation may occur as a result of gas drilling, well stimulation activities (such as hydraulic fracturing) and reinjection disposal practices.

Abandoned drinking and stock wells were identified as a possible cause of the Pavillion contamination by serving as migration pathways between aquifers (US EPA 2011b). While the review into this contamination and its causes is still underway (Chapter 6), IOGCC (2008) noted around 150,000 undocumented abandoned oil and gas wells in the United States and suggested that if these were a common conduit for vertical exchange between aquifers it would stand to reason that many more pollution incidences should have been reported. Presently, such cases seem rare (MIT 2011). In Australia, the Sydney Catchment Authority reported 984 coal and geological exploration boreholes, eight petroleum exploration boreholes, seven CSG exploration boreholes and 208 groundwater boreholes in the Woronora and Metropolitan Special Areas (SCA 2012, p. 76). This suggests that multiple opportunities exist for the vertical exchange of gas and water between what ordinarily would be considered separate hydrogeological layers. No impacts on surface water or shallow groundwater quality by past drilling have been reported, and while the risks cannot be discounted, they are probably low (SCA 2012).

Hydraulic fracturing

There is widespread community concern about hydraulic fracturing and in particular the use of chemicals involved in hydraulic fracturing (Chapter 1). From a risk management perspective (and generally for the community and industry), there is a need to clarify what hydraulic fracturing is and, in turn, what processes and activities should be put in place to manage its definable risks.

Studies in the United States have identified that communities and various social and environmental interest groups understand the term ‘hydraulic fracturing’ (or, more colloquially, ‘fraccing’) as describing the wide range of problems associated with unconventional oil and gas development. This includes the exploration, production and remediation phases (Cooley & Donnelly 2012, House 2013) (Chapter 3). Reporting by the media on shale gas, and on CSG in Australia, has inferred a broad definition that can make it difficult to determine the specific areas of concern or risk (Groat & Grimshaw 2012). In contrast, the industry and the scientific community have a much narrower definition focused on the process of using fluids or other media such as gas to fracture rock formations. The consequence of these divergent definitions is that associated terms such as PW are also likely to have multiple meanings. This will affect how the industry and the community perceive both the environmental risks associated with hydraulic fracturing and the effectiveness and desirability of regulations (e.g. House 2013). Clarification of key terms and definitions is needed.

The use of chemicals in hydraulic fracturing has been a particular point of contention for community and environmental groups and increasingly for regulators. Adopting an industry standard or regulation that prescribes which chemicals may be used in hydraulic fracturing and their maximum concentrations would provide greater transparency and increase confidence in this practice. At a minimum, such a standard or regulation must exclude chemicals known to have environmental and human health impacts, such as is the case for BETX chemicals, which are banned in a number of jurisdictions (including NSW and Qld), but it should also consider how other chemicals behave in various conditions (e.g. in anoxic conditions, which occur deep in coal reserves, and in oxygenated environments in groundwater systems).

While the industry and government report that hydraulic fracturing may have a low risk in terms of environmental impact, a precautionary and also regulatory approach is justified given the potential impacts of contamination. For example, a shallow aquifer in Alberta, Canada, became contaminated in 2011 when an accidental injection of hydraulic fracturing fluids was placed directly into sandstone at a depth of 136 m. In this case, the contamination was caused by human error because the operators had targeted hydraulic fracturing at a depth of 1500 m (Energy Resources Conservation Board 2012b). The result of the error was that BETX and other chemicals contaminated the drinking water supply.

The depth and integrity of the geology between gas reserves and shallow freshwater is a key factor in determining the risk of contamination from hydraulic fracturing. In their review of the literature, Jackson et al. (2013a) reported that there was no evidence that fracture propagation 'out of zone' to shallow groundwater had occurred from deep (>1000 m) shale gas reserves. The studies by Fisher (2010) and Fisher and Warpinski (2012) reported that the containment of fractures across four shale measures in the United States suggested that the geology was confining the vertical movement of water to a greater extent than previously thought. They also found that the minor fractures present were longer and narrower. Because coal-bed methane can be much closer to freshwater aquifers, the conclusion by Fisher (2010) on the overall safety of hydraulic fracturing may not necessarily hold.

Davies et al. (2013) reported that, in addition to hydraulic fracturing by the shale and CSG industries, natural hydraulic fracturing should be considered as a possible source of contamination of near-surface groundwater aquifers. As part of their examination of the Marcellus shale in the United States, Davies et al. concluded that the exchange of gas and water is dependent on a number of variables, such as the relative proximity of the aquifers and the depth and integrity of the sedimentary layers between aquifers. Natural fractures in the rock have the potential to propagate upwards as a result of the naturally higher pressures in deeper geological layers, effectively serving as natural conduits for PW and gas to near-surface aquifers. The Davies et al. (2013) study suggests that the chance of stimulated hydraulic fracturing extending vertically beyond 350 m is around 1%, and that the 500 m depth of sedimentary rocks between the aquifers in the Marcellus shale is likely to provide a natural barrier to the growth of vertical fractures. Research specific to Australian conditions is needed in this area to determine whether these findings are transferable.

