# Coal Seam Gas: Produced Water and Solids

Prepared for the Office of the NSW Chief Scientist and Engineer (OCSE)

Never Stand Still | Faculty of Engineering | School of Civil & Environmental Engineering

**Date: 28 May, 2014.**
Modified from original report of: 22 November, 2013.

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# Executive Summary

This background paper was prepared for the Office of the NSW Chief Scientist and Engineer (OCSE) to provide information and a discussion about produced water in relation to coal seam gas (CSG) activities. The purpose is to provide an overview of the key issues associated with produced water and solids in relation to CSG activities.

Coal seams contain both methane and water. In order to recover the methane (known as CSG), much of the water must usually be pumped out, and the coal seam aquifer depressurised. This water, known as ‘produced water’, is therefore a by-product of CSG production. The largest volumes of produced water tend to be recovered during the early stages of CSG production, decreasing exponentially over time. In the later years of gas production, very little water may be produced.

The compositional characteristics of produced water may be highly variable between coal seam basins, and even between individual wells within a basin. However, high concentrations of total dissolved solids (TDS), composed of a variety of mainly inorganic substances (e.g. sodium, bicarbonate, carbonate, chloride, etc) are generally characteristic. Such high salinity solutions can have significant detrimental impacts if discharged to freshwater streams or rivers. Furthermore, high salinity solutions, particularly those dominated by sodium (rather than calcium or magnesium) salts can severely impact soils if used for irrigation. Long-term use of such high salinity soils can disrupt soil physical structure, impeding drainage and limiting the agricultural suitability of impacted areas.

There are a variety of approaches available for the management of produced water and these may generally be categorised as either ‘disposal’ or ‘beneficial use’. A common means of disposal has traditionally been by the use of evaporation ponds. Today this practice is strongly discouraged or banned, as it is in Queensland and New South Wales. As an alternative means of disposal, there is currently significant interest in deep-well injection of either the produced water, or of concentrated produced water brines.

In general, beneficial use of produced water is now strongly preferred to disposal and a wide variety of applications are available under suitable circumstances. These include surface water discharge or in-stream flow augmentation, agricultural use (e.g. crop irrigation, livestock watering), on-site industrial use during CSG activities (e.g. dust control, hydraulic fracturing, drilling water, fire protection), off-site industrial use and potable use (i.e., augmentation of drinking water supplies).

For many beneficial use applications, and even for some types of disposal, some treatment of the produced waters will be required. There are a range of important approaches to produced water treatment. These include pH adjustment, granular filtration, membrane filtration (including reverse osmosis), adsorption and ion exchange. Some of these processes can produce high quality water, but also produce a concentrated waste stream (brine), which itself requires either disposal or further treatment for beneficial use. Few suitable brine disposal options are currently available, other than deep-well injection to aquifers assessed to be hydraulically isolated from important fresh groundwater resources. As a consequence, produced water brines are currently being stored in ponds and lagoons at a number of sites in Australia, while more permanent management solutions are being assessed.

Further treatment of concentrated waste streams to the point of ‘zero liquid discharge’ is of great interest, but continues to face a number of obstacles, primarily in terms of energy-requirements and associated operational costs. Commercial recovery of some of the major salts from the brine, such as sodium bicarbonate, has been proposed but not yet realised in Australia. Until such opportunities become available, crystallised salts will require disposal, predominantly by landfill.

The surface management of produced water, whether it involves treatment, storage, transport, disposal or beneficial use, creates opportunities for accidental release and environmental risks. A number of examples of incidents related to produced water are described in this report. Furthermore, a range of ‘worst case scenarios’ or incidents that could occur during these management stages are described as a means of stimulating what should be a key step of risk assessment and risk management.

Existing frameworks for risk assessment and risk management are described in this report, including their potential application to produced water. These frameworks draw largely from experience within the Australian water and chemical industries and, it is argued, greater harmonisation of the CSG industry with the risk management practices of these industries is warranted. The value of undertaking ‘baseline monitoring’ for produced water and salts management is identified as an important means for retrospective assessment of future impacts.

A number of knowledge gaps are identified towards the end of the report. These are areas where additional research could provide significant improvements to current practice. They encompass a range of technical concerns (water quality characterisation, treatment processes, disposal practices), regulatory concerns (risk management, best practices), and social concerns (social impacts, public acceptance, commercial opportunities).

This report deals predominantly with technical issues related to produced water. However, a brief reminder is provided at the end of the report that a number of other issues will likely be of equal importance in decisions about the management of produced water. These include issues related to cost, carbon footprint, and social concerns.

The appropriate management of produced water presents significant environmental, social, technical and economic challenges for Australian energy companies and regulators. However, if these challenges can be properly addressed, the management of produced water as a resource presents significant opportunities for Australian environments, industry, and communities.

# Errata and modifications

An earlier version of this report was published on the website of the Office of NSW Chief Scientist and Engineer with a report date of 22 November, 2013. Since then, a number of comments were received from stakeholders and some modifications have been made in response. These modifications are summarised below.

| **Location** | **Modification** |
|---|---|
| Page 7 | Reference to "*the Australian water industry*" has been changed to "*the Australian water and chemical industries*". |
| Page 12 | Previous text indicated that the Water Management Act 2000 exclusively defined mining to be mining, mineral exploration, and petroleum exploration, and therefore it did not apply to petroleum production as per statutory construction. This text has been removed and replaced with text to indicate that "*Produced water generated during CSG production in NSW has to be managed in accordance with National Water Initiative (NWI) principles (Council of Australian Governments (COAG), 2004)*". |
| Page 11 | Indicative salt production calculations for the Santos' Bibblewindi Gas Exploration Pilot Expansion project (Gunnedah Basin, NSW) were revised. Previously an assumed salt concentration of 2,500 mg/L was used and this was revised to a more typical (for that basin) 18,000 mg/L. |
| Pages 14-18 | Various facts and figures relating to the operation of existing NSW CSG activities were reconfirmed and corrected. |
| Page 16 | Previous text indicated that Santos' Leewood produced water treatment facility was completed and operational. This has been revised to state that the facility is currently under construction and it is intended that this plant will be operational during 2014. A short paragraph on the potential use of evaporation ponds at this site has been deleted (The NSW Government has imposed a ban on the use of ponds for CSG produced water evaporation and Santos have confirmed that they have no intention to use evaporation ponds at this site). The remaining term "*evaporation ponds*" has been modified to "*holding ponds*" to properly reflect their purpose. |
| Page 22 | In order to reflect changes to the Australian Drinking Water Guidelines made subsequent to the initial release of this document, the reference to benzene as a drinking water contaminant has been modified to state "*The Australian Drinking Water Guidelines provide a health-based guideline value for benzene of 0.001 mg/L, derived from a calculated excess lifetime cancer risk of one in 1 million people*". |
| Page 30 | In reference to the use of the Theis equation, the text has been changed from "*Using these established relationships…*" to "*Using sophisticated corporate models based on these established relationships…*". The paragraph immediately following the presentation of the Theis equation has now been modified to make it clear that "drawdown" refers to pressure drawdown, not drawdown of water table height. |
| Page 36 | The text has been modified by replacing "*In NSW, reinjection will require an aquifer interference approval under section 91 of the Water Management Act 2000 (NSW)*" by "*In NSW, reinjection will require approval by the appropriate planning authority, having regard to the Aquifer Interference Policy.*" |
| Page 51 | The paragraph referring to the suitability of the Australian Drinking Water Guidelines for assessment of risks from potable use of CSG water has now been modified to the following form: "*Potable use generally requires a very high level of water treatment and water quality. The Australian Drinking Water Guidelines describe minimum qualities that would need to be achieved in order to be suitable as a drinking water supply. While the guidelines apply to a wide range of drinking water sources, the risk management approach on which they are based requires a detailed system analysis to identify specific hazards (and events) that can compromise drinking water quality. Since coal seam gas produced water is an unconventional drinking water source, it would be prudent to consider additional water quality measures, beyond the current set of water quality guideline values, to ensure suitable water quality for drinking.*" |
| Page 53 | The term "*international incidents*" has now been replaced with "*incidents in countries other than Australia*". The text in this section has been rearranged and the following sentence has been added: "*Notably, this incident related to produced water from* |

| | |
|---|---|
| | *conventional oil and gas recovery, which is commonly highly contaminated and reinjected into extraction wells for disposal*". |
| Page 55 | Text relating to the issue of Directions to comply with conditions of petroleum title has been deleted since the authors have been unable to confirm that it is directly related to the incident described in this section of the report. The following sentences have been added: "*The Office of Coal Seam Gas has commented that Metgasco is 'blameless in this matter'*" and "*Subsequent to the event the NSW Office of Water/NSW Environmental Protection Authority authorised the disposal of a further 5ML of produced water in the same plant.*" |

# Overview of CSG Produced Water

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?

Methane is formed in coal seams from one of two processes dependent on temperature and depth: thermogenesis or microbial methanogenesis (National Research Council, 2010). Thermogenesis involves thermal degradation of organic matter, usually at temperatures greater than 120 °C, predominantly at high pressures associated with burial at depths greater than around 300 m. Microbial methanogenesis occurs from the decay of organic matter by microbial activity but at lower temperatures and less shallow depths than thermogenesis. Commercially accessible coal seams in Australia tend to be at depths of between 200 m - 1000 m (Geoscience Australia & ABARE, 2010).

In addition to the formation of methane, compaction and heating of organic material in coal seams leads to the development of systematic fractures or ‘cleats’ in the coal. The space in these cleats is commonly filled with a mixture of water and methane gas. The water may have been present when the organic material of the coal seam was originally deposited (known as ‘connate’ water), or later percolated from the surface through to the coal seam as it was progressively compacted.

Since methane is only partially soluble in water, and is relatively hydrophobic, the majority of the methane tends to be in a gaseous form, adsorbed to the coal surfaces within the cleats and held in place by the pressure of the water in the cleats (hydraulic head). To extract this adsorbed methane, the water must be first pumped out of the coal seam to reduce the water pressure. When doing so, the methane is desorbed, coalesces to form larger gas bubbles, and can be withdrawn from the coal seam with the water. This process is known as ‘co-production’, referring to the combined production of CSG and produced water. Produced water is also known as co-produced water and formation water. The Queensland Government uses the term CSG water.

A conceptual illustration of the co-production of produced water during CSG production is presented in Figure 1. Cleats are shown within the coal seam, containing a mixture of water (blue matrix) and methane gas (white dots). Water is pumped from the coal seam via a well, thus reducing the head-pressure in the coal seam and enabling methane to desorb from the coal surfaces and flow freely up the well bore. Water and methane may flow through separate pipes to the surface, and/or methane may be separated from the water via a gas/water separator vessel at the wellhead.

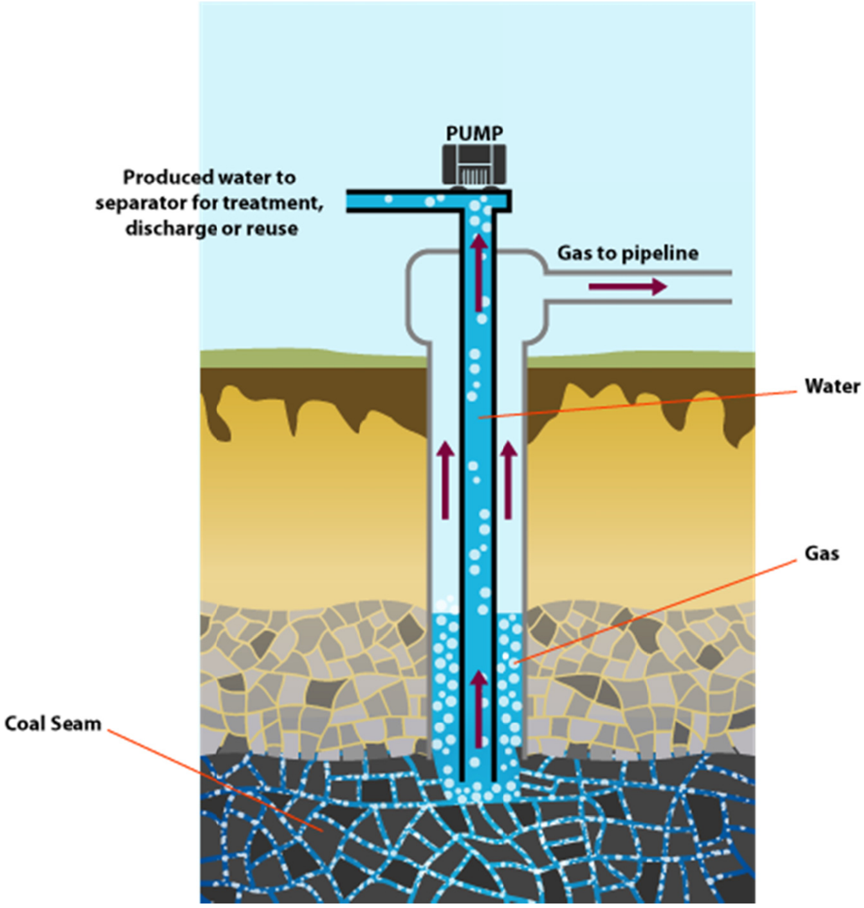

**Figure 1 Co-production of produced water during CSG extraction**

The volume of water that must be withdrawn from the coal seam in order to release methane is dependent upon a number of factors. These include the original water pressure in the coal, the physical capacity of the coal to hold and release water, and the extent to which the coal may be hydraulically connected to adjacent geological formations (National Research Council, 2010).

Produced water volumes are expected to increase substantially in Australia over the next 2-3 decades. By the end of that time period, total production was recently projected to average over 300 GL/year from known reserves (RPS Australia East, 2011). To put that in perspective, the entire area served by Sydney Water (Sydney, the Blue Mountains and the Illawarra) consumed 480 GL of potable water in 2012.

Given the high total dissolved solids (TDS) concentrations of produced water, management of this water will also require management of significant amounts of inorganic salts. According to an assessment by the Queensland Government, and assuming an average salinity of 2500 mg/L, the (2009) expected annual production rate of 25 gigalitres (GL) of produced water in the Surat Basin, would generate 62 500 tonnes of salt per year. Over a 30-year period, this amounts to 1.8 million tonnes of salt (Department of Infrastructure and Planning, 2009). The assessment noted that if the industry expands further this amount of salt would, of course, increase.

The recently approved environmental impact statement (EIS) for Santos' Bibblewindi Gas Exploration Pilot Expansion project (Gunnedah Basin, NSW), provided estimates of cumulative pilot extraction rates as shown in Table 1. Applying an average salinity of 18,000 mg/L, indicates that these pilot operations alone have the capacity to produce around 35 tonnes of salt per day during peak water production and more than 24 tonnes per day on average over the 3 year operational period.

**Table 1 Estimated cumulative extraction for Santos appraisal in Gunnedah Basin (RPS, 2013)**

| Pilot | Max extraction (kL/day) | Average extraction (kL/day) |
|---|---|---|
| Dewhurst 13-18 | 397 | 302 |
| Dewhurst 22-25 | 273 | 260 |
| Dewhurst 26-31 | 448 | 378 |
| Bibblewindi Multi-Lateral | 581 | 260 |
| Bibblewindi West | 209 | 85 |
| Tintsfield 2-7 | 43 | 23 |
| TOTAL | 1951 | 1308 |

Unfortunately, the volume of produced water from any site represents a somewhat transient local water boom as it is only available for the duration of a CSG project and most is produced in the early stages of production. Each CSG well has an expected 5-20 year life span, and a typical CSG to Liquefied Natural Gas (LNG) project with multiple supply wells may have a 25-35 year production time (RPS Australia East, 2011). Furthermore, water production from each well decreases exponentially over the operational life of the well, so the main supply point will move with the development of new wells.

In NSW, Section 60I of the Water Management (General) Regulation 2011 requires the acquisition of a water access licence for mining activities that involve the extraction of more than 3 ML of water (Parliament of NSW, 2000). Produced water generated during CSG production in NSW has to be managed in accordance with National Water Initiative (NWI) principles (Council of Australian Governments (COAG), 2004). The NWI principles are based around the national imperative to increase the productivity and efficiency of Australia’s water use, service rural and urban communities, and ensure the health of river and groundwater systems. The National Water Commission has recently called for all produced water that is made fit for purpose for use by other industries or the environment, to be included in National Water Initiative-compliant water planning and management processes (National Water Commission, 2012).

## Characteristic components of produced water

Because the water in the cleats of the coal seams has been in contact with the hydrocarbon-bearing formation for centuries, it has some of the chemical characteristics of the formation and the hydrocarbon itself. Produced water may include water originally from the coal seam, water injected into the formation (although some authors make a distinction between this ‘flow back water’ and produced water), and any chemicals added during the drilling, CSG production, and later treatment processes.

The physical and chemical properties of produced water vary considerably depending on the geographic location of the gasfield and the geological formation from which it comes. Produced water properties may also vary throughout the lifetime of a CSG project since coal seams are heterogeneous and may have pockets of variable salinity associated water.

### Salt content

Salt content (‘salinity’) can be expressed as total dissolved solids, typically in milligrams per litre (mg/L), or electrical conductivity in microSiemens per cm (µS/cm). The salt content in produced water varies widely, from nearly freshwater (10-500 mg/L) to salt levels up to ten times higher than seawater (300,000 mg/L). Lower concentrations tend to be associated with shallow coal seams exposed to recent fresh surface water recharge.

### Oil and grease

The term ‘oil and grease’ refers to a common test method that measures many types of organic chemicals that collectively lend an ‘oily’ property to the water.

## Various inorganic and organic chemicals

Many inorganic and organic chemicals that are found naturally in the formation may be transferred to the produced water through long-term contact with the hydrocarbon. The presence of specific chemicals and the concentrations of those chemicals vary widely among different produced water samples. Naturally occurring substances that have been found in hydrocarbon-containing formations include trace elements such as mercury, arsenic and lead. A very wide range of naturally occurring organic chemicals can be expected, including organic acids and polyaromatic hydrocarbons. Much attention has been paid to the semi-volatile organic chemicals, benzene, toluene, ethylbenzene, and xylenes (collectively known as 'BTEX').

## Naturally occurring radioactive material

In some locations, radioisotopes such as radium, thorium and uranium may be present in CSG formations. Low levels of this radioactivity can be transferred into produced water. Generally, the radiation levels in produced water are very low and are not considered to pose a significant risk.

## Chemical constituents of drilling and fracking fluids

Drilling and fracking fluids may contain a wide range of chemical constituents and these often vary from one operation to another. A brief summary of fracking solution components and their intended purpose is provided in Table 2, adapted from the US EPA (2011).

**Table 2 Components that may be included in some fracking solutions (US EPA, 2011).**

| Component/Additive Type | Purpose | Example compound(s) |
|---|---|---|
| Proppant | Keep fractures open to allow gas flow out | Silica, quartz sand |
| Acid | Dissolve materials, initiate cracks in the rock | Hydrochloric acid |
| Friction reducer | Minimise friction between fluid and the pipe | Polyacrylamide, mineral oil |
| Surfactant | Increase the viscosity of the fluid | Isopropanol |
| Potassium chloride | Create a brine carrier fluid | |
| Gelling agent | Thickens the fluid to suspend the proppant | Guar gum, hydroxyethyl cellulose |
| Scale inhibitor | Prevent scale deposits in the pipe. | Ethylene glycol |
| pH adjusting agent | Maintain the effectiveness of other components | Sodium or potassium carbonate |
| Breaker | Allow delayed breakdown of the gel | Ammonium persulfate |
| Crosslinker | Maintain fluid viscosity as temperature increases | Borate salts |
| Iron control | Prevent precipitation of metal oxides | Citric acid |
| Corrosion inhibitor | Prevent pipe corrosion | N,N-dimethylformamide |
| Biocide | Eliminate bacteria | Glutaraldehyde |

Chronic human toxicity has been associated with a number of common fracking fluid constituents, such as ethylene glycol, glutaraldehyde and N,N-dimethyl formamide.

Under the NSW Code of Practice for Coal Seam Gas Fracture Stimulation Activities, gas companies are required to prepare a Fracture Stimulation Management Plan that must list (Investment, 2012):

- All chemicals to be injected as part of the fracture stimulation process;
- The Chemical Abstract Service (CAS) registry number for those chemicals;
- The volumes and concentrations of those chemicals;
- Potential risks to human health arising from exposure to those chemicals;

- The risk, likelihood and consequence of surface spills of these chemicals;
- Whether chemical concentrations at the point of injection will exceed:
    - ANZECC 2000 guidelines for overlying groundwater and surface water uses that may be affected;
    - ADWG [2011] if a drinking water supply may be affected;
    - natural background concentrations if the water source is not effectively described by ANZECC or ADWG guidelines; or
    - if the chemical is not specified in ANZECC or ADWG guidelines and may have a toxic effect, then assess whether the toxic effect is likely to exceed a trigger toxicity level determined in accordance with a suitable methodology such as those described in Section 2: OECD Guidelines for the Testing of Chemicals.
- The risk, likelihood and consequence of the injected chemicals affecting the beneficial use class of the target aquifer or any other aquifer;
- How those chemicals will be stored and managed.

As a consequence of these requirements, detailed identification and assessment of chemical substances used in fracking fluids in NSW is expected to be available for all future operations.

## Coal seam gas activity in NSW

Significant CSG resources exist in the major coal basins of eastern Australia and are being developed for domestic use and potential export. More than 90% of eastern Australia's CSG is found in the Bowen and Surat basins in Queensland. The remainder is predominantly located in NSW basins including the Gunnedah basin (2%), Clarence-Morton basin (2%), Gloucester basin (1%) and the Sydney basin (<1%) (Geoscience Australia & ABARE, 2010). Although reliable data is currently lacking, there is widespread industry belief in the existence of additional large CSG reserves including in the Galilee basin (QLD).

While CSG production is well established in the Bowen and Surat basins in Queensland, there are few commercial CSG operations in NSW. Examples of the significant projects in operation or under development are provided below in order to provide some context regarding the volumes and characteristics of produced waters requiring management and/or disposal.

### AGL's Camden Gas Project

AGL's Camden Gas Project is located approximately 60 km south west of Sydney, in the Southern Coalfields of the Sydney Basin. Commercial gas production began in 2001 and currently the Camden Gas Project is NSW's only commercial CSG operation. The Camden Gas Project currently supplies approximately 5 per cent of NSW's gas needs (equivalent to 265,000 homes) (AGL, 2013a). The Camden Gas Project consists of 144 gas wells and of these 89 are currently producing gas (including 31 horizontal wells). In February 2013, plans to drill another 66 wells to the north (Northern Expansion) were suspended following strong community and government opposition (Manning *et al.*, 2013).

In the 2012 financial year, the Camden Gas Project produced less than 4.8 megalitres (ML) of water (less than two Olympic sized swimming pools) (AGL, 2013c). According to AGL, many existing wells have now stopped producing water (AGL, 2013d). The produced water is transferred using an automatic dump valve from the wellhead separators into lined drill pits or typical farm water tanks at each well site (AGL, 2012b). The risk of flooding is managed with bunding around drill pits and by monitoring of water levels and water quality.

Left untreated, the produced water is considered too saline to be used beneficially. The salinity of the produced water ranges between 7,000–15,000 µS/cm. The pH ranges from neutral to alkaline (7–8.5). Low levels of heavy metals are typically present. The produced water is either used for future drilling operations or is transported to the Rosalind Park Gas plant for treatment and storage in a holding dam. The treated water is then sent to a licensed water treatment and recycling facility. At the recycling facility, the treated produced water is mixed with other treated wastewater and may be used beneficially (AGL, 2013c).

**Table 3 Operations and produced water from AGLs Camden Gas**

| | |
|---|---|
| Operator | AGL Gas Production (Camden) Pty Ltd. |
| Location | Sydney basin, NSW. |
| Status | Production began in 2001 [1] |
| Production level | Approximately 5% of NSW's gas needs [1]. |
| Number of wells | 144 (89 producing gas) [1]. |
| Associated Infrastructure | Rosalind Park Gas Plant for water treatment and storage [1]. |
| Produced water | |
| Volume | < 4.8 ML Financial Year 2011-12 [1]<br>Northern expansion likely to produce 'a few' ML/year [3]. |
| Flow rate | Approximately 0.01 ML/day (total for all production wells based on yearly volume) [1]. |
| Conductivity | 7,000–15,000 µS/cm [1] |
| Total Dissolved Solids | Not stated |
| pH | 7–8.5 [1] |
| Impurities | Low levels of heavy metals [1]. |
| Reuse | Subsequent drilling operations [2]. |
| Storage | At well, farm water tanks or lined drill pits [2].<br>Transported to Rosalind Park Gas plant for treatment and storage in a holding dam [1]. |
| Identified risks | Overtopping [2]. |
| Risk mitigation | Bunding around drill pits [2].<br>Monitoring of water level and quality [2]. |
| Treatment | On site at Rosalind Park Gas plant [1, 2].<br>Treatment method not stated. |
| Disposal | Treated water is sent to a licensed water treatment and recycling facility [1]. |
| Beneficial use | Potentially from the recycling facility [1]. |
| Pollution incidents (related to produced water) | |
| 17 May 2011 | Foam and produced water dispersed within 40 m of a well when a workover crew failed to adjust a fully open degasser choke. No significant harm to the environment occurred. The Office of Environment and Heritage issued a warning letter [4]. |
| Pollution penalties (related to produced water) | |
| | None identified. |

[1] AGL (2013c); [2] AGL (2012b); [3] AECOM (2010); [4] Bloem (2011).

## Santos' Narrabri CSG Project

The Narrabri CSG Project produces gas from pilot appraisal at the Bibblewindi, Bohena and Dewhurst CSG pilot operations in the Pilliga Forrest (Gunnedah Basin). Most of this gas is currently used to generate electricity at the Wilga Park Power Station. Approval for this project was awarded to Eastern Star Gas in December 2008. However, since November 2011, the Narrabri CSG Project has been managed and operated by Santos Ltd. At that time, Santos withdrew the Eastern Star Gas approval and sought a renewed approval for the project appraisal.

In 2009, the Narrabri CSG Project included three key production assets, namely the Bibblewindi CSG Pilot (12 wells), the Bohena CSG Pilot (three wells) and a Bibblewindi lateral pilot (six wells). At that time, all water and gas produced from the three pilots was gathered for storage in lined evaporation ponds or was treated, reused and/or stored (Eastern Star Gas, 2009). At that time, Eastern Star gas had completed a pilot water treatment project at Bibblewindi, indicating that reverse osmosis treatment was capable of providing the project with significant reductions in saline water storage requirements. With treatment recoveries exceeding 70% and treated water TDS below 250 mg/L, it was proposed to expand the treatment capacity to permit the extension Narrabri CSG Utilisation Project with the disposal of up to 1 ML/day treated produced water into Bohena Creek (Eastern Star Gas, 2009). Reverse osmosis concentrates would be transferred to lined holding ponds. Approvals to extend the discharge of treated water to Bohena Creek were granted in 2010 and further in 2011 (Santos Limited, 2012a).

In June 2011, approximately 10,000 litres of untreated saline water leaked from a pipe near the reverse osmosis plant at Bibblewindi. Operations at the Bibblewindi Water Management Facility were subsequently suspended. Santos is currently undertaking a $20 million rehabilitation of the Bibblewindi Water Management Facility site. The plant was decommissioned and removed from the site in December 2012. The three storage ponds located at the Bibblewindi facility were also found to be unsuitable for long term use and Santos has commenced their removal and subsequent rehabilitation of the site. A number of other storage ponds in the Pilliga, including at Bohena have already been removed and site rehabilitation initiated.

Santos is now constructing a new reverse osmosis water management facility adjacent to the Pilliga on the Santos-owned property ‘Leewood’ (RPS Australia East, 2012). The Leewood Water Management Facility includes a 300 ML pond for storage of untreated produced water and a second 300 ML pond for storage of concentrated reverse osmosis brine (Santos Limited, 2012a). A smaller pond will store the desalinated produced water prior to discharge to surface water or beneficial use, such as irrigation. Santos has stated that it is not feasible to hold the water in tanks because hundreds of tanks would be need to be erected (RPS Australia East, 2012). The first stage of the Leewood Water Management Facility will involve transferring about 150 ML of brine that is currently stored in the Bibblewindi ponds (RPS Australia East, 2012).

During 2013, Santos gained approval to reinstate the CSG pilot operations at Bibblewindi, along with the construction of additional pilot wells, and operate the expanded pilot for up to three years (RPS, 2013). At each well, the produced water will be pumped through the water gathering system to Bibblewindi Water Transfer Facility via the existing flow line. The Bibblewindi Water Transfer Tank located at the Bibblewindi Water Transfer Facility will be used to provide a short buffer (up to 24 hours) prior to the produced water being pumped to the Leewood Produced Water Facility via the Leewood Water Pipeline. Once at the Leewood Produced Water Facility, produced water will be stored in one of the 300 ML ponds (RPS, 2013).

The ultimate production plan for the project includes the development of up to 850 wells to produce up to 200 terrajoules/day of gas throughout a project life of 25 years. Over this period of time, around 40 GL water and 500,000 tonnes of salt would be co-produced and require management and/or disposal.

**Table 4 Operations and produced water from Santos' Narrabri CSG Project**

| | |
|---|---|
| Operator | Santos Ltd (from 17 November 2011).<br>Former operator Eastern Star Gas (ESG) Ltd [2]. |
| Location | Gunnedah basin, NSW. |
| Status | Pilot appraisal began in 2008. Operations shutdown in Dec 2011.<br>Recommencement expected in 2014. |
| Production level | The full production level of the Narrabri CSG Project is 200 TJ/day. |
| Number of wells | Appraisal: 12 pilot wells expected within PEL 238 [2]. Will also re-enter three existing wells, drilled by ESG, to allow lateral drilling.<br>Production: approx. 850 wells (or 425 well sets) will be drilled. |
| Associated Infrastructure | 2009–2011: Bibblewindi Water Management Facility located in the Pilliga, including 3 x ponds and water treatment plant [1].<br>Under construction 2013: Leewood Water Management Facility located adjacent to the Pilliga, including 2 x 300 ML produced water and brine ponds. Proposed plans for a reverse osmosis plant, brine concentrator, and brine crystalliser [1]. |
| Produced water | |
| Flow rate | 1500 ML/year based on a 25-year average (higher flows in early production).<br>Predicted for Leewood [1]: Year 0–1 = 0.7ML/day; Year 2–3 = 1.3 ML/day. |
| Conductivity | Not stated |
| Total Dissolved Solids | 14,500 - 31,000 mg/L [1; 6]. |
| pH | 7 - 8.5 [1]. |
| Impurities | Heavy metals [1], boron, fluoride. |
| Reuse | Some onsite reuse for CSG operations (dust suppression, drilling makeup water) |
| Storage | Under construction: 2 x 300 ML produced water and brine ponds [1; 6]. |
| Identified risks | Overtopping [1]. (note: NSW Dam Safety Committee endorsement of design). |
| Risk mitigation | Tank: Earthen bund (geosynthetic clay liner) of 110% volume (55 ML).<br>Ponds: Earthen embankment capped with gravel. Lined with a polyethylene (plastic) geomembrane liner, underlain by a leak detection system, underlain by a secondary liner of smooth clayey subgrade [1]. |
| Treatment | Planned for 2015 but not yet approved, reverse osmosis desalination and brine concentration and crystallisation [1]. |
| Disposal | Disposal to surface waters [6]. |
| Beneficial use | Possible future use primarily for irrigation, and lesser for dust suppression, drilling and emergency firefighting [6]. |
| Pollution incidents (related to produced water) | |
| 2009–early 2011 | Multiple leaks and spills at the Bibblewindi Water Management Facility (see details from page 54) [3]. |
| Sometime in 2010 | An unknown volume of produced water overtopped a tank at the Bibblewindi Water Management Facility and spilled into the Pilliga and an ephemeral watercourse that was flowing at the time [4]. |
| 25 June 2011 | A water transfer pipeline cap burst causing water to spill within the besser block wall surrounding the Bibblewindi Water Management Facility. An estimated 10 kL of produced water with TDS 16,000 mg/L spilled over about 420 m leaving a black residue. About 3 kL was recovered. Soil testing detected elevated levels of salinity and sodium and some vegetative dieback occurred. Testing concluded that the black residue did not represent a health risk according to sensitive land use criteria. Operations at the Bibblewindi Water Management Facility were suspended following the incident [4]. |
| Pollution Penalties (related to produced water) | |
| March and November 2010 | Produced water from Bibblewindi Water Management Facility was discharged into Bohena Creek. The EPA fined Eastern Star Gas 2 x $1,500 for water pollution under section 120 of the *Protection of Environment Operations Act 1997* (NSW) [5]. |
| December 2011 | Formal warning to Santos for water pollution from a discharge event containing high levels of ammonia [5]. |

[1] RPS Australia East (2012); [2] RPS Australia East (2013); [3] Santos Limited (2012b); [4] Golder Associates (2012); [5] NSW Environment & Heritage (2012); [6] Santos Limited (2012a).

## AGL's Gloucester Gas Project (under construction)

AGL's Gloucester Gas Project will comprise of 110 wells during Stage 1. Concept approval for subsequent stages of up to 300 wells in total has been acquired. The first gas is expected to be available to consumers by the end of 2016 (AGL, 2012a; AGL, 2013b). The Gloucester Gas Project will incorporate a water treatment facility including a water treatment plant and four storage ponds of up to 20 ML capacity each, including a balance pond and storage ponds for produced water, treated water, and brine. AGL has proposed that the produced water could be beneficially used for irrigation in agriculture and horticulture. It is proposed that in the early stages of production, all water will be (reverse osmosis) treated prior to reuse by irrigation or stream release. However, as water production is predicted to rapidly decline (to <0.5 ML/day) after 3-5 years, it is expected that the treatment plant may be subsequently decommissioned and remaining produced water will be managed by blending with lower salinity surface waters prior to reuse or disposal.

**Table 5 Operations and produced water from AGL's Gloucester Gas Project**

| | |
|---|---|
| Operator | AGL Gloucester LE Pty Ltd |
| Location | Gloucester basin, NSW. |
| Status | Production expected to commence in 2016 [1;3]. |
| Production level | Not stated |
| Number of wells | 110 for Stage 1 [1]. Concept approval for subsequent stages (up to ~300 wells in total). |
| Associated Infrastructure | Water treatment facility including water treatment plant and three storage ponds (for storage of produced water, treated water, and a third pond was planned for evaporation of brine); water distribution pipework for production water, water balancing, and distribution of frac water [2] |
| Produced water | |
| Volume | Expected max around 730 ML/year, then substantial reduction [2]. |
| Flow rate | Expected 2 ML/day from Stage 1 (could increase to about 6 ML/day with 300 wells) (AECOM, 2009). |
| Conductivity | 3000-8000 $\mu S.cm^{-1}$. |
| Total Dissolved Solids | 6000 mg/L [2]. |
| pH | 7.5-9.5 |
| Reuse | Subsequent drilling operations and frac water [2]. Irrigation and release to streams |
| Storage | 4 x 20 ML ponds for balance and to store produced water, treated water, and brine [2]. Also 3 irrigation balance ponds on irrigation property. |
| Identified risks | Overtopping [2]. Managed by "turkeys nest" design (no inflow to them, only direct rainfall). |
| Risk mitigation | Bunding around work areas. Lined water storages (double lined for produced water and brine). Monitoring of storage water levels [2]. Also seepage monitoring around dams. Surface water and groundwater monitoring network (currently more than 50 sites). Soil monitoring. |
| Treatment | Pre-treatment (if required): Ultrafiltration, deflocculation [2]. Probably ion-exchange before reverse osmosis desalination [2]. |
| Disposal | Brine concentration and crystallisation (expected to produce three tonnes of solid salt per day). The salt will most likely be transported by truck to landfill [2]. |
| Beneficial use | Potentially irrigation for local farms (pasture and cropping). Other less-economic options listed by AGL included surface discharge; stock water; industrial; and town supply [2]. |
| Pollution incidents (related to produced water) | |
| | None identified |
| Pollution penalties (related to produced water) | |
| | None identified |

[1] AGL (2013b), [2] AECOM (2009); [3] AGL (2012a).

# Issues associated with produced water and solid waste from CSG activities

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

The management and disposal of CSG produced waters presents a number of environmental issues that require careful consideration. Each receiving environment is unique and indigenous aquatic species in the area of discharge often vary in their susceptibility to deleterious effects.

The following sections describe some specific impacts of elevated salinity discharges from produced water to some freshwater and terrestrial environments. While specific constituents, such as heavy metals, can present significant environmental concerns, only impacts relating to total dissolved solids (TDS) in general are discussed in detail. While there is a significant amount of knowledge and practical experience related to the discharge of brines from brackish water desalination plants, understanding of the full scope of environmental impacts from the discharge of produced waters from CSG activities is limited.

## Freshwater environments

Physical effects to ephemeral or perennial streams and rivers, such as bank scouring, increased bottom sedimentation, or channel erosion are all document consequences of poorly managed produced water discharge (National Research Council, 2010). Other detrimental consequences can include impacts to the chemistry of waterways, which can lead to significant ecosystem impacts. Laboratory studies indicate that exposure to elevated concentrations of total dissolved solids, bicarbonate, magnesium chloride, and/or sulphate constituents that may occur in produced water can be toxic to some freshwater organisms (National Research Council, 2010).

A key factor determining environmental impacts of produced water discharge to a freshwater environment is the relative level of salinity. For example, many of the aquatic plants (macrophytes) associated with lowland rivers in Victoria are known to be salt sensitive. Adverse effects on a number of species have been reported to occur at salinities above 2 g/L (Hart *et al.*, 1991). There are variations in sensitivity, not only between species, but also between populations of the same species from different locations. Salt sensitivity can also differ between the seeds and seedlings of a species.

There has been limited study of the salinity-tolerance of many macrophytes and microalgae in Australian rivers and streams (Clunie *et al.*, 2002). Available evidence suggests that many species are salt-sensitive and that as salinity rises, the number and diversity of species falls (Bailey & James, 2000). Salinity increases of up to around 1-2 g/L can be expected to be lethal to a large proportion of macrophytes found in parts of eastern Australia (Hart *et al.*, 1991). Sublethal effects, such as reduced growing vigour, will occur at lower salinities (Clunie *et al.*, 2002).

Aquatic invertebrates comprise a large and diverse range of species. Accordingly, their tolerance of salinity is comparatively diverse, but they appear to include some of the most sensitive of the freshwater animals (Hart *et al.*, 1991). Adverse effects are considered likely for some species at salinities in excess of 0.8 g/L (Bailey & James, 2000). Reviews of the literature have concluded that salinity impacts invertebrate fauna in a variety of ways and through several physiological mechanisms, resulting in negative effects on both species abundance and diversity (Clunie *et al.*, 2002). Toxic effects would be particularly expected for simple multicellular organisms due to their lack of osmoregulatory capabilities (Hart *et al.*, 1991). It has also been suggested that some macroinvertebrates could benefit from the change in salinity, resulting in an overall shift in species composition (Clunie *et al.*, 2002).

Many adult Australian freshwater fish appear to be salt-tolerant up to concentrations of around 10 g/L (Hart *et al.*, 1991; Clunie *et al.*, 2002). However, it is likely that other critical life stages, such as larvae, pre-hardened eggs, post-hardened eggs and fry may be considerably more sensitive (Hart *et al.*, 1991; Clunie *et al.*, 2002). As a component of a larger risk-assessment process, a cumulative distribution of salinity toxicity values has previously been prepared for freshwater fish found in the Murray-Darling Basin (Clunie *et al.*, 2002). It demonstrates the comparative sensitivity of the early life stages and shows that direct (acute) $LD_{50}$ impacts are generally likely at somewhat lower salinities than slow (chronic) $LD_{50}$ impacts. The term $LD_{50}$ refers to the level of exposure (or 'dose') that is expected to be lethal to 50 per cent of an exposed population

The tolerance of Australian frogs to elevated salinity is not currently known, but overseas studies suggest considerable differences in sensitivity within and between species (Clunie *et al.*, 2002). There is evidence that tadpoles are more sensitive to salinity than frogs and that increased salinity results in a loss of suitable breeding sites (Clunie *et al.*, 2002).

Very few studies have examined the effects of small increases of salinity on microbial organisms in Australian fresh water ecosystems (Clunie *et al.*, 2002). The available information indicates that small salinity changes may have little deleterious effect on the important biological processes of bacteria (Hart *et al.*, 1991). This is due to the ability of freshwater bacteria to adapt to small salinity changes as well as the community replacement of freshwater species with otherwise similar saltwater bacteria.

In addition to the direct impact of salinity on particular species, it is likely that changing salinity would disrupt broader ecosystem processes such as nutrient spiralling/recycling and energy flow through trophic webs (Clunie *et al.*, 2002). Such processes underpin the health and integrity of entire ecosystems.

Research undertaken by the Queensland Government has provided an indication of potential hazards associated with produced water by characterising the chemical composition of untreated CSG effluent based on an analysis of the aquatic toxicity and chemical composition of water collected from a limited number of Queensland CSG wells (Shaw, 2010). These data may be used to assess the potential benefits/hazards posed by CSG water discharges to aquatic ecosystems in surface streams.

## Terrestrial environments

Produced water may be applied to terrestrial environments, either as a means of beneficial reuse (e.g. irrigation), or simply for disposal by infiltration or evaporation. In either case, over time, salts present in the water accumulate in the soil profile as exchangeable ions. This can affect the physical and mechanical properties of the soil, such as soil structure, the degree of dispersion of soil particles, permeability, and stability of aggregates.

Application of produced water to some soils in the USA has been reported to have altered plant ecology and resulted in adverse soil ecological, chemical, and hydrologic consequences (National Research Council, 2010).

Osmotic effects caused by total dissolved salt concentration in soil water can have detrimental effects on plants. Excellent drainage and maintaining a downward flux of dissolved salts through the root zone is the only practical way to manage this. Slight to moderate impacts to irrigation may apply at TDS > 500 mg/L and more severe impacts at TDS > 2 g/L.