A different position is held by Myers (2012), who developed a model to determine how PW might move between geological layers in the Marcellus shale reserve. The model suggests that hydraulic fracturing can release fluids and contaminants from the deeper shale reserves to near-surface aquifers. Myers drew on the presence of thermogenic gas (formed by compression and at depth, as would be associated with the deeper shale gas reserves) in the near-surface drinking water aquifers as evidence of a pathway for gas exchange and to infer that this may also enable the migration of PW. The Myers model assumes that the vertical movement of fluids in the Marcellus shale occurs naturally when measured at a geological time scale and that such movement can occur in ten years or less through hydraulic fracturing. While the Myers model 'does not and cannot account for all the complexities of the geology' (p. 2), his conclusions, and those of others (Williams 2010), imply the following for the CSG industry:

- Prior to hydraulic fracturing, the subsurface should be mapped for faults.
- A reasonable distance between the coal seam and important aquifers should be established, based on the risk that hydraulic fracturing will increase pressure within the fault.
- The properties of the shale (or coal) seam should be verified after the hydraulic fracturing has occurred to assess any hydrogeological changes.
- Deep and shallow groundwater monitoring should be established to ascertain background conditions prior to the production phase of gas extraction.

Hydraulic fracturing can increase the hydraulic connection between wells (Settari et al. 2012). To minimise this risk, Settari et al. recommended that CSG wells be offset by at least 200 m from adjacent water wells. This recommendation, designed to minimize the risk to contamination, is similar to that of Canada's Energy Resources Conservation Board (2012a), which requires that fracture propagation modelling be undertaken prior to fracturing operations to assist in determining the potential area of influence of such operations. Operators must:

- consider how the risks are influenced by geology and completion (well construction) practices;
- consider how the area of influence may be affected by well stimulation operations;
- identify all wellbores, including abandoned and suspended wells that may be in close subsurface proximity;
- notify offset well licensees of pending hydraulic fracturing that may impact offset wellbores; and
- collaborate with offset well licensees to ensure the effective control of all wells.

Hydraulic fracturing also uses considerable quantities of water and in turn generates PW that must be managed by the operator. The harder and often deeper shale reserves require much more water and pressure than do coal reserves. For shale reserves, a single hydraulic fracturing treatment can use more than 1.9 ML of water, with each well using 7.5–15 ML depending on the shale formation (Groundwater Protection Council and ALL Consulting 2009, p. 63–64). Advice by Roy to the NSW General Purpose Standing Committee No. 5 (NSW Parliament 2012, paragraph 3.65) noted that the hydraulic fracturing of a CSG well would use ~0.2–0.6 ML of water.

It is evident from the literature that there are widely differing views about the risks and impacts of hydraulic fracturing, with all studies suggesting a need for more and comprehensive monitoring and reporting. Such monitoring and reporting are needed to overcome the significant social and political concerns of this practice and to inform regulators and other approval bodies on how they should address the uncertainties and risks associated with this practice (Jackson et al. 2013a).

Seismic and subsidence risks

Induced seismic events or induced earthquakes related to energy projects, including shale gas extraction and the reinjection of PW into aquifers, have been reported in a number of states in the United States. In a review of the risks of induced earthquakes associated with the energy sector, the National Research Council (2013) concluded, in relation to shale gas and associated activities, that:

- hydraulic fracturing for shale gas recovery does not pose a high risk for inducing felt seismic events; and
- the injection of produced water into subsurface aquifers does pose some risk for induced seismic events, although very few events have been documented relative to the large number of disposal wells in operation.

These findings may reflect the general lack of data and models that can be used to predict seismic impacts related to the energy sector. The National Research Council (2013) did note that local impacts can be felt, and that there is a need to undertake further research in regions in which energy production is concentrated to understand and address the potential risks.

To help understand and manage seismic risks associated with the energy sector, the National Research Council (2013) prepared a checklist (Table 8.1). This could be integrated with a traffic-light system to assist operators or regulators to determine if, when and how hydraulic fracturing or injection should occur. The traffic-light approach relates to the Modified Mercalli Intensity scale (a measurement of the damage caused by ground shaking) (USGS 2013a), in which: a green light would permit activities to continue as planned because monitoring shows that the impacts are very minor; an amber light would be instigated where moderate shaking was reported within one week of hydraulic fracturing; and a red light would signify to the proponent that it must cease all activities because strong shaking has occurred (National Research Council 2013).

Table 8.1 Criteria to determine if injection of produced water may cause seismicity (National Research Council 2013 p. 153, Table 6.1)

	QUESTION	NO APPARENT RISK	CLEAR RISK
	Background seismicity		
1a	Are large earthquakes (**M** ≥ 5.5) known in the region (within several hundred km)?	NO	YES
1b	Are earthquakes known near the injection site?	NO	YES
1c	Is rate of activity near the injection site (within 20 km) high?	NO	YES
	Local geology		
2a	Are faults mapped within 20 km of the site?	NO	YES
2b	If so, are these faults known to be active?	NO	YES
2c	Is the site near (within several hundred km of) tectonically active features?	NO	YES
	State of stress		
3	Do stress measurements in the region suggest rock is close to failure?	NO	YES
	Injection practices		
4a	Are (proposed) injection practices sufficient for failure?	NO	YES
4b	If injection has been ongoing at the site, is injection correlated with the occurrence of earthquakes?	NO	YES
4c	Are nearby injection wells associated with earthquakes?	NO	YES

The United Kingdom has not reported any onshore well ruptures attributed to seismicity, although seismic activity in the Blackpool area in 2011 has been linked to the hydraulic fracturing of shale reserves. A recommendation made in light of this incident was the need to assess the integrity of wells following a seismic event, including by undertaking repeated pressure tests and concrete bond logs (The Royal Society and The Royal Academy of Engineering 2012). The Royal Society and The Royal Academy of Engineering (2012) also concluded that the energy released during hydraulic fracturing for shale gas would be less than the energy released by the collapse of open voids in rock formations, as occurs in underground coal mining. This statement is qualified in that shale reserves are significantly deeper than coal seams.