High sodium concentrations in soil can cause deterioration of the physical condition of the soil, such as by waterlogging, the formation of crusts, and reduced soil permeability. In severe cases, the infiltration rate can be greatly reduced, preventing plants or crops from accessing enough water for good growth. The sodium adsorption ratio (SAR), a simplified index of the relative sodium status of soil solutions, is used to indicate the degree of sodicity of the soil exchange complex. $SAR_W$ is used to characterise irrigation water to predict the potential sodicity hazard to soils. $SAR_W$ is calculated as a function of the concentrations of sodium [$Na^+$], calcium [$Ca^{2+}$] and magnesium [$Mg^{2+}$] given in mol/m$^3$.

$$SAR_W = \frac{[Na^+]}{\sqrt{\frac{1}{2}([Ca^{2+}] + [Mg^{2+}])}}$$

SAR has often been used to predict potential infiltration problems. The NSW Department of Primary Industries state that when the $SAR_W$ is >3, the water is sodic, and can increase the exchangeable sodium percentage of the soil (NSW Department of Primary Industries, 2004). Summary guidelines for interpreting $SAR_W$ values are provided as follows (NSW Department of Primary Industries, 2004):

- <3: no problems as the water is non sodic;
- 3 to 6: minor effect on clayey soils may occur (depending on overall salinity);
- >6: has increasing effect on all soils at low to moderate salinity and starts to reduce growth of most crop and pasture plants;
- >9: severe risk of increasing soil sodicity on most soils.

In addition to high sodium concentrations, the anionic components of produced waters are commonly dominated by bicarbonate ($HCO_3^-$) and carbonate ($CO_3^{2-}$) ions. These ions contribute to what is known as high 'alkalinity' in water, commonly measured as mg/L $CaCO_3$ equivalent. Levels of alkalinity which may cause problems in irrigated soils are (NSW Department of Primary Industries, 2004):

- < 90 mg/L - low risk of problems occurring;
- 90–335 mg/L - moderate risk of soil problems (declining soil structure) and reduced plant growth from prolonged use, and accumulation of a white scale on plants spray-irrigated in high humidity weather;
- 335 mg/L - high risk of soil problems and reduced plant growth, and a build-up of scale which blocks metal pipes;
- 500 mg/L - may be harmful to human health, but water develops an unpleasant taste well before this level.

The effects of untreated produced water on soil physical and chemical properties, and on native and introduced vegetation density and diversity, was investigated in Wyoming, USA (Stearns *et al.*, 2005). Results indicated an increase of salinity and sodicity within local soil ecosystems at sites directly exposed to produced water. Elevated concentrations of sodium in the soil were correlated with consistent exposure to produced water. Clay-loam soils in the study area had a much larger specific surface area than the sandy soils and facilitated a greater sodium adsorption. Soils exposed to the produced water ranged from the moderate to severe SAR hazard index. Exposure to produced water appears to be related to the relative growth of introduced vegetation species and salt-tolerant species, implying the potential threat of invasion and competition to established native vegetation. These findings suggest that produced water could affect agricultural production and long-term water quality.

The salt content of produced water is typically dominated by sodium bicarbonate ($NaHCO_3$). A recent simulation modeling exercise, followed by field trials, was carried out to assess the suitability of $NaHCO_3$ rich produced waters for irrigation in South Africa (Beletse *et al.*, 2008). Modeled crop growth suggested a root zone salinity around 9000 μS/cm, and a 90% potential crop yield. In the field trials, barley, Italian ryegrass and Bermuda grass were successfully grown in a loamy sand soil (soil composed of sand, silt and clay), without leaf burn and toxicity problems, but cotton foliage was scorched when sprinkler irrigated. Furthermore, drip emitter discharge rate was observed to decrease during the trial, suggesting that clogging may be a problem with some forms of irrigation.

The Queensland Department of Natural Resources and Mines have provided a detailed assessment and guidance for salinity impacts of coal seam gas produced water on soils when used for irrigation (Biggs *et al.*, 2013).

## Current and potential drinking water resources

The management of drinking water quality in Australia is undertaken in accordance with the Australian Drinking Water Guidelines (NHMRC & NRMMC 2011). A key aspect of these guidelines is the close attention that must be paid to catchment management and the protection of drinking water resources from contamination. Current and potential future Australian drinking water resources include groundwaters (maintained in confined aquifers) and surface waters (often reservoirs fed by rivers and streams). Contamination of these resources by (untreated) produced water may expose people to numerous chemical substances as described previously. Some of these chemicals are known to present long-term health risks when present drinking waters at relatively low concentrations. As such, contamination of drinking water resources by untreated produced water (or by concentrates produced by treatment of produced water), may render water resources unsuitable for potable use.

## Human health concerns

There are a range of organic and inorganic chemical substances, known to occur in produced waters from CSG activities, which may pose risks to human health under some exposure scenarios. Depending on the type and performance of any applied treatment processes, these chemicals may persists (partially for fully) in the treated water, or may be transferred to waste solutions, requiring further treatment and/or disposal. A US review of chemical substances used during natural gas operations also reported that many chemicals used during the fracking and drilling stages of gas operations may have long-term health effects (Colborn *et al.*, 2011).

Comprehensive monitoring data (acquired with sufficiently low analytical detection limits) is difficult to source for produced water from Australian CSG basins. However, reports from the US, provide a useful overview of key chemicals that should be considered as being potentially present, until local monitoring demonstrates otherwise. In particular, Dahm *et al.* (2011) have compiled a composite geochemical database with more than 3000 CSG wellhead produced water quality entries, covering four basins in the Rocky Mountains region of the USA (see the following section of this report for more details). Among the known human health risks, the chemical 'benzene' is highlighted as having commonly exceeded (drinking water) maximum contaminant levels in untreated produced water.

Benzene occurs naturally in some coal formations and can therefore be present in produced water regardless of whether this chemical (or other BTEX chemicals) are used as drilling or fracking additives. In animal studies, benzene caused leukaemia and other cancers when administered orally and by inhalation to rats and mice (NHMRC & NRMMC 2011). It can also induce chromosome damage and gene mutation in mammalian cells. The International Agency for Research on Cancer has concluded that benzene is carcinogenic to humans (Group 1, sufficient evidence of carcinogenicity in humans) (IARC 1987). The Australian Drinking Water Guidelines provide a health-based guideline value for benzene of 0.001 mg/L, derived from a calculated excess lifetime cancer risk of one in 1 million people (NHMRC & NRMMC 2011).

Radioactivity presents an additional source of chemical health risk in some produced waters. A number of radio nuclides have been reported in produced waters from coal seams in the USA (Dahm *et al.*, 2011). These include isotopes of radium, radon and uranium. Measurements of gross alpha and gross beta particles were also reported. The Australian Drinking Water Guidelines state that 'there is evidence from both human and animal studies that radiation exposure at low to moderate doses may increase the long-term incidence of cancer. There is also evidence from animal studies that the rate of genetic disorders may be increased by radiation exposure' (NHMRC & NRMMC 2011). Consequently, the guidelines recommend that 'a guideline dose of 1 millisievert (mSv) per year should be applied for radioactivity in drinking water. When the existing or potential dose from the radionuclide content exceeds this guideline dose, a decision on the need for and the degree of remedial action (intervention) should be based on advice from the relevant state health authorities, and should include a cost–benefit analysis'.

## Solid waste disposal

In some circumstances, produced water treatment may lead to the production of solid wastes including crystallised inorganic salts (see page 39 for details). In such cases, if beneficial reuse of these salts is not practiced, they will require disposal.

The disposal of industrial waste such as crystallised salts from produced waters offers opportunities for the use of monocells in landfill design. These are particular types of landfill design which are suitable for the disposal of waste types which require to be kept separate from other types of waste to avoid undesirable chemical reactions and physical interactions either directly with other types of waste or leachate generated by contact of water with them. Their design will need to specially cater for the properties of the particular type of waste which is being placed into them. A further advantage of the use of monocells is the possibility of facilitating future mining of these substances when alternative treatment, reuse or disposal opportunities become available.

Since salts from produced waters are highly water soluble, a well-designed monocell for salt disposal would need considerable protection from ambient water in order to prevent significant loss of containment. This may be achieved by a combination of careful site selection and the use of impervious linings. However, in cases where these linings may be breached (e.g., during local flooding), salts may be dissolved in water and transported from the monocell to the environment. Depending on local conditions, these salts may then impact surface waters, groundwater and soils according to the impacts described previously in this section of this report.

# Variability of produced water volumes, compositions and risks

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.

Produced water is a necessary by-product of CSG extraction. Water must be pumped out of the coal layers (referred to as dewatering or depressuring) in order to reduce the hydraulic head (i.e., aquifer pressure) and allow the release of gas, most of which is methane. As such, produced water is by far the largest by-product or waste stream associated with gas production. Total water production, per unit gas production, is highly variable between CSG-producing basins. It is greatest in the early stages of well production, and it diminishes over time.

## Produced water volumes

The quality and quantity of produced water can be highly variable, and is determined by the natural geologic and hydrological characteristics of each coal seam.

Illustrative production curves for typical CSG wells are presented in Figure 2. This illustration shows that operator-controlled water production rates decrease exponentially over time, while methane production increases before moving into a stage of decline. Within geological constraints, water production is a function of initial, operator-controlled pumping rates that aim to reduce water pressure in the coal seam and stimulate flow of water and gas to the well. Once gas flow has been achieved, a CSG operation will gradually reduce the water production rate until the gas production rate is maximised. In many cases, water pumping may discontinue within 10 to 20 years of initial pumping, while methane production may continue (National Research Council, 2010).

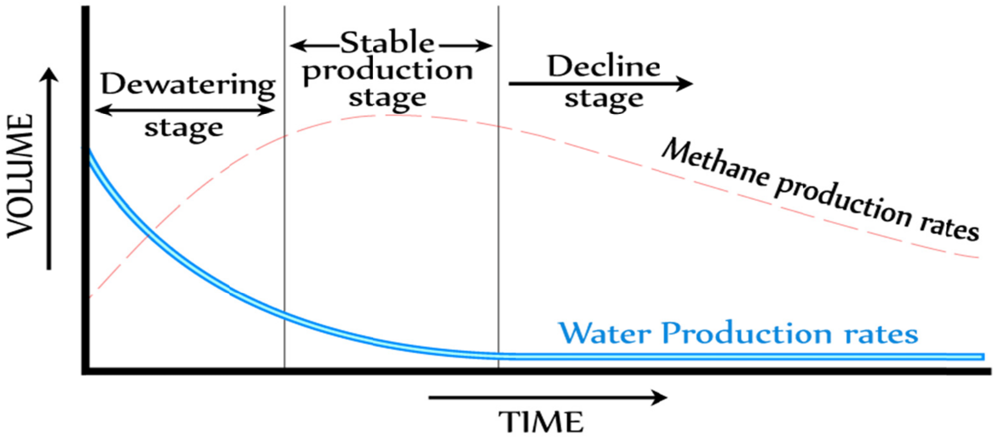

**Figure 2 Illustrative production curves for CSG wells**

The generalised trends illustrated for water and methane production (Figure 2) are useful for discussion of long-term predictions of produced water and gas volumes from a particular basin. However, the actual volume of water produced per year, the ratio of water to gas extracted from a well, and lifetime water production within and between various CSG basins will not necessarily follow any clear trend.

Local hydrogeological properties and operational practices affect the volume of water produced. For example, the rate at which pumped water flows to the surface depends on the natural hydraulic properties and water-filled porosity of the coal seam, as well as the operator-controlled pumping rate. Shallow, weakly-consolidated coal seams may have extensive internal fractures and interconnection of fractures that produce a porous and permeable formation that is capable of releasing large volumes of water. In deeper coal seams, the volume of water that must be extracted, and the rate at which that water can be pumped, is often limited by the effective water-filled porosity and permeability of the coal bed. The limited interconnectivity between fractures and cleats in these deeper coal seams often requires the use of hydraulic fracturing to stimulate gas production.

Queensland experience suggests that individual CSG wells may be expected to initially produce between 0.2-0.8 ML/day/well, decreasing substantially over ten year period (RPS Australia East, 2011). However, produced water volumes can be highly dependent on local hydrogeological conditions and other areas may be far more or less productive than this range. For example, AGL's Camden Gas project with 89 gas-producing wells produces only a fraction of this amount, only producing about 0.01 ML/day of water in total (AGL, 2013c). The total rate of water production will depend on the number of producing CSG wells in a development area and the average production rate from each well.

An Environmental Impact Statement (EIS) was prepared for Santos' major Gladstone LNG Project (known as the GLNG Project) (URS, 2009). The GLNG project involves production of CSG resources in the Surat and Bowen basins for an LNG export facility on Curtis Island, near Gladstone in Queensland. The GLNG EIS provided estimates of produced water from each of three proposed development areas. These included Roma (initial production around 12 ML/day, reducing by half over a decade), Arcadia (initially around 15 ML/day, reducing by half over 20 years) and Fairview (initially around 65 ML/day, reducing by half over a decade). It was noted that these volumes had a substantial range of uncertainty because of the significant subsurface uncertainty.

## Produced water composition

Most studies examining the compositions of CSG produced waters have focused on inorganic constituents or parameters, including electrical conductivity, sodium-adsorption ratio (SAR), nitrogen (including ammonium, nitrite and nitrate), pH, iron, silica, barium, potassium, sodium, chloride, fluoride, calcium, magnesium, sulphate and bicarbonate. As a general rule, untreated produced water is high in sodium and bicarbonate, and low in hardness (calcium and magnesium), and may also contain suspended solids, iron, silica and barium (Shaw, 2010; Alley *et al.*, 2011). Total dissolved solids concentrations can vary considerably between basins and even between individual wells. For example, produced water from some areas of the Gunnedah basin have been reported to have TDS as low as 4000 mg/L, while other areas of the same basin may be as high as 31,000 mg/L (Santos Limited, 2012a). An assessment undertaken by the Queensland Government suggested that common range for TDS in produced water was 1000-6000 mg/L (Department of Infrastructure and Planning, 2009).

Produced water may also contain a range of organic chemical substances (Volk *et al.*, 2011). Water-soluble constituents of coal are largely aromatic hydrocarbons and heterocyclic molecules, which may be produced by the cleavage of the aromatic structures within the coal matrix. Water-soluble compounds from coals and petroleum may include a wide variety of oxygen-bearing aromatic compounds (e.g. phenols, aldehydes, ketones, and various carboxy-, hydroxyl- and methoxy- bearing compounds), nitrogen-bearing compounds (pyridines and amines), and monoaromatic hydrocarbons such as BTEX, and to some extent polycyclic aromatic hydrocarbons (PAHs) and low molecular weight aliphatic hydrocarbons (Volk *et al.*, 2011).

Researchers from the CSIRO recently undertook a desktop review of available literature relating to organics in water associated with Permian coals in Australia (Volk *et al.*, 2011). They concluded that this topic had not been researched in a comprehensive manner. Where organic compounds had been found, it was often difficult to trace to their origin. The authors recommended that 'additional baseline data, together with periodic checks of organic compound concentrations throughout the production life of a gas well would assist in building a suitable database and understanding the occurrence and distribution of these compounds in deep groundwater systems'.

A compilation of water quality data from a limited number of CSG wells in Queensland is available (Shaw, 2010). These data reveal very few organic substances measurable above the analytical detection limits of the applied methodology. However, concentrations of a range of inorganic metals, anions and radioisotopes are presented. Many of these exceed relevant guidelines for aquatic ecosystems (ANZECC & ARMCANZ 2000).

A composite geochemical database was recently created with more than 3000 CSG wellhead produced water quality entries, covering four basins in the Rocky Mountains region of the USA (Dahm *et al.*, 2011). These data may not be highly representative of produced water qualities in NSW given the variable quality of produced water. However, in the absence of comprehensive local data, this database provides a valuable indication of the possible concentration range for some key contaminants. The authors claim that the 'water composition trends based on basin geology, hydrogeology, and methane generation pathway are relevant to predicting water quality compositions for beneficial use applications in [CSG]-producing basins worldwide'. Water quality database constituent information by producing basin (average, minimum, and maximum) is provided in Table 6 (Dahm *et al.*, 2011).

The water compositions in the database were dominated by sodium bicarbonate and sodium chloride type waters with total dissolved solids concentrations of 150-39,000 mg/L. Constituents commonly exceeding US standards for drinking, livestock and irrigation water applications included total dissolved solids, sodium adsorption ratio, iron and fluoride. Chemical trends in the basins were reported to be linked to the type of coal deposits, the rank of the coal deposits, and the proximity of the well to freshwater recharge (Dahm *et al.*, 2011).

**Table 6 Water quality database constituent information by producing basin (average, minimum, and maximum) (Dahm *et al.*, 2011)**

| Composite Water Quality Database Constituents/ Parameters | Greater Green River/Atlantic Rim | | | Powder River | | | Raton | | | San Juan | | | Total Entries |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Avg. | Min. | Max. | Avg. | Min. | Max. | Avg. | Min. | Max. | Avg. | Min. | Max. | |
| **Physicochemical Parameters** | | | | | | | | | | | | | |
| pH (S.U.) | 7.93 | 6.97 | 9.25 | 7.71 | 6.86 | 9.16 | 8.19 | 6.90 | 9.31 | 7.82 | 5.40 | 9.26 | 3,255 |
| Temperature (°C) | 24.4 | 15.1 | 29.5 | 22.6 | 18.0 | 28.5 | 45.3 | 13.5 | 100.0 | 28.6 | 17.9 | 42.7 | 238 |
| Dissolved Oxygen (DO) (mg/L) | 0.29 | 0.03 | 1.70 | 1.07 | 0.11 | 3.48 | 0.39 | 0.01 | 3.52 | 0.51 | 0.04 | 1.69 | 73 |
| Conductivity (µS/cm) | 3,552 | 1,010 | 10,600 | 1,598 | 413 | 4,420 | 3,199 | 742 | 11,550 | 5,308 | 232 | 18,066 | 901 |
| Total Dissolved Solids (TDS) (mg/L) | 2,148 | 610 | 6,230 | 997 | 252 | 2,768 | 2,512 | 244 | 14,800 | 4,693 | 150 | 39,260 | 3,219 |
| Total Suspended Solids (TSS) (mg/L) | 6.3 | BDL | 24.8 | 11.0 | 1.4 | 72.7 | 32.3 | 1.0 | 580.0 | 47.2 | 1.4 | 236.0 | 1,402 |
| Turbidity (NTU) | 11.9 | 0.5 | 69.0 | 8.2 | 0.7 | 57.0 | 4.5 | 0.3 | 25.0 | 61.6 | 0.8 | 810.0 | 81 |
| Sodium Adsorption Ratio (SAR)$^{\dagger}$ | 51.6 | 12.8 | 88.1 | 16.2 | 0.2 | 78.9 | 72.2 | 6.1 | 152.9 | 68.3 | 1.1 | 452.8 | 3,169 |
| **Organic Parameters** | | | | | | | | | | | | | |
| Dissolved Organic Carbon (DOC) (mg/L) | 1.16 | 0.55 | 2.36 | 3.18 | 1.09 | 8.04 | 1.26 | 0.30 | 8.54 | 3.21 | 0.89 | 11.41 | 81 |
| Total Organic Carbon (TOC) (mg/L) | 1.18 | 0.45 | 2.35 | 3.52 | 2.07 | 6.57 | 1.74 | 0.25 | 13.00 | 2.91 | 0.95 | 9.36 | 82 |
| Specific Ultraviolet Absorbance (SUVA) (L/mg-m)$^{\ddagger}$ | 1.09 | 0.31 | 2.18 | 1.12 | 0.46 | 1.83 | 2.67 | 0.00 | 10.70 | 3.32 | 0.00 | 25.23 | 81 |
| Ultraviolet absorbance (UVA) at 254nm (1/cm) | 0.012 | 0.004 | 0.030 | 0.038 | 0.005 | 0.110 | 0.029 | 0.000 | 0.197 | 0.110 | 0.000 | 1.404 | 81 |
| UVA at 272nm (1/cm) | 0.009 | 0.002 | 0.025 | 0.026 | 0.003 | 0.070 | 0.024 | 0.000 | 0.175 | 0.085 | 0.000 | 1.098 | 81 |
| UVA at 436nm (1/cm) | 0.001 | 0.000 | 0.008 | 0.001 | 0.000 | 0.003 | 0.001 | 0.000 | 0.020 | 0.010 | 0.000 | 0.163 | 81 |
| Oil and Grease (mg/L) | 5.32 | 1.00 | 11.0 | n/a | n/a | n/a | 9.10 | 0.60 | 17.6 | n/a | n/a | n/a | 51 |
| Total Recoverable Petroleum Hydrocarbon (TRPH) (mg/L) | 0.75 | BDL | 3.00 | BDL | BDL | BDL | BDL | BDL | BDL | 2.55 | BDL | 10.00 | 16 |
| Benzene (µg/L) | n/a | BDL | BDL | n/a | n/a | n/a | 4.7 | BDL | 220.0 | 149.7 | BDL | 500.0 | 947 |
| Ethylbenzene (µg/L) | n/a | BDL | BDL | n/a | n/a | n/a | 0.8 | BDL | 18.0 | 10.5 | BDL | 24.0 | 35 |
| Toluene (µg/L) | n/a | BDL | BDL | n/a | n/a | n/a | 4.7 | BDL | 78.0 | 1.7 | BDL | 6.2 | 926 |
| Xylenes (total) (µg/L) | n/a | BDL | BDL | n/a | n/a | n/a | 9.9 | BDL | 190.0 | 121.2 | BDL | 327.0 | 64 |
| **Radionuclides** | | | | | | | | | | | | | |
| Gross Alpha (pCi/L) | n/a | n/a | n/a | n/a | n/a | n/a | 10.6 | 0.2 | 46.1 | n/a | n/a | n/a | 30 |
| Gross Beta (pCi/L) | n/a | n/a | n/a | n/a | n/a | n/a | 15.6 | 0.7 | 122.0 | n/a | n/a | n/a | 38 |
| Radium-226 + Radium-228 (pCi/L) | 4.29 | 0.20 | 17.0 | 0.88 | BDL | 2.70 | 0.44 | BDL | 5.00 | n/a | n/a | n/a | 449 |
| Radon 222 (pCi/L) | n/a | n/a | n/a | n/a | n/a | n/a | 34.2 | 0.30 | 139 | n/a | n/a | n/a | 134 |
| Uranium (mg/L) | 0.03 | BDL | 0.17 | BDL | BDL | BDL | 0.34 | BDL | 2.50 | 0.08 | BDL | 0.65 | 83 |
| **Inorganic Parameters** | | | | | | | | | | | | | |
| Alkalinity (as $CaCO_3$) (mg/L) | 1,488 | 524 | 2,792 | 1,384 | 653 | 2,672 | 1,107 | 130 | 2,160 | 3,181 | 51 | 11,400 | 2,347 |
| Aluminum (Al) (mg/L) | 0.014 | BDL | 0.068 | 0.018 | BDL | 0.124 | 0.193 | BDL | 2.900 | 0.069 | BDL | 0.546 | 163 |
| Antimony (Sb) (mg/L) | BDL | BDL | BDL | BDL | BDL | BDL | BDL | BDL | BDL | BDL | BDL | BDL | 81 |
| Arsenic (As) (mg/L) | 0.027 | BDL | 0.300 | 0.001 | BDL | 0.004 | 0.010 | BDL | 0.060 | 0.001 | BDL | 0.020 | 308 |
| Barium (Ba) (mg/L) | 1.31 | 0.05 | 6.95 | 0.61 | 0.14 | 2.47 | 1.67 | BDL | 27.40 | 10.80 | BDL | 74.0 | 619 |
| Beryllium (Be) (mg/L) | BDL | BDL | BDL | BDL | BDL | BDL | BDL | BDL | BDL | BDL | BDL | BDL | 81 |
| Bicarbonate ($HCO_3$) (mg/L) | 1,630 | 524 | 2,870 | 1,080 | 236 | 3,080 | 1,124 | 127 | 2,640 | 3,380 | 117 | 13,900 | 3,255 |
| Boron (B) (mg/L) | 1.15 | 0.30 | 2.21 | 0.17 | BDL | 0.39 | 0.36 | BDL | 4.70 | 1.30 | 0.21 | 3.45 | 1,771 |

| Composite Water Quality Database Constituents/ Parameters | Greater Green River/Atlantic Rim | | Powder River | | Raton | | San Juan | | Total Entries |
|---|---|---|---|---|---|---|---|---|---|
| | **Avg.** | **Min. – Max.** | **Avg.** | **Min. – Max.** | **Avg.** | **Min. – Max.** | **Avg.** | **Min. – Max.** | |
| Bromide (Br) (mg/L) | 0.72 | BDL - 2.26 | 0.09 | BDL - 0.26 | 4.86 | 0.04 - 69.60 | 9.77 | BDL - 43.48 | 1,073 |
| Cadmium (Cd) (mg/L) | BDL | BDL - BDL | BDL | BDL - 0.002 | 0.002 | BDL - 0.003 | 0.002 | BDL - 0.006 | 81 |
| Calcium (Ca) (mg/L) | 12.73 | 1.50 - 51.2 | 32.09 | 2.00 - 154.0 | 14.47 | 0.81 - 269.0 | 53.29 | 1.00 - 5,530 | 3,239 |
| Carbonate ($CO_3$)(mg/L) | n/a | n/a - n/a | 2.17 | 0.00 - 139.0 | 51.30 | 1.30 - 316.33 | 40.17 | 0.00 - 1,178 | 1,848 |
| Chloride (Cl) (mg/L) | 336 | 4.5 - 2,190 | 21 | BDL - 282 | 787 | 4.8 - 8,310 | 624 | BDL - 20,100 | 3,135 |
| Chromium, total (Cr) (mg/L) | 0.002 | BDL - 0.021 | 0.012 | BDL - 0.250 | 0.105 | BDL - 3.710 | 0.002 | BDL - 0.023 | 495 |
| Cobalt (Co) (mg/L) | BDL | BDL - BDL | BDL | BDL - BDL | 0.001 | BDL - 0.018 | 0.001 | BDL - 0.017 | 81 |
| Copper (Cu) (mg/L) | 0.005 | BDL - 0.087 | 0.078 | BDL - 1.505 | 0.091 | BDL - 4.600 | 0.058 | BDL - 0.706 | 748 |
| Cyanide, free (CN) (mg/L) | 0.005 | 0.005 - 0.009 | n/a | n/a - n/a | 0.366 | BDL - 3.000 | n/a | n/a - n/a | 88 |
| Fluoride (F) (mg/L) | 4.92 | 1.20 - 17.50 | 1.57 | 0.40 - 4.00 | 4.27 | 0.59 - 20.00 | 1.76 | 0.58 - 10.00 | 135 |
| Hydrogen Sulfide ($H_2S$)(mg/L) | n/a | n/a - n/a | n/a | n/a - n/a | 4.41 | BDL - 190.0 | 23.00 | 23.00 - 23.00 | 574 |
| Iron (Fe) (mg/L) | 1.33 | 0.03 - 11.69 | 1.55 | BDL - 190.0 | 7.18 | 0.09 - 95.90 | 6.20 | BDL - 258.0 | 2,689 |
| Lead (Pb) (mg/L) | 0.003 | BDL - 0.058 | BDL | BDL - BDL | 0.023 | BDL - 0.233 | 0.023 | BDL - 0.390 | 124 |
| Lithium (Li) (mg/L) | 0.16 | 0.05 - 0.34 | 0.13 | BDL - 0.34 | 0.32 | 0.01 - 1.00 | 1.61 | 0.21 - 4.73 | 249 |
| Magnesium (Mg) (mg/L) | 7.32 | 0.60 - 33.95 | 14.66 | BDL - 95.00 | 3.31 | 0.10 - 56.10 | 15.45 | BDL - 511.0 | 3,191 |
| Manganese (Mn) (mg/L) | 0.04 | BDL - 0.43 | 0.02 | BDL - 0.16 | 0.11 | 0.01 - 2.00 | 0.19 | BDL - 1.34 | 1,845 |
| Molybdenum (Mo) (mg/L) | 0.023 | BDL - 0.049 | 0.005 | BDL - 0.029 | 0.002 | BDL - 0.035 | 0.020 | BDL - 0.040 | 81 |
| Nickel (Ni) (mg/L) | 0.005 | BDL - 0.01 | 0.141 | BDL - 2.61 | 0.015 | 0.004 - 0.11 | 0.020 | BDL - 0.13 | 99 |
| Phosphate ($PO_4$) (mg/L) | 0.08 | BDL - 0.68 | BDL | BDL - BDL | 0.04 | BDL - 1.00 | 1.89 | BDL - 9.42 | 239 |
| Potassium (K) (mg/L) | 30.29 | 1.70 - 484.0 | 11.95 | BDL - 44.00 | 6.37 | BDL - 29.40 | 26.99 | BDL - 970.0 | 1,475 |
| Selenium (Se) (mg/L) | 0.009 | BDL - 0.119 | 0.006 | BDL - 0.046 | 0.017 | BDL - 0.100 | 0.018 | BDL - 0.067 | 164 |
| Silica ($SiO_2$) (mg/L) | 5.04 | 4.11 - 5.69 | 6.46 | 4.40 - 12.79 | 7.05 | 4.86 - 10.56 | 12.37 | 3.62 - 37.75 | 81 |
| Silver (Ag) (mg/L) | 0.003 | 0.003 - 0.003 | 0.003 | 0.003 - 0.003 | 0.015 | BDL - 0.140 | BDL | BDL - BDL | 108 |
| Sodium (Na) (mg/L) | 824 | 240 - 2,400 | 356 | 12 - 1,170 | 989 | 95 - 5,260 | 1,610 | 36 - 7,834 | 3,255 |
| Strontium (Sr) (mg/L) | 0.04 | 0.01 - 0.15 | 0.60 | 0.10 - 1.83 | 5.87 | BDL - 47.90 | 5.36 | BDL - 27.00 | 145 |
| Sulfate ($SO_4$) (mg/L) | 0.45 | BDL - 7.62 | 5.64 | BDL - 300.0 | 14.75 | BDL - 253.00 | 25.73 | BDL - 1,800 | 1,174 |
| Tin (Sn) (mg/L) | 0.008 | BDL - 0.022 | 0.006 | BDL - 0.028 | 0.008 | BDL - 0.021 | 0.017 | BDL - 0.039 | 81 |
| Titanium (Ti) (mg/L) | BDL | BDL - BDL | BDL | BDL - 0.002 | BDL | BDL - 0.002 | 0.004 | BDL - 0.020 | 81 |
| Total Nitrogen (TN) (as mg/L N) | 0.04 | 0.03 - 0.11 | 0.48 | BDL - 4.70 | 2.61 | BDL - 26.10 | 0.46 | BDL - 3.76 | 369 |
| Vanadium (V) (mg/L) | BDL | BDL - BDL | BDL | BDL - BDL | 0.001 | BDL - 0.013 | BDL | BDL - BDL | 81 |
| Zinc (Zn) (mg/L) | 0.014 | BDL - 0.136 | 0.063 | BDL - 0.390 | 0.083 | 0.010 - 3.900 | 0.047 | 0.005 - 0.263 | 219 |

Note: Constituent entries are formatted as follows: Constituent name (abbreviation/chemical symbol) (units)

n/a - Data not available; BDL - Entries are below detection limit (see Supporting Information, Table 1); [†] SAR is the sodium adsorption ratio, Na, Ca, and Mg are all in units of meq/L; [‡] SUVA is calculated based on the following equation: SUVA = (UVA @ 254 / DOC) x 100, UVA @ 254 in units of 1/cm, DOC in units of mg/L.

Dahm *et al.* (2011) observed that numerous chemical substances present in these CSG wells exceeded US drinking water standards, at least occasionally. These included bulk water quality parameters (pH and TDS), one organic chemical (benzene) and a range of inorganic ions (aluminium, arsenic, barium, cadmium, chloride, chromium (total), copper, fluoride, iron, lead, manganese, selenium, silver and sulphate). The vast majority of wells from all four basins exceeded at least one regulatory drinking water standard. A significant number exceeded standards other than just TDS and iron. Concentrations of benzene exceeded the US Drinking Water Maximum Contaminant Level (MCL), which is 5 micrograms per litre, in 23% of samples from one basin and 80% of samples from another.

A subsequent study undertook a principal component analysis (PCA) to reveal that produced water quality variability was related to a number of identifiable factors (Dahm *et al.*, 2013). These were

- aquifer recharge that dilutes constituent concentrations (37% of variability);
- dissolution of soluble aquifer minerals such as sodium and exchange of calcium and magnesium (14% of variability);
- coal depositional environment influence on chloride and trace metal fractions (14% of variability).

Relative concentrations of sodium/chloride/bicarbonate were observed to correlate to marine influence in the coal depositional environment. Similarly relative concentrations of sodium/calcium/magnesium were correlated to well proximity to recharge.

These observations may assist greatly in future predictions of produced water quality (and its variability) from CSG wells in NSW. Such predictions would require an assessment of potential opportunities for freshwater recharge of aquifers and compositional characterisation of the aquifer materials.

## Predicting produced water volumes at the CSG planning stage

Prediction of produced water volumes at the CSG planning stage is undertaken by hydrogeologists, based on an understanding of the groundwater hydrology and CSG production projections.

The standard approach is to undertake what is known as an ‘aquifer test’ or ‘pumping test’ (Ferris *et al.*, 1962). This involves ‘stimulating’ the aquifer through extractive pumping and measuring the drawdown in adjacent observation wells. Piezometers are used to measure the pressure at specific distances away from the well being pumped.

An aquifer test is typically conducted by pumping water from the test well at a steady rate for a set period of time (usually on the order of days). As water is pumped from the test well, the water pressure in the aquifer declines. This pressure decline produces drawdown (change in hydraulic head) in an observation well. Drawdown decreases with radial distance from the test well and increases with the length of time that the pumping continues.

The aquifer characteristics which are evaluated by most aquifer tests are (Ferris *et al.*, 1962):

- Hydraulic conductivity: The rate of flow of water through a unit cross sectional area of an aquifer, at a unit hydraulic gradient ($L.day^{-1}.m^{-2}$);
- Specific storage (‘storativity’): a measure of the amount of water a confined aquifer will produce for a certain change in head;
- Transmissivity: The rate at which water is transmitted through a unit thickness of an aquifer under a unit hydraulic gradient. Transmissivity is equal to the hydraulic conductivity times the thickness of an aquifer.

The mathematical relationship commonly used to describe the flow of groundwater through an aquifer is known as the groundwater flow equation. There are considerable quantities of theory and mathematics that underpin the groundwater flow equation. Not least of which is known as Darcy's law, used to describe the flow of fluid through a porous medium (Hansen, 2003). Coal is a naturally fractured material, but the permeability of gas and water can be highly variable depending on the coal rank (Shen *et al.*, 2011).

The data obtained from an aquifer test is used to fit a solution or appropriate model to the groundwater flow equation. There are numerous such models available and an appropriate selection may be made depending on what factors are assumed to be most important in the specific case. These factors may include the presence and influence of leaky aquitards, unconfined flow, dual porosity (due to fracturing) or heterogenous aquifers. Nearly all analytical aquifer test solutions are based on the 'Theis equation' or a modification of it (Meier *et al.*, 1998; Giao, 2003):

$$s = \frac{Q}{4\pi T} W(u) \qquad u = \frac{r^2 S}{4Tt}$$

where s is the measured drawdown in the observation well , u is a dimensionless time parameter, Q is the pumping rate ($m^3/s$), T and S are the transmissivity ($m^2/s$)and storativity (unitless) of the aquifer around the well, r is the distance from the pumping well to the observation well (m), t is the time since pumping began (s), and W(u) is the 'well function' (called the *exponential integral* in non-hydrogeology literature (Tseng & Lee, 1998)).

The Theis equation can be used to calculate an appropriate pumping rate, given a required drop in aquifer pressure drawdown. This process reduces the water pressure to the target level that needs to be maintained to keep the gas flowing from the coal seam. Typically, this target pressure level is about 35 metres above the top of the coal seam (Klohn Crippen Berger, 2012).

Using the Theis equation, the pumping rate (Q) is adjusted over time to simulate the lowering of the groundwater pressure to the target level, and the ongoing pumping that is then required to keep the water pressure at this target level.

Using sophisticated corporate models based on these established relationships and some standard assumptions; CSG companies are able to forecast produced water quantities over the projected life of a CSG well. CSG companies in Queensland are required to include such forecasts in their environmental impact statements and CSG water management plans.

The Queensland State Government has commissioned the development of a tool capable of forecasting where, when, and how much CSG water will be produced in the Surat and southern Bowen basins under various industry expansion scenarios up to the year 2060 (Klohn Crippen Berger, 2012). The tool, known as the 'water production tool', can now be used to:

- forecast the volumes of CSG water likely to be produced at different locations and times;
- help identify when and where efforts for managing CSG water may need to be focused;
- indicate how alternative industry expansion paths are likely to affect the volume of CSG water produced;
- give a rough estimate of the volume of salt brought to the surface in the CSG water.

Recently, there has been interest in the possibility of operating CSG wells with enhanced methane recovery and reduced water production (Hamawand *et al.*, 2013). The approach is based on the injection of gasses such as nitrogen ($N_2$) and carbon dioxide ($CO_2$) into the coal seam. Detailed aquifer modelling has been reported to project production of both gas and water under these circumstances (Jamshidi & Jessen, 2012).

# Approaches for management of CSG produced water

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.

In conventional oil and gas fields, produced water is sometimes reinjected into the formation to enhance oil and gas recovery. However, reinjection into the same producing formation is not widely practised with CSG production since doing so would hinder additional methane recovery. Consequently, other options must be considered for storage, disposal or use of produced water.

The options available can be generally categorised as disposal or beneficial reuse of produced water. From the perspective of gas companies, both have the same purpose, the cost-effective removal of the major waste by-product of CSG production in compliance with regulations. However, from a regulatory perspective, beneficial reuse implies that there is a clear, identifiable benefit from the reuse of the resource and this is discussed further in the following section of this report.

Depending on the chemical composition of the produced water, as well as the nature of a proposed disposal or beneficial reuse practice, some produced water can be disposed or reused without treatment to improve water quality. However, since produced water is typically saline it will require some form of treatment before it is suitable for some disposal practices or most beneficial reuse practices.

## Factors influencing the management of produced water

Decisions regarding the management of produced water will involve an assessment of opportunities for disposal of untreated water, as well as potential treatment techniques that can make produced water quality suitable for beneficial reuse. These decisions will be influenced by a variety of factors as described below.

### Regulatory requirements and constraints

The regulation of CSG and produced water management is governed by various State Government Acts, and consequently, varies between the Australian States. In Queensland, CSG extraction, including co-produced water, is primarily regulated through the Petroleum and Gas (Production and Safety) Act 2004. Specific guidance on CSG water management is then provided in the CSG Water Management Policy (Queensland Government - Department of Environment and Heritage Protection, 2012). Relevant legislative frameworks in NSW include The Water Act 1912 (NSW) and the Water Management Act 2000 (NSW). There are currently efforts to nationally 'harmonise' the regulatory framework for CSG activities and the management of produced water. This is being achieved through the development of the National Harmonised Regulatory Framework (Standing Council on Energy and Resources (COAG), 2012). The purpose of this framework 'is to provide a suite of national and global leading practices to consider and implement in the assessment and ongoing regulation of proposed projects for CSG exploration and production'.

The management of produced water in NSW and QLD has, in recent years, been increasingly constrained by environmental regulation. Disposal of untreated produced waters to surface water is rarely considered a viable option. Furthermore, the previously common use of evaporation ponds is now highly constrained in both states (see discussion below). Such regulation has led to considerable pressure on CSG companies to consider alternative management options, commonly involving engineered water treatment and/or beneficial reuse.

## Proximity to suitable disposal or beneficial reuse sites

Specific local conditions are commonly a significant factor determining the viability or desirability of various approaches to produced water disposal and beneficial reuse. In the first instance, local conditions will play a major role in determining which practices may be able to meet regulatory requirements constrained by environmental factors such as suitable sites for water discharge. Secondly, local conditions will largely determine the level demand or ‘consumptive capacity’ for produced water. For example, the consumptive capacity for some disposal practices may be influenced by factors such as evaporation rates or deep-well recharge capacity. Similarly, the consumptive capacity of beneficial reuse practices will be influenced by factors such as the availability of suitable agricultural practices or other sources of water demand.

The need to transport water over long distances can add significant capital and operational costs to the management of produced water. Similarly, the need to transport water to multiple sites (i.e., distributed disposal or reuse) can markedly influence costs. As such, both the transportation distance and the degree of ‘concentration’ of suitable consumptive capacity will influence the overall viability of disposal or beneficial reuse opportunities.

## Water composition

The chemical composition of produced water will determine which disposal or beneficial reuse applications -if any- may be acceptable without the need for water treatment. The availability of such non-treatment opportunities will, in most cases, be extremely attractive to gas companies since they would allow the avoidance of significant costs that may be associated with water treatment. In some circumstances, these may include costs associated with additional transportation, water storage, land use, and disposal of treatment wastes.

Even in circumstances where treatment is required prior to disposal or beneficial reuse, initial water composition can significantly influence treatment costs. In some cases, the suitability of some potentially less expensive treatment processes (e.g., ion exchange compared to reverse osmosis) will be dependent upon initial inorganic and organic chemical concentrations. Furthermore, the initial composition can influence the costs associated with the operation of specific treatment processes. This is because ionic concentrations of treatment feedwaters can influence the energy requirements for treatment, the proportion of water recovered, and the production of wastes requiring further treatment and/or disposal.

## Capital and operational costs

CSG producing companies are commercial enterprises and therefore profitability plays a major role in decision-making. As such, the minimisation of financial costs (or maximisation of profits) associated with the management of produced water is a major determining factor. Many of the costs are directly related to proximity to suitable disposal or beneficial reuse sites and the initial water composition as described above. Costs associated with produced water management will include both capital costs (e.g., water storage, land acquisition, pipelines, treatment infrastructure) and operational costs (e.g., energy consumption, chemical use, human resources, waste disposal).

Most CSG companies will undertake a ‘lifecycle costing analysis’, including both capital and operational costs, as well potential salvage or disposal costs to be incurred at the end of the operation. Such lifecycle costing is typically undertaken in net present value (NPV) terms, accounting for factors such as inflation and opportunity cost. As a consequence, opportunities to delay the incurrence of some costs, as opposed to up-front expenditure may be viewed as attractive in some circumstances.