Subsidence is also an important part of a risk assessment for underground energy projects. Underground coal mining can result in the deformation of ground surfaces that can be measured in metres, which in turn can lead to the cracking of valley floors, creek lines and other fluvial features affecting surface and near-surface water quantity and quality (SCA 2012). The deformation of ground surfaces caused by the removal of CSG and associated groundwater is likely to be in the order of centimetres to tens of centimetres (Geoscience Australia and Habermehl 2010). While the subsidence associated with underground coal mining is known to affect the hydrology of streams in Sydney's drinking water catchments (NSW Department of Environment and Climate Change undated, SCA 2012) the impacts of subsidence from CSG projects are generally considered low, although they should be monitored (Geoscience Australia and Habermehl 2010).

The presence of faults does not necessarily mean that they provide pathways for groundwater movement, and nor does it mean an increase in the risk profile. Mineralisation and mineral precipitation over many years can seal fractures and form natural hydraulic barriers (Henning 2005). Opinions differ on the influence of faults in the Surat and Bowen basins in Qld on regional groundwater flows (Queensland Water Commission 2012). Golder Associates (2009) suggested that such faults are likely to reduce hydraulic connections, while Hodgkinson et al. (2010) concluded that they do not affect lateral regional groundwater flows. This difference in opinion suggests that further targeted research is needed to assess the influence of regional geological structures on groundwater flows (a view also expressed in Queensland Water Commission 2012, p. 37). A study by Warner et al. (2012) on whether there is natural migration of gases and saline water from deeper shale reserves to shallow groundwater concluded that natural pathways can and do exist that may explain the presence of certain gases and high concentrations of some elements in near-surface aquifers. The authors cautioned, however, that shale gas development could increase the risk of contamination through pre-existing pathways. The potential for faults to extend from deeper shale and coal resources to near-surface aquifers represents a risk (Hodgkinson et al. 2010, Warner et al. 2012) that should be examined as part of any project proposal.

Surface operations and infiltration

CSG extraction is a spatially distributed industry with a footprint far greater than the sum of its individual well heads. Risks to land and water resources from PW extend far beyond the surface expression of the well heads; vertically, CSG wells intersect various geological layers, including groundwater aquifers, and horizontally they impact on land and surface water systems.

Gathering pipelines for gas and PW (depending on the treatment and disposal methods) require a network of pipes linking individual well heads to treatment or disposal systems. While safety risks for low-pressure gas and low-pressure water (the volumes of which will depend on production rates) are lower than for other types of gas pipeline regulated within the oil and gas industry (GAO 2012), there remains a need to ensure that surface and subsurface pipelines:

- are constructed to a suitable quality;
- have adequate maintenance and inspection processes;
- have recorded locations that are accurate and accessible within centralised, publically accessible data bases (e.g. 'dial before you dig'); and
- have been assessed for the longer-term integrity of their pipes and network connections, to inform future projects.

It should also be recognised that the risk of accidental damage to the supporting infrastructure of such pipelines is higher near residential and peri-urban areas compared with agricultural areas (this is often because mining companies own the land in agricultural areas, or they lease it from existing farmers, who have greater knowledge of their land and where pipe networks are located).

The clearing of vegetation, and surface disturbance related to drill pads, can have on-site impacts (such as erosion) that can carry contaminants from the drill area to the surrounding environment. Sediment yields from well pads during storms can be equivalent to typical construction sites, in the range 15–40 tonnes per hectare per year (Groat and Grimshaw 2012). While individual pads may have a relatively small surface area, many wells are required for a commercial project, and they can have an impact over each of the main stages of CSG extraction: exploration, production and remediation (Chapter 3).

Historically, the storage of PW has mostly been achieved through on-site and usually lined containment ponds (API 2009). These ponds have been a significant source of groundwater contamination from leaks, overflows due to extreme precipitation episodes, and the failure to empty the ponds over several years (Jackson et al. 2013a). In many jurisdictions, storage is required to be contained in closed-loop steel tanks and piping systems (for example, refer to the recommendations made by The Royal Society and The Royal Academy of Engineering 2012), although such 'best practice' is far from universal (for example, refer to the North Dakota Produced Water Management state regulations[5]).

Groundwater hydrology

Aquifers, and wells within aquifers, generate varying volumes of groundwater. Over the life of a CSG well, the quantity of PW will also vary, typically being greater at the beginning and tailing off as the well approaches the end of its productive life. These changes also influence the risks to groundwater hydrology. The extraction of large volumes of groundwater can result in depressurisation, leading to changes in the connectivity between surface and groundwater systems. This depressurisation can occur over short and long time intervals. Many CSG reserves in NSW are located below drinking and agricultural groundwater sources, and changes in pressure have the potential to cause a drawdown of higher-quality near-surface supplies to lower groundwater systems and reduce surface water flows in connected streams and may result in subsidence that affects surface water systems, ecosystems (such as upland swamps), irrigation and grazing lands (Williams et al. 2012, p. 42). The extent of such effects will depend on geological conditions (thickness and permeability) and in particular on the degree of hydraulic connectivity and hydraulic gradient (Queensland Water Commission 2012).