## Social considerations and community preferences

The nature and location of CSG activities in Australia has occasionally led to tensions between CSG producing companies and other community members. Consequently, the concept of a ‘social licence to operate' has been viewed as an increasingly important factor by the CSG industry in Australia (Williams & Walton, 2013). Much of the focus in developing such a 'social licence' has been directed towards establishing effective community engagement in decision making. Therefore, a logical outcome of this process may be the increased influence of community preferences in the selection of produced water management options. Community preferences may reflect direct benefits to communities, such as access to otherwise unavailable water resources. Alternatively, some water management options may be viewed less favourably by communities, such as those which may be perceived (by communities) to lead to unacceptable risks of negative health or environmental impacts.

## Disposal of produced water

Disposal of produced water is the conventional management approach, based on the need to dispose of a waste by-product from CSG production. Low cost options have generally been preferred by gas companies, however increasingly stringent environmental regulations have significantly limited opportunities for direct discharge of untreated produced water into rivers and streams. Consequently, the most common disposal options have tended to include the use of evaporation ponds and, in some cases, reinjection to groundwater aquifers.

### Surface impoundments for infiltration and/or evaporation

The discharge of untreated produced water into constructed ponds or storage basins, and lined or unlined impoundments is a common method of produced water disposal in parts of North America (National Research Council, 2010). In some cases, impoundments may be used for storage prior to future treatment and disposal or reuse. However, in many cases, the primary purpose is to facilitate evaporation or infiltration of produced water into the underlying soil. Those that are primarily designed for evaporation are commonly referred to as 'evaporation ponds' or 'evaporation basins'.

Evaporation ponds normally comprise simple, relatively shallow ponds for the evaporation of water. They may be well suited for the management of some produced water from inland operations in hot, dry areas. In some instances, evaporation may be enhanced by atomisation, which involves high-pressure spraying of the produced water into the atmosphere above the impoundments. This process produces small airborne water droplets, hence increasing the overall surface area and accelerating evaporation.

Impoundments have some advantages for gas companies. They are comparatively simple to construct and, in some circumstances, may require minimal maintenance or operator attention compared to mechanical systems. Typically the only required mechanical equipment is a pump to deliver the produced water to the pond. As a result, impoundments can be relatively inexpensive to implement in areas with low land acquisition costs.

However, the use of impoundments may be limited by the need for large areas of land in regions where the evaporation or infiltration rates are low compared to the water production rate. Furthermore, impoundments designed for infiltration will transfer the salt-load from the produced water to the groundwater table. Depending on the relative initial salinities of the produced water and the ambient groundwater, this may have severe impacts to groundwater quality over a large area.

Similarly, poorly designed or constructed evaporation ponds may risk contamination of underlying groundwater aquifers by seepage. In most cases, impervious layers of clay or synthetic membranes are required to prevent loss by seepage.

A further concern is the potential for impoundments, through infiltration and percolation of produced water, to dissolve and/or mobilise naturally occurring constituents in the underlying soil, such as sulphate, selenium, arsenic, manganese, barium and TDS.

Optimum sizing of evaporation ponds is dependent upon prevailing annual evaporation rates (including the effect of salinity on evaporation rate) and the anticipated produced water volumes requiring disposal. The evaporation rate determines the necessary surface area while the optimum depth is dependent on the required surge capacity, water storage, storage capacity for the salts, and necessary freeboard for rainfall and wave action. There are various methods available for the determination or estimation of these parameters (Ahmed *et al.*, 2000).

Impermeable liners are required in most circumstances and these should be mechanically strong enough to withstand stress during salt cleaning (Ahmed *et al.*, 2000). In some cases, liners can be covered in sands to facilitate salt removal without damage. Alternatively, if no salt is removed from the pond for the first year or two of operation, a hardpan may be developed helping to seal the base. A hardpan can only develop if the pond is allowed to completely dry out during the hottest periods of the year. In case of leakage, ponds may also be constructed with seepage-collection systems. The use of hardpan seals may not always be optimum in all circumstances and requires careful management and monitoring. For example, in some cases, the hardpan may crack while drying out (Figure 3). In such cases, when the evaporation pond is re-filled there is a risk that water will leak from the pond through cracks in the pan.

**Figure 3 Evaporation ponds showing evidence of cracking (photos by Terry Fagg).**

A number of natural and human-influenced differences between individual impoundments can influence the way in which produced water stored in the impoundment may affect the groundwater beneath the impoundment. These include the substrate (e.g., soil or bedrock) on which it is constructed, lining, the volume of the impoundment and volumes of balances of produced water entering the impoundment over time, the means by which produced water travels to the impoundment (through a pipe or overland), the length of time the water is in the impoundment, and the local climate.

In early 2009, the Queensland Government released a discussion paper outlining its position with regard to the management of produced water (Department of Infrastructure and Planning, 2009). It considered that the current use of evaporation ponds as a primary produced water management option presented significant ecological risks to landscapes, shallow aquifers, and nearby water bodies, particularly when considering the likely expansion of the CSG industry. Furthermore, this approach would not maximise beneficial use of produced water. The preferred option was to tighten the current requirements with respect to the management of produced water to achieve more environmentally sustainable outcomes and better utilisation of the water resource (Department of Infrastructure and Planning, 2009). As a result, the Queensland Government determined that evaporation ponds would be discontinued as a primary means for disposing of produced water. However, it would allow limited use of evaporation ponds necessary for water aggregation and the temporary storage of brine from treatment facilities provided that these ponds were fully lined to an appropriate standard (Department of Infrastructure and Planning, 2009).

In 2011, the NSW Minister for Resources and Energy announced a series of new 'conditions on coal and coal seam gas mining' (Hartcher, 2011). These included 'a ban on the use of evaporation ponds relating to coal seam gas'. Consequently, in NSW, CSG companies must treat or otherwise dispose of produced water. While they must not store water with the intention of having it evaporate, in some cases temporary holding ponds or dams may be approved for various treatment processes (Hartcher, 2012). Both Metgasco's operations in Casino and Santos' operations in the Pilliga use ponds to hold water extracted during coal seam gas operations.

## Deep–well injection

In North America, deep-well injection, the reinjection of produced water into underground formations (also known as managed aquifer recharge), is the most common onshore management approach used in petroleum production (National Research Council, 2010). In some cases, deep-well injection is adopted as the least cost disposal option. In others, the reinjection serves an additional beneficial purpose to maintain groundwater pressure, thus minimising impact from surface water and surface subsidence.

In some CSG-producing basins of North America, deep-well injection is the almost exclusive means of produced water disposal. The produced water in these basins is characterised by high TDS and relatively low production volume per unit of gas production (National Research Council, 2010). Geological formations suitable for reinjection in these basins also tend to be well known from historical data associated with water disposal from traditional oil and gas production wells.

Usually, a nearby injection well must be found or newly drilled because the costs of gathering and transporting water can be substantial. Typical North American injection wells are old gas wells with depths of 3,000 m, which is significantly deeper than most CSG wells in Australia. These old wells are commonly fractured to facilitate permeability.

In most cases, disposal of CSG produced waters by deep-well injection requires some form of initial water treatment. This treatment is primarily aimed at preventing 'plugging' of the aquifer and hence maintaining acceptable injection pressures. Filtration to remove fine particulate material is most commonly required to minimise structural plugging. The addition of scale and corrosion inhibitors or bactericides may also be required. These are used to prevent the *in situ* formation of fine particulates by salt precipitation or other chemical changes within the aquifer. Furthermore, treatment by chlorination to control bacterial contamination is common for deep-well reinjection of produced waters.

In a number of cases, the reinjection of produced water has been associated with seismic activity (earthquakes). It has been known since the 1960s that earthquakes can be induced by fluid injection (Davies *et al.*, 2013). More recently, one study in the United States showed a marked distribution of 'unnatural' earthquakes around some reinjection wells, but was not been able to demonstrate why some wells appear to be affected more than others (Frohlich, 2012b). A plausible, but unproven, explanation is that fluid injection may trigger earthquakes if pressures, rates, and permeability are sufficient to allow fluid to reach a rock fault, reducing the fault strength (Frohlich, 2012b). Most earthquakes associated with gas extraction are of low magnitude and are only occasionally severe enough to be reported by nearby residents or receive media attention (Frohlich, 2012a).

The Draft National Harmonised Regulatory Framework for Coal Seam Gas included the key finding (Standing Council on Energy and Resources (COAG), 2012):

> *The use of reinjection as a means of disposal of waste water and brine into suitable underground systems is a method that has not been widely considered in Australia. Governments should evaluate international leading practices for application in Australia.*

In NSW, reinjection will require approval by the appropriate planning authority, having regard to the Aquifer Interference Policy. Before granting an aquifer interference approval, the Minister must be satisfied that 'no more than minimal harm will be done to any water source, or its dependent ecosystems, as a consequence of its being interfered with in the course of the activities to which the approval relates' (*Water Management Act 2000* (NSW) s 97(6)). Table 1 of the NSW Aquifer Interference Policy lists the water table, water pressure, and water quality impacts that the Minister must take into account before issuing an aquifer interference approval (NSW Department of Primary Industries, 2012). Whether or not produced water would do no more than minimal harm would need to be assessed on a case-by-case basis, but it generally accepted that produced water is incompatible with most native groundwater in Australia (RPS Australia East, 2011).

### Disposal to municipal sewers

Disposal to municipal sewers is a relatively commonly practiced method for disposal of concentrates from brackish water desalination plants in the USA (Mickley, 2001). Such practices, could conceivably also be safely applied to CSG produced water (and produced water concentrates) in some circumstances.

The most significant advantage of disposal to sewers is that the process makes use of existing infrastructure, negating the need for new pipes and pumps. In some cases the transportation of the brine over large distances may be facilitated by the flow of existing wastewater in the sewers. This would imply significant energy savings compared to alternate means of brine transportation.

However, in cases where biological treatment processes are in place at the end of the municipal sewer, disposal of brine to the sewer may often only be suitable for relatively small produced water volumes discharging into large capacity sewage-treatment facilities. This is due to the detrimental effects of salinity on biological treatment processes (Wang *et al.*, 2005; Wu *et al.*, 2008; Li *et al.*, 2013). Such impacts may cause impaired removal or organic chemicals and nutrients, resulting in significantly reduced effluent quality.

## Treatment of produced waters

Beneficial reuse of CSG produced waters (see the following section) is an increasingly important alternative to disposal. Most produced water will need some form of treatment before it can be beneficially reused. The levels of specific constituents found in a particular produced water sample and the desired type of reuse will determine the types of treatment that are necessary. Commercially available water treatment techniques can be employed individually or in combination to attain the water quality necessary to support any beneficial use, but at variable cost. Technologies available for the treatment of produced water have recently been reviewed in some detail by a number of authors (Fakhru'l-Razi *et al.*, 2009; Nghiem *et al.*, 2011).

### Adjustment of pH conditions

Adjustment of water pH can be achieved relatively simply and with minimal expense. Elevated pH can be neutralised by the careful addition of suitable acidic substances. This could include a range of weak and strong acids, as well chemical mixtures designed to provide a buffering (pH stabilising) effect. While the approach is relatively simple and inexpensive, initial testing and on-going monitoring is required to properly tailor the approach to the specific water requiring treatment.

However, pH adjustment by chemical addition will have little or no effect on most of the dissolved inorganic anions and cations of concern. Furthermore, pH adjustment may exacerbate turbidity levels due to precipitation of some substances, or may lead to elevated dissolved concentrations of some substances due to the solubilisation of some suspended particulates. It may be possible to incorporate careful pH adjustment with granular filtration or membrane filtration (see below) to achieve some level of removal of some key inorganic contaminants. However, careful process assessment and optimisation would be required to achieve this result.

### Granular filtration

Filtration using granular material such as sand or charcoal is widely used for removing particles from water. Filtration through crushed walnut shells is a relatively common treatment technique for produced water in the USA. This is an effective and relatively inexpensive process for treating elevated turbidity. However, is not effective for removing highly soluble inorganic anions and cations.

## Membrane filtration – including reverse osmosis

Synthetic (polymeric) membranes are increasingly being used in a diverse range of water treatment applications. Four general types of pressure-driven membranes are currently widely used: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). The distinction between these types of membranes is somewhat arbitrary and subject to differing interpretations, but the membranes are loosely identified by the types of materials rejected, operating pressures, and nominal pore size.

MF and UF membranes are relatively porous and only really effective for the removal of suspended particulate and colloidal materials. Accordingly, these are employed for the treatment of particles, sediment, and algae. They are increasingly used as an alternative to granular filtration for treating elevated turbidity.

NF membranes can be highly effective for the removal of divalent (doubly charged) cations such as $Ca^{2+}$ and $Mg^{2+}$ and therefore are increasingly widely used in water softening plants. NF is likely to be useful for the removal of some of the specific inorganic ions (e.g., aluminium). However only RO membranes are effective for the removal of a wider range of monovalent and non-charged inorganic species. Accordingly, RO is likely to be required in order to achieve a significant reduction in TDS by membrane filtration (Mondal & Wickramasinghe, 2008; Nghiem *et al.*, 2011).

RO (and to some degree NF) can be used to achieve a significant reduction in the concentrations of most ionic cations and anions. Precise performance depends on membrane selection, process design and operational conditions, but TDS removal of 90-99% can be routinely achieved.

RO membranes are configured as flat sheets. The sheets are folded over a porous spacer and sealed on three sides to create an envelope. The open side is sealed onto a perforated tube that will carry permeate that passes across the membrane and travels through the porous spacer. The active surface which is located on the outside of the envelope is wrapped in a mesh spacer. The mesh encased membrane is wound around the central permeate tube to create a spiral wound element with channels defined by the mesh spacer (Figure 4). Individual elements are coupled together along the permeate tube and loaded into a pressure vessel.

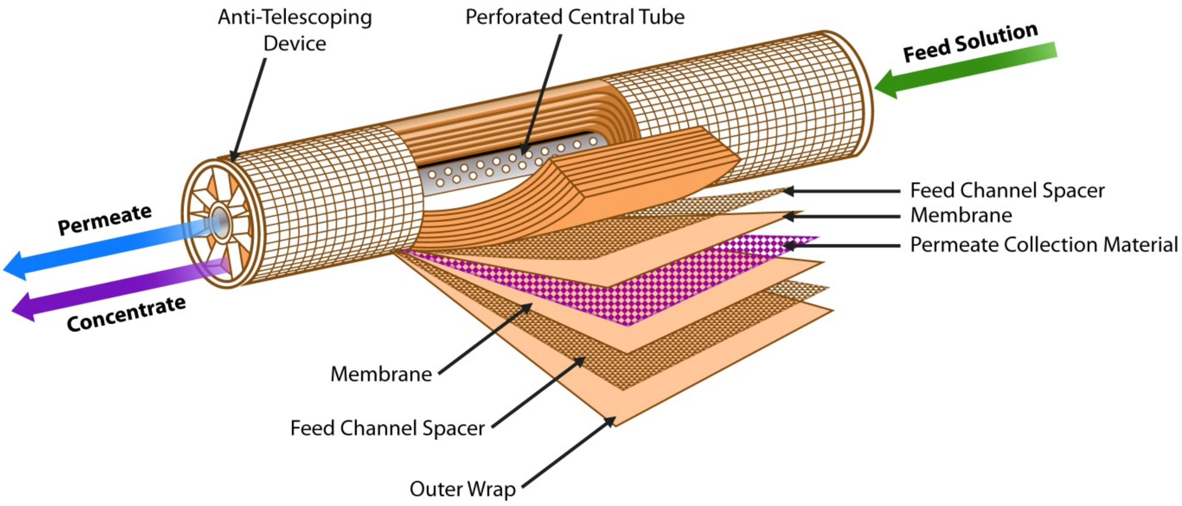

**Figure 4 Schematic of a single RO element (Khan, 2013).**

A bank of pressure vessels is connected to a high pressure feed manifold located on the discharge side of the high pressure feed pump. Water under pressure is forced through the channels in each element defined by the mesh spacer. A portion of the feed water travels across the membrane and collects in the permeate tube while the balance of the water is discharged as concentrate out the end of the vessel. The ratio of permeate produced to the feed water is referred to as the process recovery. The feed pressure required is determined by the pressure loss through the channels plus the sum of the pressure loss across the membrane and the osmotic pressure of the salts retained on the membrane surface.

Modern RO membranes (known as ‘thin film composite’ membranes) have been designed with chemical functional groups attached to the membrane surface to facilitate electrostatic repulsion of susceptible chemicals in the feed water. Such functional groups include sulfonic acid and carboxylic acid groups, which are negatively charged under normal pH conditions (typically pH 6–8). Solutes which are also negatively charged can be efficiently rejected by such membranes.

A US study investigated the viability and cost effectiveness of ultra-low pressure reverse osmosis (ULPRO) and NF membranes as potential techniques for beneficial use of produced water by meeting potable and irrigation water quality standards and concentrating iodide in the brine (Xu *et al.*, 2008). The performance of two ULPRO membranes and one NF membrane was compared to a conventional RO membrane. Cost analysis showed that the ULPRO membrane system provided marginally lower overall operational costs than RO for meeting drinking water standards. The ULPRO membrane operation resulted in even lower treatment cost than RO and NF for meeting irrigation water standards, especially under circumstances where energy costs were assumed to be high.

Similarly, a recent study reported the effective removal of fluoride and total dissolved solids from CSG produced water with a movable ULPRO system (Liu *et al.*, 2013). This system produced water quality meeting local standards for irrigation and livestock watering. The flexible deployment and small footprint of this system was advantageous for use in CSG producing areas with low and transient water production.

The primary disadvantages of using high pressure membranes such as RO for water treatment generally include relatively high capital and operational costs and relatively high energy requirements and hence a relatively large carbon footprint. The energy requirements increase with initial salinity of the water and reduction in membrane porosity.

Membrane fouling, caused by chemical precipitation on the membrane, is a common operational hazard and must be carefully managed, usually by pre-treatment of the source water (Mondal & Wickramasinghe, 2008).

Furthermore, these processes also produce a concentrated waste stream known as a concentrate or brine. While the volume of this concentrate may be significantly reduced (70-90%) compared to the original produced water volume, it must ultimately still be disposed of. The use of evaporation ponds and deep-well injection are among the most common disposal techniques for membrane concentrates in inland environments. There is considerable interest in further concentrating these brines for zero liquid discharge, but currently very few commercial applications exist (Khan *et al.*, 2009).

## Adsorption

Many organic chemicals and some inorganic water contaminants such as arsenic and lead can be removed from water by adsorption to a solid material. The primary adsorbent materials used in water treatment are powdered activated carbon (PAC) and granular activated carbon (GAC). PAC is added directly to the water and is usually removed by sedimentation or filtration. GAC is most commonly operated as a fixed filtration bed, through which the water is drawn under gravity or with assisted head pressure. Other adsorption media, including various clays, polymers, zeolites and resins may also be useful for some applications.

While there are a number of mechanisms involved, the GAC and PAC adsorption processes rely upon a relatively high 'hydrophobicity' of the contaminants to be adsorbed. Therefore, while they can be used for treatment of some forms of arsenic and some heavy metals, they are not generally effective for most inorganic anions and cations. As such, they would be expected to have negligible impact on the overall salinity of most wastewaters like produced water.

Furthermore, adsorption materials require intermittent regeneration and ultimate disposal. These processes produce waste streams, which will contain any removed arsenic or heavy metal substances.

### Ion exchange

Ion exchange is a process used in water treatment to remove specific dissolved ionic constituents that can cause aesthetic, health or ecological impacts. In drinking water applications, ion exchange is primarily used for water softening and demineralisation (e.g., removal of $Ca^{2+}$, $Mg^{2+}$, $Na^+$, $Cl^-$, $SO_4^{2-}$, $NO_3^-$) or to target specific local problem chemicals such as barium, radium, arsenic, perchlorate and chromate. Ion exchange treatments have been developed specifically in response to the need to reduce $Na^+$ (and hence reduce SAR) in produced waters (National Research Council, 2010). Among the most widely used in produced water is known commercially as the 'Higgins Loop' (Colorado School of Mines, 2009).

Synthetic polymeric resins are most commonly used for ion exchange water treatment processes. Such resins can be designed to selectively remove either cations or anions. The resins can be regenerated using various salt or acid solutions, depending on the particular application. Resins known as 'strong acid exchangers' and 'strong base exchangers' can be used to exchange a wide variety of ionic substances with hydrogen ions ($H^+$) or hydroxide ions ($OH^-$), respectively. These hydrogen ions or hydroxide ions may be subsequently neutralised by further pH adjustment.

The unique aspect of the Higgins Loop is that it performs resin regeneration continuously, with minimal need for system downtime during regeneration. As such, this process is commonly known as 'continuous ion exchange' and is currently being marketed as less costly (compared to RO) treatment process for the Australian CSG market.

While ion exchange is useful for targeting specific problem substances, it remains ultimately an 'exchange' process where one chemical species is replaced by another. Even where exchange takes place with neutralisable hydrogen ions or hydroxide ions, there will always be counter-ions associated with the neutralisation process, such that the water will not be truly 'purified'. Furthermore, like adsorption processes, ion exchange resins require regeneration, resulting in a concentrated waste stream, which must be ultimately disposed of.