Greater understanding of local and regional hydrogeological conditions is needed, including by quantifying the potential for vertical movement of contaminated water between aquifers, particularly between CSG measures and aquifer recharge areas (which may be used to dispose of PW) and aquifers used for drinking water, livestock and irrigation (Chapter 9). Among other things, hydrogeological models need to be developed and validated on an ongoing basis using reliable, transparent and accessible monitoring data that can be peer-reviewed as well as assessed by regulators as part of operating approvals. A critical use of such models will be in assessing risks more accurately and therefore improving the quality of the information supplied by applicants and the decisions made by regulators.

An example of progress in the development of modelling has been provided by the Queensland Water Commission (2012), which assessed cumulative impacts in the Surat Basin. This assessment concluded, among other things, that the maximum impacts of CSG extraction will occur at different times at different geographic locations, but that such impacts are expected to persist for long periods in the absence of the reinjection of PW.

Because of the complexity of groundwater systems, any modelling of the impacts of CSG extraction must be validated and tested by the ongoing monitoring of local and regional groundwater and surface water systems. At the macro level, care is needed when applying what may be average quantities of PW per well in CSG projects. The National Water Commission (2012b) estimated that relatively wet coals in Qld can generate 126–281 GL/year of PW. The size of this range has implications for how PW treatment and disposal systems are designed and managed.

The total volume of PW generated by CSG projects, particularly from wetter coals, can be large enough to affect local and regional hydrology (for example, Queensland Water Commission 2012). This may require a re-examination of groundwater licensing approvals to determine which use (for example, CSG, agriculture or drinking water) should get priority for groundwater withdrawals. Regional-scale estimates of the withdrawal of groundwater in the Murray Darling Basin from CSG

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[5] www.netl.doe.gov/technologies/pwmis/regs/state/ndakota/index.html.

projects are in the range of 468–914 GL/year (Williams et al. 2012). Even the lower end of this range is large compared with current recharge, estimated at 323 GL/year (Kellett et al. 2003). Current groundwater use is estimated at 549 GL/year (Williams et al. 2012, p. 47), indicating that groundwater in the Basin is already over-allocated. For drier aquifers, such as those in the Sydney Basin, withdrawals of groundwater for CSG extraction will be significantly less and are likely to be within the capacity of the system. For example, the PW for 80 boreholes associated with the Camden gas field has not exceeded 4 ML/year (SCA 2012).

As noted by the Sydney Catchment Authority in its submission to the Planning Assessment Commission on the exploration project proposed by Apex (NSW Planning Assessment Commission, 10 July 2013), the hydrological impacts may be predicted to be small, but assessments should draw on the known effects of longwall mining, which has operated in the catchment for many years. In particular, longwall mining has affected both groundwater quantity and quality, and it is possible that the dewatering of flooded mine workings to increase gas production and depressurisation may also affect groundwater systems and in turn the drinking water catchment (NSW Planning Assessment Commission 2013). The risk, as noted in the Sydney Catchment Authority's own review of CSG, is low, although the lack of data to quantify the risk has supported a precautionary approach to refuse CSG exploration in the catchment.

Cumulative impacts

A key risk not accounted for in any detail is that posed by the cumulative impacts on PW, including its extraction from coal seams and subsequent reuse or disposal. This is particularly relevant where CSG operates within connected aquifers, such as in the Great Artesian Basin. There are risks to both water quality and water quantity. Assessing and managing this risk is the role of the National Water Commission, supported by relevant state agencies (where the impacts are within the respective jurisdiction). Such assessment and management must address geographic-scale impacts (e.g. site, project and catchment) and temporal-scale impacts (e.g. during the production and remediation stages).

Both NSW and Qld have identified CSG as a major growth industry and part of their overarching economic development programs. How shorter-term economic benefits should be weighed against possible environmental impacts is an area that needs to be explored as part of a wider review of methods for assessing the risks and viability of the sector and of specific projects.

Reuse and disposal

Reuse and disposal options for PW (including brine) have not been explored adequately in a commercial setting, and nor have they been considered adequately by government as part of holistic urban and regional planning. Business cases that support a sustainable industry for the management and beneficial use of PW are needed. Similarly, there needs to be robust community discussion on future government policy and funding to enable or support the long-term and sustainable management of the sector and its generation of PW.

Cost of cleanup

Make-good and cleanup provisions accompanying approvals may exceed the financial and other resource capacity of CSG companies, particularly in the event of a significant environmental or human health incident. The adequacy or otherwise of bonds, deeds and other financial or contractual obligations, and ultimately the capacity of CSG companies to honour these obligations, and the willingness of government to accept final responsibility, remain key risks, particularly for low-probability and high-consequence or unforeseen events.

Fluctuations in the price of gas may affect the continuity of current CSG projects. Approval conditions need to consider business continuity and the impact of discontinuity on ongoing monitoring and maintenance requirements.

Suggestions arising from this chapter

- Reports by environmental or mining regulators on contamination events must be made publically accessible as soon as practicable.
- A biennial summary of non-compliance (including pollution) issues should be prepared by an independent government agency and inform the ongoing review of policy and practice of the coal seam gas sector.
- Investigate the importance of unintended gas migration as a possible pathway for groundwater contamination by produced water in the major coal seam gas areas in NSW
- Consider the establishment of a national well integrity monitoring and testing program to determine the performance and long term condition of wells related to their use, construction and maintenance.
- Adopt a national risk based approach to managing the on and off shore seismic impacts of petroleum and gas projects
- Develop local and regional groundwater models to assess the temporal and spatial impacts of coal seam gas and other activities.

Chapter 9. What are the knowledge gaps/unknowns/research gaps in relation to CSG activities and produced water and solids?

Structure
- Baseline data
- Groundwater quality monitoring frameworks
- Fate of chemicals
- Coal seam/shale gas relationships
- Targeted monitoring
- Groundwater models and longer-term monitoring
- Data accessibility
- Cumulative impacts
- Treatment and disposal
- Well integrity
- Risk assessment
- Suggestions arising from this chapter

Baseline data

There is limited peer-reviewed literature and a lack of publicly accessible data on the environmental impacts of CSG (and shale gas) and the associated produced water. This has been the conclusion of many reports at a catchment scale (e.g. SCA 2012), at a state level (e.g. NSWLC 2012) and for large aquifers such as the Great Artesian Basin (National Water Commission 2012b) and is consistent with international experience (e.g. Jackson et al. 2013a) and other government agencies, such as the United States Environmental Protection Agency (e.g. US EPA 2012a). The paucity of information is likely the result of the following four factors: the recent emergence of the industry; a limited regulatory framework in the initial years of the sector; the short time since amendments to pollution licensing and the requirements to publish monitoring data (NSW EPA 2012); and, for academic research, the high cost of drilling groundwater wells.

While new monitoring programs and research investigations have or are being commissioned or funded by government and industry, increased efforts and coordination are still required. As noted throughout this report, a lack of baseline data and knowledge, such as on groundwater quality and quantity, aquifer dynamics, geological conditions and the fate of chemicals when interacting in these environments, continues to be a major limitation in the development of evidence-based policy and regulation, the informed applications of proponents, and the evaluation of the impacts of contamination events.

Past monitoring by government and public water authorities not yet in the public domain, and data collected by industry (which may currently be held ‘in confidence’), need to be collated and independently reviewed. This would be most effective if done in an atmosphere of increasing trust and transparency (aimed at both government and industry) and with an explicit aim of determining baseline environmental conditions and developing strategic tools (such as models). The voluntary release of data and their independent review is highly preferable to adversarial action initiated, for example, through the courts, and would help increase public confidence.

Groundwater quality monitoring frameworks

The three distinct phases in unconventional gas projects – exploration, production and remediation (Chapter 3) – provides clear opportunities for regulators, industry and independent researchers to monitor, assess and publish results on the hydrogeological and chemical fate and transport of various chemicals over the life cycle of a project. Such data can inform the assessment of the impacts of existing and future projects at the local and regional scales. A number of government agencies have developed hydrological frameworks and monitoring strategies that will assist in developing standard monitoring protocols. From a hydrologic perspective, the Queensland Water Commission (2012) proposes six objectives for a monitoring strategy (Box 9.1).

Box 9.1. Suggested groundwater hydrological strategies for CSG projects (modified from Queensland Water Commission 2012, p. 62–63)

Objective	Purpose
Establish background trends	Monitoring is needed to establish background trends in advance of impacts occurring from water extraction by petroleum tenure holders. Identification of these trends is essential to separate the impact of CSG development from other factors such as climate. Background trends also provide useful insight into the functioning of groundwater systems by enabling development of regional water level and water pressure models
Identify changes in aquifer conditions within and near areas of coal seam gas development	Monitoring is needed in and around existing and developing gas fields to identify, at an early stage, impacts on water pressure and water quality resulting from CSG water extraction. The volume of water produced, and therefore the potential impacts, will be greater for some fields compared with others and the monitoring sites need to be positioned appropriately and installation timed accordingly.
Identify changes in aquifer conditions near critical groundwater use	There are areas where existing groundwater use is concentrated or of critical importance, for example towns in the area that rely heavily on groundwater. Water pressure and water quality monitoring sites need to be located to ensure early understanding of any unexpected impacts on water levels or water pressure propagating toward these areas.
Identify changes in aquifer conditions near springs	In some catchments, springs of high ecological value may be fed by aquifers. A water monitoring program should quantify water pressure in aquifers near springs. There is also a need to improve understanding of how the hydrology of springs relates to the conditions in underlying aquifers.
Improve future groundwater flow modelling	Groundwater flow models are based on a conceptualisation of the hydrogeology of the groundwater flow system. Monitoring needs to provide information that not only improves understanding of the flow systems but also assists in future updates and the calibration of models.
Improve understanding of connectivity between aquifers	The connectivity between coal formations and surrounding aquifers is a key issue. Monitoring is needed at multiple sites, with monitoring points established in multiple geologic units at each of those sites, to improve knowledge about connectivity.

From the perspective of water quality, Jackson et al. (2013a) suggested a program to establish solid baseline data on the chemistry of groundwater aquifers that would aid forensic investigations associated with contamination or possible contamination events (Box 9.2). This program would differ from the Qld model (Box 9.1) because it would focus on characterising groundwater quality (including related gases) for the purpose of informing the assessments of contamination or other impacts from unconventional gas extraction.

Box 9.2 Suggested water-quality sampling parameters for groundwater monitoring (Jackson et al. (2013a) p. 504–5).