## Concentrate volume reduction (to zero liquid discharge)

Concentrate volume reduction would not be expected to help with discharge methods where the concentrate is eventually mixed with receiving water. In such cases, it would tend to make the concentrate less compatible with the receiving water. On the other hand, volume reduction may be useful prior to some disposal options such as evaporation ponds or deep well injection, which may benefit from smaller volumes. Accordingly, it is considered that in the absence of options for evaporation ponds or deep well injection, there is usually little to be gained by minimising the volume of concentrate unless this is done as part of a 'zero liquid discharge' (ZLD) processing scheme (Neilly *et al.*, 2009).

ZLD means that no liquid wastes leave the boundary of the water treatment plant. ZLD will transfer the challenges of disposal from those for a concentrated liquid solution to those of a solid. The difficulties associated with the disposal (including costs) of mixed solids can also be expected to be significant in most cases and should be carefully considered for all proposals.

Some of the most commonly used commercially available ZLD technologies include thermal brine concentrators, spray dryers, high recovery RO, evaporation ponds, crystallisers, and enhanced evaporation systems (Mickley, 2005). Among the enhanced evaporation systems, there are three main techniques for minimising energy consumption. These are the so-called ‘multiple effect arrangement’, ‘thermal vapour recompression’ (TVR) and ‘mechanical vapour recompression’ (MVR). These three techniques may be applied individually or in combination.

The multiple effect arrangement employs numerous heating stages where the vapour produced in each stage is used as the heating medium of subsequent stages (as opposed to being *lost* to the condenser). A TVR system relies on vapour from a boiling chamber being recompressed to the higher pressure of a heating chamber so that further energy is added to the vapour. The elevated pressure causes the saturated steam temperature to be raised proportionally, enabling the vapour to be reused for further heating. Steam jet vapour recompressors, which have no moving parts, are used for this purpose. An MVR system is similar in principle to a TVR system, except the vapour is recompressed to a higher pressure by means of a mechanically driven compressor. Advantages of MVRs include reduced energy consumption, rapid evaporation (high throughput), and the availability of relatively simple systems. An MVR evaporator can produce final effluents with salt concentrations up to 280 g/L depending on the initial water quality (Mickley, 2005). The limiting factor is typically the onset of sodium sulphate or sodium chloride crystallisation.

ZLD has been used at coal-fired power plants in the USA since the mid-1970s (Ciszewski, 2004). One example is the Texas Independent Energy Guadalupe Power Plant in Marion, Texas. This plant incorporates an MVR evaporator for brine concentration and then a crystalliser. There, 99 per cent of the wastewater is recovered as high-quality distillate of 5-10 mg/L TDS (Ciszewski, 2004). The blowdown from the brine concentrator is then further treated by a steam-driven calandria crystalliser which, coupled with a dewatering pressure filter, reduces the waste stream to solids suitable for off-site disposal.

A similar operation is in place for the ZLD treatment of coal mine drainage at Debiensko, Poland (Sikora & Szyndler, 2004). In this scheme, all of the drainage from two mines is treated by two evaporators and a crystalliser, preventing the discharge of 310 tons per day of salt to local surface waters.

Another common mechanism for recovery of saline wastewaters is a falling-film evaporative brine concentrator (Madole & Peterson, 2005). These installations are very effective but require large amounts of energy, making them vulnerable to rising energy costs as well as maintenance costs associated with exotic metallurgies. They are also capital-intensive, require a fairly large ‘footprint’, and are said to be complex and difficult to operate in a variable plant environment.

In addition to the established technologies, there are a number of emerging technologies that may well prove to be highly suitable for brine concentration and ZLD. The most promising of these include membrane distillation (MD) and forward osmosis (FO) (Shaffer *et al.*, 2013). MD is a membrane filtration process that can make use of low-grade heat to drive separation in the vapour phase. In this case, the liquid feedstream is unable to penetrate the membrane pores due to the hydrophobic nature of the membrane, and a difference in partial pressure drives the transport of water vapour across the membrane. Like RO treatment, FO involves the transport of water across a highly selective membrane that retains dissolved solids in the feedwater. However, instead of using a pressure differential to drive the transport of water across the membrane, the FO process relies upon an osmotic potential differential across the membrane. In order to achieve this, a concentrated ‘draw solution’ is required. In most cases, this draw solution will require regeneration (reconcentration) after use, this aspect of the process is currently the major limitation to full-scale cost-effective application (Cath *et al.*, 2006).

Both MD and FO have previously been demonstrated to have strong potential for low-energy desalination of high-salinity water. However, apart from a few laboratory (Hickenbottom *et al.*, 2013), and pilot scale (McGinnis *et al.*, 2013) studies, full scale evaluation of these technologies for produced water treatment has not been reported. Shaffer *et al.* (2013) give an excellent review of the advantages and challenges of applying MVR, MD, and FO technologies to produced water desalination, and identify directions for future research and development.

Very recently, a new approach was proposed using a gas hydrate-based process (Cha & Seol, 2013). This involves the formation of a crystalline gas hydrate substance composed of water and gaseous molecules. As such, other impurities are excluded from the crystalline structure, which can subsequently be dissociated, producing purified water. The technique itself is not new, but until now has required such low temperatures for gas hydrate formation that it has not been considered viable. The work recently published by (Cha & Seol, 2013) describes a potential improvement to the technique, with which the gas hydrates may be formed at higher temperatures, thus more energy-efficiently.

## Selective salt recovery

One option to increase the commercial viability of ZLD is the selective recovery and sale of dissolved salt products. Salts, which may be recoverable in commercial quantities from produced water include:

- Sodium bicarbonate;
- Sodium carbonate (soda ash);
- Sodium chloride (common salt).

Sodium bicarbonate has numerous commercial applications including in glass manufacturing, mining, food and animal feed. Sodium carbonate is used to make glass, washing power, detergents, pharmaceuticals and as a food additive.

A previously Australian company (now based in the USA), Geo-Processors, promote a process technology termed ‘ROSP’ which is the linked operation of reverse osmosis and an integrated process call SAL-PROC$^{TM}$ for selective salt extraction. The SAL-PROC$^{TM}$ process involves multiple evaporation and cooling steps, supplemented by mineral and chemical processing (Neilly *et al.*, 2009).

Until recently, there was a commercial salt recovery operation in Australia via a Consortium Agreement between Penrice Soda Holdings (Osborne, South Australia) and GE Power & Water (Penrice Soda Holdings Limited, 2011). Penrice was Australia’s only commercial manufacturer of sodium carbonate and sodium bicarbonate. The consortium was to provide the Australian CSG industry with a brine removal mechanism. Using water from several CSG projects, Penrice conducted laboratory and small scale field trials, extracting sodium carbonate, sodium bicarbonate and sodium chloride from produced waters. However, the venture was ultimately unsuccessful with Penrice ceasing to produce these products in 2013 (ABC News, 2013).

Another notable technique being developed by the University of Wollongong with funding from the National Centre of Excellence in Desalination in Australia, is to use the saturated CSG brine as feed stock for the production of sodium hydroxide using membrane electrolysis (Simon *et al.*, 2013). Early research results confirm that the electrolysis of sodium bicarbonate is thermodynamically more favourable than that of sodium chloride. Since commercial sodium hydroxide is commonly sold with a moisture range of 12 – 30% (wt./wt.), this technique does not require complete removal of water for commercial application.

The productions of soda ash and sodium hydroxide are based on well-establish technologies (namely selective precipitation and membrane electrolysis, respectively). Thus, they both have the potential of being commercialised over a relatively short time frame.

## Solid waste and concentrated brine disposal

If ZLD, or significant volume reduction, is to be achieved at CSG sites, the disposal of a solid by-product or highly concentrated brine will be necessary. The NSW Parliamentary Inquiry into Coal Seam Gas provided a key recommendation (Recommendation 5) 'that the NSW Government not approve any coal seam gas activity without a solid waste management plan included in the relevant approval' (New South Wales Parliament Legislative Council, 2012).

Ideally, opportunities for commercial salt production could play a significant role and managing these products. However, as described above, commercial opportunities have tended not to be realised on a significant scale. This is largely because of the relatively low commercial value of the salt products that may be recovered, compared to the costs of recovering them. If such opportunities are not available, waste disposal will be necessary.

The availability of disposal options for concentrated brines and crystallised salts will depend on how they are classified and regulated the state government environment departments. In Queensland, brine is defined in the CSG Water Management Policy (2012) as saline water with a total dissolved solid concentration greater than 40,000 mg/L and is classified as a 'regulated waste'. Crystallised salts from produced water are also classified as a 'regulated waste'. As such, they must only be disposed of at a facility that is authorised to accept the waste under the *Environmental Protection Act 1994*. Transportation of the waste also has tracking requirements under the *Environmental Protection (Waste Management) Regulation 2000*.

As part of the environmental authority application process, Queensland CSG operators are required to show how they plan to manage CSG water including the management of brine. This management must accord with the CSG Water Management Policy 2012. CSG operators are also required to submit an annual evaluation of how effective and appropriate management of CSG water has been. Their environmental authority can also be amended to include measurable criteria to ensure that brine is managed properly. Measurable criteria are criteria against which the applicant will monitor and assess the effectiveness of the management of all CSG water and saline waste associated with the activity (Queensland Government - Department of Environment and Heritage Protection, 2013). These criteria must address the following:

- the quantity and quality of the water used, treated, stored or disposed of;
- protection of the environmental values affected by each relevant CSG activity;
- the disposal of waste.

The NSW EPA does not currently oversee any significant disposal of concentrated brines or crystallised salts (Prifti, 2013). However, according to the NSW Waste Classification Guidelines (Department of Environment Climate Change and Water NSW, 2009), concentrated brines would be classified as 'liquid waste' and would likely require waste tracking when transported within NSW or interstate. The crystallised salts are not preclassified, and therefore a chemical assessment would be required to determine the classification.

### Evaporation basins

Conventional approaches to concentrated brine disposal are essentially the same as those for produced water disposal, as described above. These include the use of surface impoundments and evaporation ponds. The relevant issues are the same as those described for produced water disposal by surface impoundments for evaporation.

### Deep-well injection

Concentrated brines may be disposed of by deep-well injection, just as (non-concentrated) produced waters may be disposed of this way. Queensland CSG tenure holders have conditions on their environmental authorities which state that in accordance with the CSG Water Management Plan, they must investigate (among other options) 'the viability of the injection of brine into a natural underground structure that is geologically isolated and does not contain groundwater and does or could supply water for potable or agricultural purposes'. Santos' Fairview project is currently authorised to re-injected brine into the Timbury Hills Formation under Environmental Authority PEN100178208 (schedule G).

The deep-well injection of brine in NSW would be subject to the requirements of the Aquifer Interference Policy (NSW Department of Primary Industries, 2012).

**Landfill**

Landfill may be considered as a solution for solid waste disposal in some cases. However, since the relevant salts are all highly water soluble, containment is an important issue (see earlier discussion on page 23).

The Queensland Department of Environment and Heritage Protection are currently reviewing their model environmental authority conditions for petroleum (including CSG) activities (Menzies, 2013). However, the only regulated waste that is currently authorised to be disposed of in a purpose-built landfill monocell is solid salt resulting from the treatment of coal seam gas water produced during the conduct of the authorised petroleum activities. It is generally required that the solid salt landfill monocell must be designed and constructed by a suitably qualified person, and in accordance with the following siting requirements (Menzies, 2013):

(a) the landfill is located on land under the freehold ownership of the holder of this environmental authority;

(b) the landfill is not located within 100 m of the boundary of the freehold land;

(c) the landfill must be located such that there are no below ground structures that are likely to bring water into contact with the exterior of the containment and have systems to prevent such contact;

(d) the landfill must be designed to minimise the surface area to volume ratio of the containing structure;

(e) the landfill must be located with a sufficient buffer distance from the boundary of the relevant petroleum tenure / freehold tenure to minimise the risk of any adverse impact on sensitive environments, land with high ecological value, agricultural lands and useful surface water and groundwater;

(f) the landfill must be designed and located so that it is protected from any potential adverse consequences of regional or local flooding to the probable maximum flood level.

A number of requirements for permeabilities and other design features for landfills are also generally stipulated with when constructing and operating the landfill monocell (Table 7).

**Table 7 Permeabilities and Special Requirements for Landfill Features (Menzies, 2013)**

| Landfill Feature | Minimum Permeability (m/s) | Minimum Thickness (mm) | Special Requirements |
|---|---|---|---|
| Base and walls of landfill cells and subcells | $1 \times 10^{-9}$ | 900 | Constructed in at least two (2) layers; and lined with a flexible membrane liner |
| Base and walls of seepage collection dam and leachate drains | $1 \times 10^{-9}$ | 900 | Constructed in at least two (2) layers; and lined with a flexible membrane liner |
| Interim landfill cover | Not relevant | 500 | Interim cover to be applied between salt waste placement events |
| Final landfill cover | $1 \times 10^{-8}$ | 700 | Additional minimum cover of top soil of 150 mm |

Suitable banks and/or diversion drains are typically required to be installed and maintained to exclude stormwater runoff from entering the solid salt landfill monocells. Furthermore, the solid salt disposal landfill monocell must be designed, installed and operated with an under liner leak detection and seepage management system that will allow the rapid detection of any passage of contaminants through the liner and also allow for the collection, monitoring and proper disposal of all such seepage.

According to advice received from the NSW EPA (Prifti, 2013), whether any restrictions would apply to the landfilling of crystallised salts would be dependent upon how such salts were classified under the NSW Waste Classification Guidelines (Department of Environment Climate Change and Water NSW, 2009). This classification would be based on chemical assessment of the salts. There would be no disposal restrictions on the disposal of crystallised salts to an existing landfill if the waste is classified as general solid waste. Restrictions would apply if it was classified as restricted solid waste or hazardous waste via an immobilisation approval. Notably, the NSW Waste Guidelines stipulate that immobilisation approvals will only be issued where it is not possible to reuse, recycle or reprocess the waste.

**Marine discharge**

Marine discharge of highly concentrated produced water brines appears not to have been widely considered, but may present an optimal solution in some circumstances. In some cases, existing infrastructure, such as the marine outfalls of seawater desalination plants may be available via commercial agreement with relevant entities. A number of Australian seawater desalination plants are known to have carefully designed diffuser systems for optimal concentrate dispersion in a suitably turbulent marine environment. Furthermore, many Australian seawater desalination plants are currently operating at less than full capacity, implying the availability of additional discharge capacity. Similarly, even the use of existing municipal wastewater outfall infrastructure may be possible, but additional challenges would need to be addressed in terms of blending ratios and controlling precipitation reactions. Since high salt concentrations can detrimentally impact biological wastewater treatment processes, blending to wastewater outfalls may need to take place subsequent to biological treatment.

By careful compositional analysis to determine appropriate blending ratios, combined marine discharge may present significantly fewer environmental risks than other disposal options. However, this approach would likely face a number of social obstacles including community opposition to marine discharge of wastewaters. Furthermore, concentrated brine solutions would most likely need to be tankered to a suitable blending location, implying the need for increased truck movements in some urban areas.

Due to transportation difficulties and associated high costs, marine discharge of concentrated produced water brines is unlikely to be viable for CSG operations located in inland areas.

# Beneficial reuse of produced water

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

Beneficial use refers to a reasonable quantity of water applied to a non-wasteful use. Potential beneficial use options for produced water include agricultural, industrial and environmental applications. The determination of a specific beneficial use will depend upon state jurisdiction, and the circumstances of each case.

A number of states in the USA have developed formal description of what is permitted to be recognised as a 'beneficial use', as opposed to a waste discharge (National Research Council, 2010). This is significant due to the differing requirements and costs imposed for beneficial use and waste discharge.

## Criteria determining suitable beneficial reuse of produced water

The current management and beneficial uses of produced water are highly dependent on applicable regulations, produced water quality, and costs of transportation and treatment. Produced water quality varies from very high quality (fresh) to having very high total dissolved solids (TDS) concentrations (brackish), which is not suitable for direct reuse. For the relatively fresh (low TDS) produced water, the water may be managed by a wide range of activities including direct discharge, storage in impoundments, livestock watering, irrigation, and dust control. For the water that is not suitable for direct use, treatment will be required prior to reuse, or the water will need to be disposed through deep well injection, evaporation/percolation, or permitted commercial disposal facilities. Key criteria that will determine the suitable use or management of a CSG produced water are described below (Drewes, 2011).

### Water quality

Water quality criteria will be in terms of key characteristics of source waters and definitions of potential uses (e.g., potable, irrigation, in-stream flows). If the quality of produced waters at the source does not meet the water quality needs for a given potential use, the technological feasibility and cost of water treatment can be assessed to determine whether it is possible to match supplier and potential buyer through water treatment. Even in cases where advanced treatment (such as by reverse osmosis) is required, the initial produced water quality may have a significant impact to the cost of treatment, and hence the commercial viability of potential beneficial reuse applications.

### Water quantity

Water quantity, or 'scale' of an operation is important in terms of the volume of water produced over a relevant time interval (e.g., daily, seasonally, annually). Relevant issues include matching of a beneficial use need/demand and the available supply. It will also be important to consider whether water users' needs or demand are sufficient to justify the required infrastructure investment.

### Supply timing and reliability

Supply timing and reliability are important in terms of whether the quantity of produced water that is likely to be supplied matches the needs of potential users, in terms of consistency throughout the year and meeting seasonal demands. This is also likely to be influenced by factors such as energy prices, which influences suppliers' decisions about when wells and gas fields are operated.

### Duration of supply

The number of years the produced water supply is likely to last (as determined by the expected duration of economically profitable energy development from a well), will be a key factor in its suitability for some applications.

### Location/Delivery

The physical proximity of the extraction and use application of produced water will need to be considered. Also important are the types of delivery mechanisms (e.g., in-stream transport, dedicated new pipe and pump infrastructure) that impact the cost and feasibility of transporting produced water from source to application. The availability of existing infrastructure and transportation costs associated with the shipment of produced water (by pipeline or tankering) will have a major impact on whether treated or untreated CSG water is seen or used as a resource.

### Economics

The economics of whether the value to potential users (buyers) of the produced water exceeds the cost to gas companies (sellers) of delivering suitable qualities and quantities of produced water will determine overall viability of reuse. Whether the cost savings or revenues generated for sellers are sufficient to warrant their investment in delivering suitable produced water to buyers (compared to their alternative options for managing the produced water) will be determinative. Important factors will include the availability of alternative water sources and the potential commercial value of goods that may be produced using produced water.

### Institutional factors and associated uncertainty

Factors that influence regulatory, public perception and business operating conditions and decisions for the suppliers or buyers will all be important. For sellers, key institutional factors and uncertainties include water quality liability, beneficial use permits, water rights, fluctuations in energy markets and prices, and other potential changes in regulatory or other institutional factors that impact their ability to operate or complete transactions. Similar uncertainties also impact buyers' decisions about otherwise developing contracts to acquire produced water for their intended beneficial uses.

## Approaches to beneficial reuse of produced water

According to guidelines prepared by the Queensland Government, 'Beneficial use of CSG water is not a method for disposal of it as a waste. Beneficial use of CSG water is only to be carried out at such a level that benefit accrues to the user of the resource' (Department of Environment and Heritage Protection, 2013). This requirement infers considerable restrictions and minimum standards on how produced water could be used in a manner accepted to provide a clear benefit to the user of the resource. Furthermore, the guidelines state that 'the concept of beneficial use is one that does not diminish with time. If CSG water is used in accordance with the guidance in this document, there should be no unexpected issues demonstrated as adverse environmental effects, extending years after the beneficial use activity ends'.

Given available demand and suitable treatment capacity, there is an essentially limitless range of beneficial use applications to which produced water could be applied. As such, the exclusion of any particular application from the discussion provided here should not be taken to imply that such an application is unsuited. However, the specific types of beneficial reuse applications described below have been selected due to apparent interest in their deployment from either within Australia or internationally.

### Surface water discharge / in-stream flow augmentation

Discharge to surface waters is a relatively common means of produced water disposal internationally. For example, In the United States most produced water from the Powder River Basin in Wyoming, Montana and the Raton Basin in Colorado has been piped directly into Tongue River drainage for many years, as the water is relatively fresh (National Research Council, 2010). However a lack of clear regulatory protocols may have contributed to this practice (National Research Council, 2010). The quality and flow rate of produced water discharges into the environment need to be matched to that of the target water source as large quantities of incompatible water can dramatically alter aquatic ecosystem function. Key quality parameters commonly include pH, turbidity, total dissolved solids as well as concentrations of some specific ions such as chloride. In North America, surface discharge is most common at production wells with high volumes of produced water and low concentrations of dissolved solutes (National Research Council, 2010). Nonetheless, treatment to reduce salinity and other constituents, or to manage sodium adsorption ratios (SAR), may be required under prevailing discharge regulations.

In Australia, the quality of discharges to surface waters are regulated by the state-based environment protection agencies (EPAs). In assessing and regulating discharges, the EPAs refer to a variety of guidelines and other documentation, including The Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC & ARMCANZ 2000). The Queensland Government have produced a decision support system to support management decisions relating to the risks posed to surface water systems from CSG water disposal (Takahashi *et al.*, 2011). This incorporates research undertaken to apply direct toxicity assessment using laboratory organisms to assess 'whole effluent toxicity' (Takahashi *et al.*, 2012b).