Minimum screening parameters needed to address the occurrence and source of free and dissolved hydrocarbons in groundwater samples: • dissolved methane, ethane and BTEX concentrations; • stable isotope analysis of carbon and hydrogen in both free and dissolved methane; • stable isotope analysis of carbon in both free and dissolved ethane; • fixed gases (including argon) and hydrocarbon gas chromatography of samples containing dissolved methane and ethane concentrations above a predetermined threshold or in free gas samples; • charge-balanced major ion analyses; • parameters useful for identifying the redox state of shallow groundwater samples; and • routine monitoring, sampling and analysis of gases derived from the headspace of water wells.
Additional parameters for forensic investigations designed to address impacts from potential point sources on shallow groundwater: • volatile organic compounds (including benzene, toluene, ethylbenzene, *o*-xylenes, *m*-xylenes, *p*-xylenes, 1,2,4, and 1,3,5- trimethylbenzenes) and semi-volatile organic compound analysis using standard GC/MS methods; • stable isotope analyses of hydrogen and oxygen in water; • stable isotope analysis of carbon in dissolved inorganic carbon; • fixed (including argon) and hydrocarbon gas chromatography; • stable isotope analysis of carbon in methane, ethane, propane, butane and CO_2; • stable isotope analysis of hydrogen in methane; and • BTEX compounds (i.e. benzene, toluene, ethylbenzene, o-xylenes, m-xylenes, p-xylenes, 1,2,4, and 1,3,5trimethylbenzenes) using standard GC/MS methods.

Fate of chemicals

There are few peer-reviewed published studies (and most of those that exist are from North America) related to the groundwater occurrence and fate of the various chemicals used in shale and CSG projects (Jackson et al. 2013a). More work is needed to describe and quantify the impacts of chemicals such as glycols, amines and corrosion inhibitors used by the industry for hydraulic fracturing and other purposes and their fates in deep and oxygen-limited environments. Such research could inform future regulation and best-practice guidelines on the permissibility of certain chemicals and their allowable concentrations and locations of use.

The United States Environmental Protection Agency is undertaking investigations in relation to the impacts of hydraulic fracturing, focusing largely on unconventional gas extraction from shale gas reserves (US EPA 2011a), but the results are not expected until 2014. Given the differing geological and hydrological conditions in Australia in which CSG projects may take place, similar studies should be undertaken as industry–regulator–academic partnerships across a range of locations and geophysical environments, including wet and dry coals, deeper and shallower coal reserves and locations near critical groundwater systems (such as drinking water catchments).

Coal seam/shale gas relationships

The extraction of CSG shares many similarities with shale gas extraction in the methods of exploration, production and remediation, but there are also significant differences that relate to specific hydrogeological conditions. With limited peer-reviewed and government research into CSG in an Australian context, it is necessary to draw on related research to inform discussions on environmental impacts and risks. A deeper understanding of the similarities and differences between coal seam and shale gas activities should inform technical and scientific understanding and processes. Equally importance is the need to separate ‘fact from fiction’: on the one hand, opponents of the industry cite examples of contamination from shale gas production that may have no physical or technical relevance, and, on the other, the industry emphasizes the differences to avoid or minimize comparisons.

Targeted monitoring

Monitoring and related investigations should include an examination of chemicals considered to be a threat to the environment and public health, as well as of chemicals that serve as tracers or indicators of produced water and how it moves within and between groundwater systems. Such monitoring and research should focus on CSG projects in close proximity to urban areas and that may affect known drinking, irrigation and stock groundwater reserves.

The safety of CSG extraction in drinking water catchments is a critical area of public discourse and decision-making. As evidenced by the 1998 'outbreak' of *Cryptosporidium* in Sydney's water supply, any pollution of drinking water catchments related to CSG extraction could invoke a significant public concerns about public health and reduce confidence in the CSG industry. In this context, obtaining a greater understanding of the impacts on ground and surface water systems of mining generally and specifically of the produced water generated by CSG projects is critical.

Geological faults and other anomalies that may facilitate vertical exchange between aquifers as a result of hydraulic fracturing (natural or artificial) should be monitored at a project level as part of broader seismic studies, particularly given the proximity of many coal seams to drinking water aquifers. Such studies should seek to differentiate the impacts of local and regional subsidence and enhanced faults in the rock strata that may influence surface and groundwater exchange.

The current policy of the NSW Government to ban CSG extraction based on geography and land use (e.g. in south-west Sydney within 2 km of residential land, and near Broke, which has an important viticulture industry) should be supported by evidence-based science that determines the risk to the environment and public health in each case. The NSW Government has seemingly adopted a precautionary (and possibly political) approach, which has the potential to create a precedent in which an industry is effectively banned from certain areas, even though it may not have a higher risk profile than other types of mining or industrial activity. In this context, location-specific policy that considers, among other matters, the type of coal (wet or dry), its position relative to groundwater aquifers, whether hydraulic fracturing is to be employed under the proposal, and how produced water would be treated and disposed, should inform approval processes and licensing. This would be highly preferable to an approach that draws on inappropriate analogies from mining practices that may have limited applicability and transference of risks.

The presence of elevated levels of methane gas in drinking water aquifers near shale gas wells is becoming well established (Warner et al. 2012, Jackson et al. 2013a). The risk of gases associated with unconventional gas projects contaminating water supplies requires further monitoring in a range of geological conditions, particularly in the relatively shallow coal reserves that occur in Australia. The risk should also be considered in the context of environmental and health guidelines.

Groundwater models and longer-term monitoring

There is a lack of development, review and ongoing assessment of underground water models. To ensure public confidence, such modelling should be funded and undertaken at arm's length from CSG operators and be subject to peer-review publication. The development of groundwater models should be integrated with regional modelling undertaken by government, such as for the Great Artesian Basin, and water authorities should also undertake locally based modelling.

Models must be validated by long-term monitoring programs that combine a range of data sources, including data collected by industry as part of its regulatory requirements and through government-funded monitoring.

The potential for groundwater recharge under various climate-change scenarios should also be examined, because changes in rain and surface and subsurface flows are likely to have an impact on produced water volumes.

Data accessibility

A centralised system for monitoring data and water-quality models needs to be established and maintained by an independent government agency. This should include data on water quality and quantity, as well as data on, for example, pollution incidents, work health and safety, pipeline performance, well integrity and validation, and the performance of contractors, including well-drilling and auditing/inspection companies. The United States Geological Survey (USGS 2013b) presents an example of the type of approach that might be undertaken. The USGS keeps a publically accessible database of 58,707 historical records which can be downloaded by state, or the whole database for the United States, in ASCII or Microsoft Access database format. Locational and ownership data are reported, as are the parameters pH, charge balance, mass balance and concentrations of bicarbonate, calcium, chloride, magnesium, potassium, sodium, sulfate and TDS. The strength of these data for comparison with elsewhere, for design of drilling fluids, planning casing/concrete longevity, treatment methods, budgeting for the cost of brine disposal and so on is substantial. For example, TDS concentrations of the whole USGS database have an arithmetic mean of 86,000 mg/L and a maximum of 399,000 mg/L. With this information, produced water managers could budget for costs of membrane replacements and power costs in reverse osmosis plants, and the cost of brine disposal. This historical database would benefit enormously with updating using newer data from the last 35 years. Australian produced water generators now routinely have multi-element data collected from the inductively coupled plasma group of instruments (e.g. ICP-AES, HR-ICP-MS) which, together with determinations of total petroleum hydrocarbons and selected organic compounds, could be used to create a database far superior to the archival data presently in the USGS (2013b). In Australia, the peak body for geoscience data capture and archival is supposed to be Geoscience Australia, but a search of their website revealed no produced water data. If Geoscience Australia is unwilling or unable to collate the data and make it publically available, then a responsible NSW Government Department or Office would be a logical repository for NSW data.

Cumulative impacts

There are few studies on the cumulative impacts of CSG activities on environmental and human health. Such studies are particularly important where extraction will or is occurring within regional-scale linked coal (and hydrological) basins by one or more operators and where current extractions of groundwater occur for domestic, stock or irrigation purposes. The need for studies on cumulative effects links with the need for greater understanding of the connectivity of groundwater systems, particularly where the volume of produced water is high and may (in combination with other extractions) approach the rate of natural recharge.

Investigations into the cumulative effects of the use of produced water for irrigation are also needed. They should consider the accumulation of chemicals in the soil, surface and near-surface movement, and the implications for stream water quality, ecology and function.

Treatment and disposal

The management of suitable treatment and disposal options for produced water requires ongoing testing and validation of the efficacy of treatments and how residuals are subsequently disposed of (Chapter 4). This is particularly relevant in regions that produce significant amounts of produced water (such as wet-coal environments), where many CSG projects are in production (using and generating significant quantities of produced water that can impact on local water resources), and for facilities that have previously relied on evaporation ponds and other surface containments that represent a higher risk of surfacewater contamination (Chapters 6 and 8).

The use of aquifer injection as a disposal option requires further monitoring and modelling, particularly in environments where vertical exchanges between aquifers are known to happen, even if measured over tens to hundreds of years. This issue is particularly relevant to the aquifers of the Great Artesian Basin. The likelihood of future coal and CSG projects needs to be considered in any aquifer injection program, because disposal from one operation may cause problems for future mining endeavours. In this respect, a medium-term to long-term plan for mining and its potential in a specific area and groundwater system should be required as part of any approval or licensing arrangement.

The monitoring of aquifer injection programs must draw on international experience. Although the literature is currently limited, such monitoring is a focus of the United States Environmental Protection Agency (US EPA 2012a).

Well integrity

Breaches in the integrity of wells, including in concreting and casings, are among the more important aquifer contamination pathways (Chapter 8). Ongoing research on the specifications and techniques for, and long-term integrity of, concreting is essential to improve industry performance as well as public confidence in this practice. Existing wells must be monitored if there is to be a commitment to continuous improvement in well design, installation and maintenance. Performance data should be peer-reviewed and, where possible, the industry and independent research organisations should collaborate to share the costs of drilling and monitoring.

Risk assessment

An inclusive risk assessment process should be established by the NSW Government to identify and (where possible) quantify the risks, including consequence and likelihood. Stochastic modelling should be used to assess the risk profile, drawing on relevant national and international experience related to a broad range of produced water and on-shore gas industries.

Suggestions arising from this chapter

- Improve baseline water quality and quantity data collection and guidelines for data collection and analysis.
- Undertake targeted monitoring to determine the possible impacts of coal seam gas and produced water for higher risk areas such as drinking water catchments, key agricultural lands and near residential areas.
- Develop protocols and independent testing and validation schemes to assess the integrity of wells over their entire life cycle.