Most streams and rivers in NSW are ephemeral rather than perennial, meaning that natural flows may be high, but irregular. This may be a significantly complicating factor given the production profile of a CSG well which produces sustained flows (See Figure 2 earlier). In some cases, this may be partially addressed by substantial onsite water storage capacity. Recent Queensland Government research has produced guidance for the management of waterway flow regimes, specifically for the purpose of managing ecosystem health response to CSG produced water release (McGregor *et al.*, 2012).

Establishing that a proposed produced water discharge is environmentally safe may require thorough engineering analysis including hydrodynamic modelling of the discharge; whole effluent toxicity testing and salinity tolerance analysis of the aquatic species endemic to the area of discharge. In circumstances where there is a high density of CSG operations (or other discharging activities) within a water catchment, assessment of the cumulative impacts of these discharges may also be appropriate (Dunlop *et al.*, 2013).

## Agricultural use

Agriculture is the major user of water in Australia (Australian Bureau of Statistics, 2012) and can generally accept a lower water quality than municipal users. However, salinity, sodium adsorption ratio (SAR), and other toxic constituents are all major concerns for agricultural uses.

### Crop irrigation

Irrigation is potentially a high-value beneficial use of produced water. For some relatively low TDS produced waters, or those appropriately amended by ion-exchange processes, irrigation of some crops may be possible without the need for membrane desalination.

However in addition to salinity, sodicity, and toxicity issues, the optimal application rate needs to be determined because using saline water requires more irrigation water to be applied in order to leach salts past the plant root zone. Alternatively, in the USA, subsurface drip irrigation has been used to uniformly discharge produced water below ground, near the bottom of the root zone (Bern *et al.*, 2013a; Bern *et al.*, 2013b). Nonetheless, in either situation, over-irrigation can increase pressure on groundwater systems and force saline groundwater into waterways or cause water tables to rise.

Water quality has a dramatic effect on soil productivity and crop health. The major water quality parameters for crop irrigation include salinity, sodium adsorption ratio (SAR), pH, alkalinity (carbonate and bicarbonate), and concentrations of specific ions (i.e., chloride, sulfate, boron, and nitrate-nitrogen ($NO_3$-N)). Other irrigation water constituents that may affect suitability for agricultural use include heavy metals and microbial contaminants.

Halophytic (salt loving) and salt tolerant pasture species have become important productive means of utilising saline-impacted agricultural lands in Australia (National Dryland Salinity Program, 2001). A number of trials have been conducted to study and promote various species, but no single pasture species, or group of species, appears to be ideally suited to all situations. A range of promising crops and a couple of case studies have previously been reviewed (National Dryland Salinity Program, 2001). However, the aim of that work was primarily to identify means of making productive use of lands already impacted by salinity.

The Queensland Government have provided a detailed assessment and guidance for salinity impacts of coal seam gas produced water on soils and surface streams when used for irrigation (Biggs *et al.*, 2013). Subsequently, the following criteria have been developed to apply to the general approval for beneficial use of produced water for irrigation purposes (Department of Environment and Heritage Protection, 2013):

- Irrigation shall not be applied to Good Quality Agricultural Land (definition cited);
- Irrigation shall not be applied to land where the standing water table of an aquifer that is in productive use is less than 30 m from the ground surface anywhere within the planned irrigation area;
- The maximum electrical conductivity (EC) shall not exceed 3,000 μs/cm;
- The maximum sodium adsorption ratio (SAR) shall not exceed 8;
- The maximum bicarbonate ion concentration shall not exceed 100 mg/L;
- The maximum fluoride concentration shall not exceed 1 mg/L;
- Irrigation techniques shall only include drip, centre pivot or lateral move irrigation machines fitted with low energy precision application systems;
- Flood or related surface irrigation is specifically excluded;
- The annual water application rate shall not exceed the water deficit (calculated on a daily basis);
- Deep drainage, due to irrigation, shall not exceed 15% of the rate of irrigation water applied to the surface;
- Irrigation shall not be undertaken in circumstances where soil erosion is likely to occur;
- Irrigation shall not be undertaken at a rate that results in water run-off to permanent water courses.

Many Queensland CSG producers are currently trialling irrigation projects or are involved in the construction of pipelines that will supply treated produced water to irrigators:

- Santos has established the Fairview Irrigation Project near Injune (South West Queensland), the first large scale produced water irrigation trial in Australia (Santos Limited, 2013). The project uses treated produced water from Santos's Fairview and Springwater operations to drip-irrigate 240 hectares of legume forage crops and 2,000 hectares of Eucalypt plantation. Santos hopes that the Fairview Irrigation Project will produce enough high-quality forage for 1,500 head of cattle, and potentially up to 400 cubic metres of saw logs per hectare for milling when the trees are ready for harvesting.
- Australia Pacific LNG is currently operating two separate irrigation projects (Australia Pacific LNG, 2013). The first is a 300 ha Pongamia plantation. Pogamia is currently being researched elsewhere as a potential biofuel. The second involves irrigating about 530 ha of broad acre crops such as sorghum, chickpea, and lucerne for fodder.
- In 2011, Arrow Energy received a Beneficial Use Approval from the Queensland Government to use treated produced water on irrigated crops, soil and groundwater on its subsidiary owned 12,000 acre mixed cropping and grazing property (Arrow Energy, 2011). Produced water is treated by microfiltration and reverse osmosis at Arrow's nearby Daandine gas field. The RO permeate is then conditioned with a combination of calcium chloride, calcium carbonate (lime), calcium sulphate and magnesium sulphate to meet specific water quality standards imposed by the Queensland Government. The Beneficial Use Approval is valid for five years and allows a maximum of 3653 ML/yr of treated produced water to be irrigated on specific sites. Arrow's long term goal is to supply treated produced water to existing irrigators through substitution of landholders' water allocations.

- Queensland Gas Company (QGC), in partnership with the bulk water service provider SunWater, have recently completed the 20 km Kenya to Chinchilla Weir Pipeline project to deliver treated produced water from its Kenya water treatment plant into Chinchilla Weir (SunWater, 2013a). This project has a design capacity of about 31 GL/yr. The water from the weir will be provided mainly to agricultural water users but some of the water is also expected be used to supplement the Chinchilla municipal water supply.
- QGC and SunWater are also developing the 120 km Woleebee Creek to Glebe Weir Pipeline project. This pipeline will deliver treated produced water from the QGC Curtis Island LNG project for beneficial use by mining and irrigation users along the pipeline route as well to the Dawson Valley Water Supply Scheme (SunWater, 2013b). The project has a design capacity of 36 GL/year.
- In NSW's Gloucester Basin, untreated produced water from pilot production at AGL's Gloucester Gas Project was used for pasture irrigation (RPS Australia East, 2011).

**Livestock watering**

Treated or blended produced water has been used for livestock watering in Queensland as well as North America. For example, In Queensland's Surat Basin, Arrow Energy supplies up to 4 ML per day of untreated produced water to local beef cattle feedlots (Ogg, 2009).

To some degree, animals are able to ingest a variety of different water qualities without adverse health effects. However, highly saline water or water containing toxic chemicals may be hazardous to animals and may even render the milk or meat unfit for consumption. When evaluating the suitability of produced water for livestock watering, a number of factors should be considered, including water quality, local conditions, availability of alternate supplies, seasonal changes, and age and health conditions of the animals.

The Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC & ARMCANZ 2000) provide for recommended concentrations of TDS for livestock, as set out in Table 8.

**Table 8 Tolerances of livestock to TDS in drinking water (ANZECC & ARMCANZ 2000).**

| Livestock | Total Dissolved Solids (mg/L) | | |
|---|---|---|---|
| | No adverse effects on animals expected | Animals may have initial reluctance to drink or there may be some scouring, but stock should adapt without loss of production | Loss of production and a decline in animal condition and health would be expected. Stock may tolerate these levels for short periods if introduced gradually. |
| Beef cattle | 0-4000 | 4000-5000 | 5000-10000 |
| Dairy cattle | 0-2400 | 2400-4000 | 4000-7000 |
| Sheep | 0-4000 | 4000-10000 | 10000-13000* |
| Horses | 0-4000 | 4000-6000 | 6000-7000 |
| Pigs | 0-4000 | 4000-6000 | 6000-8000 |
| Poultry | 0-2000 | 2000-3000 | 3000-4000 |

*sheep on lush green feed may tolerate up to 13000 mg/L TDS without loss of condition or production.

The QLD Government have developed criteria to apply to the general approval for beneficial use of produced water for livestock watering (Department of Environment and Heritage Protection, 2013). These are primarily defined by maximum total dissolved solids concentrations for pregnant and lactating livestock (<5,000 mg/L), beef cattle (<5,000 mg/L), dairy cattle (<4,000 mg/L), sheep/goats (<6,000 mg/L), horses (<6,000 mg/L), pigs (<6,000 mg/L), and poultry (<3,000 mg/L). However concentration limits are also provided for a range of specific inorganic constituents in livestock drinking water including aluminium, arsenic, cadmium, chromium, fluoride, lead, mercury, radionuclides and selenium.

## Industrial use during CSG production

There are a number of onsite activities, directly relating to CSG production, which require water. The onsite use of produced water may have a number of significant advantages, including minimal transportation costs and the ability to directly manage supply. Although minimum quality requirements will apply for many applications, the lack of third-party involvement may significantly reduce the burden of guaranteeing strict compliance with some water quality characteristics.

### Dust control

Some oil and gas regulatory agencies in the USA allow operators to spray produced water on dirt roads to control the dust. Similarly, the Queensland Department of Environment and Heritage Protection has identified dust suppression as a beneficial reuse application for produced water (Department of Environment and Heritage Protection, 2013).

Generally, this practice is controlled so that produced water is not applied beyond the road boundaries or within buffer zones around stream crossings and near buildings. Environmental concerns associated with dust mitigation using produced water include salt build up along roadways; migration of water and associated pollutants off the roadway; impacts to vegetation; and salt loading to river systems. In many cases, the risk of damage to soils or the ecology of flow paths leading away from roads on CSG tenures is likely to preclude application of produced water without some form of treatment (Department of Environment and Heritage Protection, 2013).

In addition to salt-related concerns, impacts of other pollutants in produced water must be considered. These include hydrocarbons, heavy metals, and chemical additives used during drilling, stimulation, or workover of the wells.

The Queensland Government has developed the following criteria that apply to the general approval for beneficial use of produced water for dust suppression (Department of Environment and Heritage Protection, 2013):

- The maximum concentration of total dissolved solids shall not exceed 3,000 µS/cm;
- The maximum sodium adsorption ratio (SAR) shall not exceed 15;
- The maximum bicarbonate ion concentration shall not exceed 100 mg/L;
- Dust suppression can only be carried out in a particular location for a period not exceeding three months, whereupon more permanent solutions for dust suppression shall be developed, if required.

### Hydraulic fracking

Some CSG wells require hydraulic fracking to enhance production. Most fracking operations require hundreds of thousands of litres of water. Local water supplies may not be adequate to meet the demand for fracking water, and trucking of fracking flow-back water off-site for disposal may be very expensive. Produced water or fracking flow-back water can be treated and reused for new fracking operations. The reuse of produced water for fracking may assist in relieving some of the demand from fresh water supplies.

### Drilling water

Drilling operations for the construction of CSG wells require considerable volumes of water. Available (treated or potentially untreated) produced water may be suitable for use as drilling water in some circumstances. However, since drilling operations are generally not continuous at a specific well field, this beneficial reuse application is likely to consume only a small proportion of produced water.

### Fire protection

Treated or untreated produced water, maintained in storage, may provide a certain degree of fire protection. While this is not a reliable consumptive use of produced water, it may represent considerable value in terms of stored volume for such emergencies.

## Off-site industrial use

Off-site industrial use – involving industries other than CSG production – can present attractive beneficial reuse opportunities in some circumstances. A key requirement for financial viability is, in most cases, an industry with a large, relatively continuous and reliable water demand at a single or small number of locations. Likely examples include operations such as coal washing or power-plant cooling. In some cases, it may be possible to use untreated produced water. However, in most cases, treatment will be required, either prior to delivery of the water to industry, or once delivered. Furthermore, many industrial applications, such as coal washing, will still require storage and, ultimately treatment and/or disposal, of the reused water.

Just as the beneficial reuse of produced water requires a reliable demand, most end users will require a reliable supply. Given the water production profile of CSG wells, a continuous level of supply may not always be achievable and some storage capacity may be required to buffer production. Furthermore, the relatively short supply period for produced water from most CSG wells may not provide a strong incentive for major investment in water transport infrastructure.

A number of off-site industrial produced water use projects are currently operational or under development in Queensland. Examples include:

- Arrow Energy provides untreated CSG co-produced water to the Wilkie Creek coalmine coal washing plant near Dalby (Surat Basin) (RPS Australia East, 2011).
- At QGC's CSG-Condamine Power Station near Chinchilla (Surat Basin), produced water is treated onsite for cooling and steam production (RPS Australia East, 2011). Other power stations in the region are also using CSG produced water for operational purposes.
- QGC and SunWater are developing the 120 km Woleebee Creek to Glebe Weir Pipeline project. This pipeline will deliver treated produced water from the QGC Curtis Island LNG project for beneficial use by mining (and irrigation) users along the pipeline route (SunWater, 2013b).

## Potable use

Treating produced water to a level suitable for potable use (i.e., as a component of a drinking water supply) is technically possible using available treatment processes such as reverse osmosis. In some cases, this may prove to be an economically and socially favourable option.

Potable use generally requires a very high level of water treatment and water quality. The Australian Drinking Water Guidelines describe minimum qualities that would need to be achieved in order to be suitable as a drinking water supply. While the guidelines apply to a wide range of drinking water sources, the risk management approach on which they are based requires a detailed system analysis to identify specific hazards (and events) that can compromise drinking water quality. Since coal seam gas produced water is an unconventional drinking water source, it would be prudent to consider additional water quality measures, beyond the current set of water quality guideline values, to ensure suitable water quality for drinking.

Potable reuse of a diverse range of produced water from other petroleum activities is practiced in a number of locations internationally. For example, in Wellington, Colorado produced water from oil production is used to recharge an aquifer that is drawn upon for town supply. It is estimated that this could increase the town's drinking supply by 300 per cent (Stewart, 2006). In the South African municipality of eMalahleni, acid mine drainage from four different collieries is treated by reverse osmosis (and salts are recovered from the brine by precipitation) prior to reuse by a number of applications, including supplementation of the municipalities water supplies (Bhagwan, 2012). It is reported that this project averted a water supply crisis in eMalahleni, while also controlling a major environmental water contamination problem in the region.

Although it is technically feasible to treat produced water to drinking standards, the greatest barrier is likely to be public acceptance. Fears about 'unknown unknowns', that is unknown toxic effects or unknown toxic compounds are likely to affect the public's perception of potable reuse of treated produced water (Society of Petroleum Engineers (USA), 2011). Nonetheless, there are a number of potable water use projects, currently being planned for produced water in Australia, such as the two discussed below.

**Roma Managed Aquifer Recharge Study**

Santos is currently partnering with the CSIRO and environmental consultant URS to study the potential of injecting treated produced water into underground aquifer systems in the Roma area to boost town water supplies (Santos Limited, 2013).

The Roma Managed Aquifer Recharge Study will explore the feasibility of using produced water to augment town water supplies for the Maranoa Regional Council in south-east Queensland. This one-year study is based on the concept of developing a field of wells that would inject up to 3–10 ML/day of treated produced water into the Gubberamunda Formation. It is hoped that this ground-breaking research could relieve the draw on Roma's municipal water supplies. Following detailed reviews, technical investigations and stakeholder consultation, the project team intends to drill a test injection well at Roma and undertake a one-month trial (Santos Limited, 2013).

**QGC/SunWater Kenya to Chinchilla Weir Pipeline project**

QGC, in partnership with the bulk water service provider SunWater, recently completed the construction of the 20 km Kenya to Chinchilla Weir Pipeline project with some of the water expected to supplement the Chinchilla (QLD) municipal water supply (SunWater, 2013a).

This scheme was conceived, designed and constructed by SunWater for QGC. SunWater are also the owners and operators of the scheme. The scheme has involved the construction of an approximately 20 km buried pipeline taking water from a desalination plant at Kenya and transferring it to the Chinchilla Weir. It will also provide connections to a number of farms along the pipeline route and downstream of the Chinchilla Weir. By supplementing water in the Chinchilla Weir, the treated produced water will provide part of the drinking water supply to the township of Chinchilla. This aspect of the project is known as the Chinchilla Weir Water Supply Scheme.

The Kenya Water Treatment Plant was officially opened by the Queensland deputy premier on 23rd October, 2013. In doing so, he stated his opinion that 'there is a huge resource, a huge potential for the replication of this sort of investment' (Australian Associated Press, 2013). It is anticipated that the pipeline will transport up to 85 ML per day of treated produced water.

The treated produced water will be made available for beneficial use by the agricultural customers located along the pipeline with the remainder of the water supplied to customers along the Condamine River, upstream and downstream of the Chinchilla Weir, where it will mix with river water before being taken by customers, including the Western Downs Regional Council. Following the release into the weir, the Western Downs Regional Council will further treat the blended water in their water treatment plant prior to it being made available for public consumption.

SunWater is currently preparing a Recycled Water Management Plan in liaison with QGC to ensure that safeguards are in place for drinking water supplies. This plan will be reviewed and approved by the Queensland Water Supply Regulator, part of the Department of Energy and Water Supply, before water can be discharged into the weir.

# Incidents related to produced water and solids

Discuss any known incidents related to produced water and solids in Australia and internationally (e.g. Pilliga spillage)

The management of produced water from oil and gas operations has been implicated in a number of incidents in countries other than Australia, leading to significant environmental impacts including significant areas of vegetative dieback in the vicinity of spills.

A recent example is the Apache Corp produced water spill of around 10 ML near Zuma City, Alberta (Canada) (Young & Paperny, 2013). This was discovered in June 2013 and is estimated to be the 10th largest produced water spill since 1975. The affected area covered 42 hectares of muskeg (bog) and wetlands. An Apache Corp spokesperson stated that the produced water 'had already been treated to remove hydrocarbons' (Dawson, 2013). A Dene Tha First Nation spokesperson stated that 'every plant and tree died' in the area affected by the spill and that is was likely that the spill had gone undetected for months (Young & Paperny, 2013). Notably, this incident related to produced water from conventional oil and gas recovery, which is commonly highly contaminated and reinjected into extraction wells for disposal.

In 2012, flooding caused by Hurricane Isaac displaced a produced water tank in Louisiana, USA. About 50 barrels (about 8 kL) of produced water was discharged into Lake Washington in the Gulf of Mexico (National Response Center, 2012).

Fortunately, produced water spills of this scale have not occurred in Australia. However, a number of recent incidents are described below. These incidents highlight some of the risks that do exist for produced water management in Australia.

## AGL's Camden Gas Project: Foam and water emission

On 17 May 2011, an AGL gas operations workover team conducted routine maintenance at its Sugarloaf 3 well, located near Campbelltown approximately one kilometre away from the Glen Alpine residential area (AGL, 2011). The team used water, soap and air to clean sand and coal debris from the well. In this instance, the workover team detected a large amount of produced water in the well and increased the amount of soap in order to bring the water to the surface. The degasser choke was fully open and this resulted in excessive foaming. A visible white plume of foam shot upward for two to five minutes and dispersed within 40 metres of the well. The workover team assumed the foam was harmless and did not attempt to adjust the operation of the degasser.

Independent soil sampling concluded that there was no evidence that the release of foam had caused adverse environmental impacts at the well site (AGL, 2011). Although a Sydney Catchment Authority's water storage canal was located down slope of the release area, the Office of Environment and Heritage considered that it was unlikely that the foam would have carried to the canal. The canal was empty at the time of the incident and the canal was built with culverts to prevent surface flows into the canal.

The Office of Environment and Heritage found that the workover crew failed to operate the degasser in a proper and efficient manner, in breach of AGL's environmental protection licence (pollution licence). The Office of Environment and Heritage determined that a formal warning was the appropriate regulatory response given AGL's cooperation and corrective action to reduce the likelihood of this type of incident reoccurring (Bloem, 2011).

## Santos’s Narrabri CSG Utilisation Project: Produced water spills

The Narrabri CSG Utilisation Project’s Bibblewindi Water Management Facility was located within the Pilliga, the largest remnant forest in NSW. Prior to December 2011, produced water was pumped into ponds at the Bibblewindi Water Management Facility, where the water was treated by reverse osmosis and the brine returned to the ponds.

Between 2009 and 2011, a number of leaks and spills occurred at the Bibblewindi Water Management Facility. The former operator, Eastern Star Gas Ltd, did not reliably record these incidents (Santos Limited, 2012b). For example sometime in 2010, a tank at the Bibblewindi Water Management Facility overflowed and an unknown volume of produced water spilled into a nearby ephemeral watercourse that was flowing at the time. However, Eastern Star Gas did make brief record of 16 incidents involving leaks or spills of produced water, as listed in Table 9 (Santos Limited, 2012b).