- Examine the impact of coal seam gas activities related to seismic activity and enhancing natural faults.
- Develop local and regional scale groundwater models that can consider project and cumulative impacts across spatial and temporal scales.
- Quantify the fate of chemicals used in well construction, maintenance and hydraulic fracturing.
- Undertake a review of the applicability and transferability of the environmental impacts and regulatory response to shale gas activities with coal seam gas operations in Australia.
- Review the long term applicability of produced water treatment systems and disposal methods.
- Establish an accessible portal for monitoring data related to coal seam gas activities including water quality and quantity, geological conditions, pollution incidents, pipeline performance and well integrity. The NSW Government should support independent review and publication of findings that in turn should inform a culture of best practice in policy, regulation, industry practice and community engagement.

Chapter 10. Any other comment you believe relevant to the understanding or management of these issues.

Structure

- Integrity of drilling
  - Quantity of wells and continuous improvement
  - Directional drilling
- Groundwater ecosystems
- Data sharing and accessibility
- Clarification of terminology and understanding of risk

Integrity of drilling

Quantity of wells

The mining, agricultural and water sectors drill hundreds of wells per year. This frequent and repetitive activity can enable the industry to implement a program of performance monitoring and continuous improvement (MIT 2011). Such a program could cover site preparation, well construction, monitoring, production (including hydraulic fracturing) and remediation. Requiring drilling operators to contribute data to a central repository on the performance of their wells and other data, such as on the construction, location and geology of the wells, and who was involved in developing them (such as the drilling company, operator and monitoring company) can help industry practice and assist in regulatory oversight.

Directional drilling

The exploration and production of unconventional gas reserves are likely to increase the use of directional drilling techniques. The available literature, including that reviewed in this study, focuses on the integrity of vertical wells, suggesting that performance monitoring of directional drilling wells is lacking. More such monitoring is needed, therefore, and should include how casings, concrete and other protection measures withstand various pressures (vertical and horizontal), how subsidence within a coal seam may impact on well integrity, and whether the combination of horizontal and vertical wells changes the probability that produced water will migrate to near-surface aquifers.

Groundwater ecosystems

Most stygofauna are invertebrates, mainly crustaceans, that live in groundwater ecosystems. They are little described in comparison with surface or other aquatic fauna, and while their habitats are well understood, their distribution and importance are not. However, preliminary work suggests substantial complexity and diversity (Cosmos 2009). There has been a recent discovery of three new species of stygofauna in the groundwater of the Pilliga State Forest in northeastern NSW (Australian Geographic 2013) indicating that much remains to be learnt about these fauna (Bradford et al. 2009). Stygofauna have a variety of values: they have intrinsic value (as all species have a right to exist), they contribute to biodiversity and ecosystem processes, and they are an indicator of water quality. However we have little idea as to their role in maintaining groundwater quality, or their role in nutrient fluxes and other ecosystem services. They may even contribute to future option values for humanity, such as genetic resources or pharmaceuticals. Additional basic research, including inventory, on stygofauna is urgently required. The main barriers to this happening are a lack of scientists trained in stygofaunal taxonomy and ecology, and inadequate recognition by companies and regulators of the actual and potential importance of stygofauna.

Data sharing and accessibility

A publically accessible online database should be developed for the monitoring of groundwater and surface water during all aquifer interference activities (as defined by the NSW Aquifer Interference Policy 2012), including those that require licensing by the NSW Environment Protection Authority and planning or mining approval. Similar schemes are currently operated by the US Geological Survey (USGS 2013) and in Texas (Burnett 2009), although the quantity and particularly the quality of data could be improved.

Clarification of terminology and understanding of risk

Apart from the specific environmental issues associated with produced water, there is a general problem associated with key terms used in the CSG and shale gas industries. A qualitative study of 16 representatives of state and federal agencies, academia, industry, environmental groups and community-based organizations in the United States found that there was general disagreement about the meaning of the term fraccing (Cooley & Donnelly 2012). This finding is similar to those of other researchers, who have also found that industry representatives tend to have a narrow definition of the term, referring to the process by which fluids are injected into a wellbore, while community groups and environmental activists tend to have broader definitions that encompass well construction and completion, the hydraulic fracturing process, and well production and closure (Cooley & Donnelly 2012, US EPA 2011, ProPublica 2012).

Cooley and Donnelly (2012) reported that spills and leaks were the most commonly cited concerns about hydraulic fracturing, with the management (including treatment) of wastewater (that would incorporate produced water and water withdrawals), particularly in arid regions, the other most cited environmental issues. Notably, less than one-third of interviewees specifically identified chemical use and the associated risks of groundwater contamination as a key issue (p. 14).

More broadly, a key issue that seems to underline much of the environmental discourse on the impacts and acceptability of unconventional on-shore gas projects is the lack of social approval for projects, or what House (2013) has termed their 'social licence to operate'. In many respects, this lack of social approval reflects a mutual lack of confidence and trust between the three major stakeholders: industry, regulators and the community. Implicit in the tension between these stakeholders is a failure by:

- industry to prove their claim that their activities do not cause environmental harm;
- government to ensure that environmental and planning regulations are proactive (and not continually trying to catch up with the rapid expansion of the industry); and
- the community to differentiate between the substantiated and unsubstantiated impacts of related activities, especially in light of significant differences in the physical conditions, operating and regulatory environments and standards and practices of industries that may have little bearing on the project they are opposing.

To improve community engagement on, and understanding of, CSG in NSW, there is a need to clarify language and terminology, explain the risks (in terms of certainty) based on independent and reputable science, and proactively discuss which studies and incidents may be relevant in specific cases (and why).

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