**Table 9 Eastern Star Gas record of 16 incidents involving leaks or spills of produced water (Santos Limited, 2012b).**

| Date | Incident |
|---|---|
| 13 Jan 2010 | Water leak at the RO plant at the Bibblewindi Water Management Facility. Water had flooded around the main switchboard. |
| 10 Jan 2010 | Water leak at the RO plant at the Bibblewindi Water Management Facility |
| 22 September 2010 | Water leak at the RO plant at the Bibblewindi Water Management Facility |
| 24 November 2010 | Water leak at the well site. Severe washout from wellhead to boundary fence |
| 02 December 2010 | Water leak at the well site. Drain running onto ground without storage tank. |
| 04 May 2011 | Water spill at the well site. Production water overtopped a 1 kL storage drum. The spill area covered 40 $m^2$ within the project boundary. The water soaked into the soil to a depth of approximately 80 mm. |
| 07 May 2011 | Water spill at the RO plant. An operator attempted to start a sump pump but it failed to start as there was no power. The power had been turned off during recent maintenance. |
| 15 May 2011 | Water spill at the RO plant at the Bibblewindi Water Management Facility. A sump pump failed to start after a shutdown of the RO units. The spill area covered 18 $m^2$ and was contained within the gravel pad of the RO units. |
| 18 May 2011 | Water spill at the RO plant at the Bibblewindi Water Management Facility. One of the RO units was designed to perform a brine flush every time the unit was switched off or loses power. There was a power failure that morning at time when the sump tank had a high level of water. The flush water was enough to overtop the sump tank. |
| 25 May 2011 | Water spill at the RO plant at the Bibblewindi Water Management Facility. One of the RO units was designed to perform a brine flush every time the unit was switched off or loses power. There was a power failure that morning at time when the sump tank had a high level of water. The flush water was enough to overtop the sump tank. |
| 08 June 2011 | Water spill at the Bibblewindi Water Management Facility. A brass bung was removed to perform water testing at Pond 1. However the bund could not be replaced. The spill area covered 3 x 30m over the access road and access locations between the Bibblewindi ponds. |
| 25 June 2011 | Water spill at the Bibblewindi Water Management Facility (see discussion below) |
| 03 June 2011 | Water spill at the well site. About 1–3cm of water collected on the ground adjacent to the well site. |
| 21 July 2011 | Water leak at well site. Water spitting out of a pressure release value with no controls in place. |
| 12 August 2011 | Water spill at Bibblewindi Water Management Facility. Silt form the banks of Pond 1 had washed outside the boundary fence. It was noted that the silt could wash into surrounding waterways if not contained. |

| | |
|---|---|
| 14 August 2011 | Water spill at the well site. A drill pit liner had pulled back leaving one wall uncovered. Water ran over the exposed soil. |

On 25 October 2011, an estimated 10 kL of produced water spilled after a transfer pipeline cap burst within a besser block wall at the Bibblewindi Water Management Facility causing water to overtop a sump (Santos Limited, 2012b). The spill travelled about 420 m to a nearby road, resulting in an area of vegetative dieback caused by the produced water (Golder Associates, 2012).

Subsequent soil testing detected elevated salt and sodium in the vicinity of the spill. Furthermore, a black residue of clayey sand was visible on the ground. However, soil investigations concluded that the black residue did not pose a health risk for sensitive land uses (Golder Associates, 2012). On 15 December 2011, operations at the Bibblewindi Water Management Facility were suspended.

In July 2012, the EPA fined Eastern Star Gas $3,000 over two produced water discharge events that occurred in 2010 where produced water from Bibblewindi Water Management Facility was discharged into Bohena Creek (NB. the maximum penalty for a corporation is $1 million). The EPA also served Santos with a formal warning for a December 2011 discharge event that contained high levels of ammonia (NSW Environment & Heritage, 2012).

In June 2012, the Resources Minister Chris Hartcher announced that NSW Government was initiating prosecution against Santos for Eastern Star Ltd's failure to notify the EPA for six months about the October 2012 spill and its failure to lodge environmental management reports (Foschia, 2013). In September 2013, a Santos spokesperson stated 'Santos accepts it will be held responsible for the reporting failures, despite the fact they occurred when the operating company had different ownership and management, and has thus pleaded guilty' (Klan, 2013).

## Metgasco's Clarence Moreton Program: Produced water disposed of at unlicensed facility

Over May 2011–March 2012, Metgasco sent about 1.4 ML of produced water to the Casino sewage treatment plant, which was operated by Richmond Valley Council. The sewage treatment plant is licensed by the NSW Environment Protection Agency (EPA) and the acceptance of the water did not comply with conditions of the license.

The EPA formally cautioned Richmond Valley Council for permitting the practice (Cubby, 2012). The Office of Coal Seam Gas has commented that Metgasco is 'blameless in this matter'. The council was ordered to stop the process in April 2012, almost 12 months after it first began accepting water from Metgasco which was being stored in holding ponds as part of the company's CSG exploration activities. After this incident was reported in the media, the Chief Executive of the CSG company issued a statement stating that 'the use of the sewage treatment plant is an appropriate disposal mechanism for what is essentially just salty water' (Turnbull & Frazier, 2012). Subsequent to the event the NSW Office of Water/NSW Environmental Protection Authority authorised the disposal of a further 5ML of produced water in the same plant.

# Worst case scenarios

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

The assessment of worst-case scenarios is an important aspect of risk assessment, and therefore, of risk management. As described in the following section of this report, comprehensive risk assessment should involve the detailed consideration of what are known as 'hazardous events'. These are events that lead to the exposure of hazards (e.g., salinity, toxic chemicals) by receptors such as people or other species. Hazardous events can result in environmental impacts or loss of availability of otherwise valuable resources.

Hazardous events can include natural phenomena (e.g., earthquake, major rain event or flooding), or could be the consequence of human error (e.g., poor design or operational mistakes) or even sabotage (e.g., vandalism). When assessing risks associated with CSG produced water management, it is appropriate to consider a wide range of potential hazardous events with reference to some of the 'worst case scenarios' described below.

The likelihood of these scenarios occurring is very difficult to generalise and will, to a large degree, depend upon specific circumstances at individual sites. Nonetheless, they are all scenarios that should be considered during planning and risk assessment and subject to risk management when circumstances deem appropriate.

## Stored CSG produced water present risks to adjacent soils, surface water and groundwater

Produced water may be stored onsite in storage tanks or waste impoundment pits or holding basins. There is potential for releases, leaks, and/or spills associated with the storage or CSG waters, which could lead to major impacts to soils, contamination of shallow drinking water aquifers and impacts to surface water bodies. Uncontrolled discharges to ephemeral streams will disrupt natural flow regimes with potentially significant ecological implications.

## Stored concentrates and residuals from produced water treatment pose risks to adjacent soils, surface water and groundwater

Produced water can be effectively treated using water treatment technologies such as reverse osmosis. However, such treatment processes merely concentrate the salts and other contaminants, rather than eliminate them. The concentrate or brine must still be disposed of (Khan *et al.*, 2009). In many cases, these concentrated waste solutions are being stored in impoundments while longer-term solutions are being considered. Spills or overflows caused by flooding may lead to significant loss of containment with major impacts to local soils and surface waters. Furthermore, seepage from impoundments risks impacts to shallow groundwater aquifers and adjacent soils.

## Reinjection of produced waters into other aquifers has the potential to contaminate those aquifers

In some locations, produced water is disposed of by deep well and/or aquifer injection. Such practices have the potential to disrupt future opportunities for beneficial use of the native waters in the receiving aquifer.

## Transportation of produced water and brine presents risks to soil and surface waters

Produced water may be transported from site to site for treatment, disposal or beneficial reuse. This transport could involve the use of dedicated pipelines or, in some cases, tankering. Furthermore, the brine, such as that remaining after reverse osmosis treatment, will also need to be transported for further treatment or disposal. Both the use of pipelines and tankering involve the possibility of spills. These spills may present risks to soils and surface waters in the vicinity of the spill.

## Poorly planned irrigation with produced water presents risks to soil qualities

Attempts to beneficially reuse produced water without adequate treatment for applications such as irrigation poses risks to soil quality and shallow groundwater quality. High levels of dissolved salts and high sodium adsorption ratios can have long-term impacts to the productive capacity of some soils.

## Poorly planned livestock watering with produced water presents risks to animal health and welfare

Reuse of produced water for livestock watering requires careful adherence to water quality requirements, generally determined by maximum total dissolved solids concentrations. Exceeding acceptable levels for various types of animals presents risks to the health and welfare of the animals. Furthermore, produced water may also contain toxic trace inorganic chemicals such as lead, mercury and arsenic. Toxic trace organic chemicals such as benzene may also be present.

## Poorly planned industrial uses of produced water present environmental risks as well as risks to some industrial processes

While potential industrial applications of produced water may be diverse, various risks may be associated with the compatibility of treated or untreated water qualities for various applications. High salinity solutions carry the potential to deposit salt residues in circumstances where water is evaporated, or even exposed to minor chemical changes leading to scaling of transfer pipes and other industrial equipment. Whenever produced water is stored there is an inherent risk of leaks, spills, or escapes, which is a potential threat to surrounding soils and surface waters.

## Poorly planned potable use of produced water presents risks to drinking water quality

The use of produced water to supplement drinking water supplies has inherent risks associated with potential inadequate treatment for the removal toxic chemical substances. While treatment processes such as reverse osmosis can be very effective for the removal of inorganic and organic chemical substances, the actual performance of this process is dependent upon specific membrane selection and operational conditions. In some cases, the removal of some trace chemicals, such as benzene, may be variable and particular attention will need to be paid to the confirmation of final water quality. Practices such as the blending of untreated produced water with RO permeates to manage water stability also present risks in terms of exposure to toxic trace chemical substances.

## Disposal of produced water via sewage treatment plants risks impacts to the treatment process and environmental impacts

Many municipal sewage treatment plants rely on biological treatment processes (e.g, activated sludge treatment, trickling filters) to produce effluents suitable for environmental discharge. However, high levels of salinity (and particularly sudden increases in salinity) can negatively impact the performance of biological treatment processes (Wang *et al.*, 2005; Wu *et al.*, 2008; Li *et al.*, 2013). In such cases, effluent qualities may be severely diminished leading to the discharge of poorly treated effluent to the environment. This may lead to significant impacts to water quality including algal growth and reduced oxygen concentrations. The effluents from many Australian sewage treatment plants are also reused for irrigation, including municipal irrigation (parks, golf courses) and agricultural irrigation. Consequently, these irrigated soils may be the ultimate receptor of the discharged salinity.

# Risk assessment and risk management

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.

Among the key issues to be addressed for any produced water reuse project are the satisfactory assessment and management of health and environmental risks. There are various approaches and frameworks that may be applied to these types of risk assessment and risk management. Some approaches are focused on assessing risks to health and the environment based on the assumption that systems will operate as they are designed to do. Others place a higher emphasis on the possibility of things going wrong, which may occur as a consequence of ‘hazardous events’ such as process failures, extreme environmental events, human errors, and sabotage. As such, the different approaches vary in their applicability to various types of scenarios and risk management. Adding to the level of uncertainty, authors from the CSIRO have recently highlighted the fact that further research is required to better assess the ecological risks from gas recovery operations, including produced water management (Batley & Kookana, 2012).

When considering health risks posed by water contaminants, an important distinction is made between acute and chronic exposure risks. Acute exposure risks relate to potential health impacts from short-term exposure and (for chemicals) are usually associated with high doses. Chronic exposure risks relate to ongoing or long-term exposure and may often be associated with much lower doses or concentrations. The concentrations of toxic chemical substances in water are rarely sufficient to present acute risks and most health concerns (e.g., cancer) are associated with chronic long-term exposure. Nonetheless, with highly saline water, acute environmental impacts can occur through large-scale spills and other types of discharge.

## Frameworks for managing water quality risks

Australian water quality guidelines developed since 2004 have exhibited a significant philosophical departure from the traditional focus on ‘end point monitoring’ as a means of water quality compliance. Instead, they have adopted a ‘risk management’ approach, also embodied in the World Health Organization Guidelines for Drinking Water Quality and the Water Safety Plans described therein. This approach emphasises the assessment and management of possible means by which contaminants may be introduced to water, and preventative measures for minimising such contamination. With reduced emphasis on end-point monitoring, Australian regulations have focussed on implementation of risk management plans.

In many cases, the management of produced water and associated salts from CSG operations may have interacting fields of influence with the management of current and future drinking water supplies. This overlap could arise as a consequence of undertaking CSG operations within drinking water catchments, where both intentional and accidental releases may potentially influence drinking water quality. Alternatively, disposal or beneficial reuse applications may lead to potential interactions with drinking water quality management. In all such cases, the ongoing effective management of risks to drinking water quality would be facilitated by a consistent approach to risk assessment and risk management for CSG-related activities.

### The enHealth Framework

Australia has important national guidelines for the assessment of human health risks from environmental hazards (enHealth Council, 2012). These guidelines are commonly referred to as the ‘enHealth guidelines’ and are consistent with the human health risk assessment framework that was pioneered by the US National Research Council nearly three decades ago (National Research

Council, 1983) and now used (in adapted form) throughout the world. While the importance of this framework and the general approach are not in doubt, it is arguably insufficient for properly assessing risks associated with CSG extraction or exploration activities.

The enHealth framework requires the identification and characterisation of 'hazards', which in this case applies to potentially toxic chemicals. The assessment of dose-response relationships of the chemicals, in conjunction with assessment of their expected levels of exposure are used to determine the risks associated with specific hazards (chemicals). However, an important consideration for CSG activities, which is not adequately addressed by the enHealth guidelines is that of potential 'hazardous events' (see the following section for details).

## Australian Water Quality Guidelines

The *Australian Drinking Water Guidelines* (ADWG) introduce a framework for management of drinking water quality (NHMRC & NRMMC 2011). A key component of the framework is system analysis and management, which involves understanding the entire water supply system, the hazards and events that can compromise drinking water quality, and the preventive measures and operational control necessary for ensuring safe and reliable drinking water.

The ADWG provide the following key definitions for a water quality risk management context:

- A **hazard** is a biological, chemical, physical or radiological agent that has the potential to cause harm;
- A **hazardous event** is an incident or situation that can lead to the presence of a hazard (what can happen and how);
- **Risk** is the likelihood of identified hazards causing harm in exposed populations in a specified timeframe, accounting for the severity of the consequences.

The ADWG accept that realistic expectations for hazard identification and risk assessment are important and that rarely will enough knowledge be available to complete a detailed quantitative risk assessment. Instead, the guidelines have adopted a risk prioritisation process, adapting the risk matrix approach presented in the risk management guidelines published by Standards Australia & Standards New Zealand (2004). A likely outcome of such risk assessments is the identification of specific areas where further information and research is required.

### Assessment of hazardous events

It is general accepted within the Australian water industry that the greatest risks to drinking water quality are not those that can be identified according to when the activities are being undertaken in a manner in which they are proposed and approved. On the contrary, the greatest risks tend to be associated with unintended circumstances, such as extreme weather events or human errors or misjudgements. As an example, large CSG operations, especially those involving fracking, require extensive quantities of chemical substances to be present on site. This chemical storage creates risks of accidental releases, such as spills or leaks. Surface spills or releases can occur as a result of tank ruptures, equipment or surface impoundment failures, overfills, vandalism, accidents, fires or improper operations. Released fluids may flow into a nearby surface water body or infiltrate through the soil to the groundwater. Any risk assessment that only considers conditions associated with normal operations, without comprehensive assessment of potential hazardous events will underestimate the true environmental and human health risks associated with the operation.

The incorporation of hazardous events in risk assessment (and risk management) is most effectively addressed by the Australian Drinking Water Guidelines (NHMRC & NRMMC 2011) as well as the Australian Guidelines for Water Recycling (NRMMC, EPHC & AHMC 2006). Accordingly, the consultation of these guidelines should be mandatory for the assessment of all CSG proposals and activities, until dedicated national CSG risk assessment guidelines can be made available.

The level of risk for each hazardous event can be estimated by identifying the likelihood (Table 10) that it will happen and the severity of the consequences (Table 11) if it does. Guidelines and criteria developed for specific combinations of source water and end use should be referred to when estimating risk. The likelihood and consequences can then be combined to provide a qualitative estimation of risk, using a suitable risk matrix (Table 12). Risks that are judged to be very high will generally be the focus of critical control points.

**Table 10 Qualitative measures of likelihood (NRMMC, EPHC & AHMC 2006)**

| Level | Descriptor | Example description |
|---|---|---|
| **A** | Rare | May occur only in exceptional circumstances. May occur once in 100 years |
| **B** | Unlikely | Could occur within 20 years or in unusual circumstances |
| **C** | Possible | Might occur or should be expected to occur within a 5- to 10-year period |
| **D** | Likely | Will probably occur within a 1- to 5-year period |
| **E** | Almost certain | Is expected to occur with a probability of multiple occurrences within a year. |

**Table 11 Qualitative measures of consequence or impact (NRMMC, EPHC & AHMC 2006)**

| Level | Descriptor | Example description |
|---|---|---|
| **1** | Insignificant | Insignificant impact or not detectable |
| **2** | Minor | Health – Minor impact for small population<br>Environment – Potentially harmful to local ecosystem with local impacts contained to on-site |
| **3** | Moderate | Health – Minor impact for large population<br>Environment – Potentially harmful to regional ecosystem with local impacts primarily contained to on-site. |
| **4** | Major | Health – Major impact for small population<br>Environment – Potentially lethal to local ecosystem; predominantly local, but potential for off-site impacts |
| **5** | Catastrophic | Health – Major impacts for large population<br>Environment – Potentially lethal to regional ecosystem or threatened species; widespread on-site and off-site impacts |

**Table 12 Qualitative risk estimation (NRMMC, EPHC & AHMC 2006)**

| | Consequences | | | | | |
|---|---|---|---|---|---|---|
| Likelihood | | 1-Insignificant | 2-Minor | 3-Moderate | 4-Major | 5-Catastrophic |
| | A Rare | Low | Low | Low | High | High |
| | B Unlikely | Low | Low | Moderate | High | Very high |
| | C Possible | Low | Moderate | High | Very high | Very high |
| | D Likely | Low | Moderate | High | Very high | Very high |
| | E Almost Certain | Low | Moderate | High | Very high | Very high |

The Australian Drinking Water Guidelines apply the assessment of hazardous events primarily to potential impacts to human health. However, the Australian Guidelines for Water Recycling clearly indicate the application of this approach to environmental risks as well.

An important group of potential hazardous events related to the management of produced water are various types of spills that may occur. A study of produced water spills in California between 1979 and 1995 identified categories of spills relating to their cause and typical consequences (Gamache, 1996). These included:

- Spills that involve, or were close to the wellhead, including stuffing box leaks, damaged polish rods, loose well bonnets, plugged flowlines and cracked pipes. These spills typically involved small volumes;

- Spills that involve pipeline corrosion, whether internal or external. Pipeline corrosion resulted in a high frequency of spills across all volume categories;
- Pipeline spills that were caused by mechanical problems away from the wellhead, including breaks at welds, loose flanges, accidental leaks due to damage by heavy equipment and other causes, breaks at repair clamps, overpressured lines, and breaks at pipeline gauges. Mechanical problems resulted in a small frequency of spills;
- Valve source leaks caused by human error, vandalism, and broken valves from freezing or vibration. Valve problems resulted in a high frequency of spills;
- Tank overflow spills caused by human error, level indicator malfunctions, pump failures, power failures, instrument error including loss of instrument air to valves, and bad switches. Group five spills overflows occur most frequently in the medium to large volume range categories. The strength of this trend illustrates the importance of bunding around tanks and maintaining bunds to contain any spills;
- Unusual spills including wellkicks, steam breakouts through the annulus, blowout preventer equipment (BOPE) failure, sump overflows, tank leaks from ruptures and splits, oil forced out of a gas stack, packer failures, and unknown sources. This group represented less than 12 per cent in all the volume ranges. However, spills in this group were considered important because they generally occur as isolated cases and are difficult to prevent and control.

To assess and manage risks associated with produced water in a manner consistent with Australian water quality guidelines, the likelihood and consequences of each of these types of hazardous events (for example) would require careful case-by-case analysis.

**Health-based guideline concentrations**
Health-based guideline concentration values are provided for a large number of organic and inorganic chemicals. These represent concentrations that, based on present knowledge, do not result in any significant risk to the health of the consumer over a lifetime of consumption. Guideline values for chemical substances were derived using human data where available or, in most cases, by using animal data adjusted by appropriate safety factors for extrapolation to humans.

The ADWG explicitly recognise that pathogenic substances present the greatest threat to the safety of drinking water supplies. However, there is currently only one water quality stipulation for monitoring of microorganisms. This is that *Escherichia coli (E. coli)* should not be detected in a minimum 100 mL sample of drinking water. If detected, immediate corrective action must be taken. Although most *E. coli* is non-pathogenic, the intention is that the absence of this abundant faecal organism is an indication that drinking water treatment and protection of distribution systems have been effective. As such, the role of *E. coli* is for verification of effective management.

It is now well established that some waterborne pathogens are more resistant to some common drinking water disinfection processes (e.g., chlorination) than *E. coli*. Therefore, monitoring of *E. coli* serves as a useful verification of the disinfection process, but cannot be relied upon entirely. Instead, water quality and safety is maintained by the use of identified ‘critical control points’ (CCPs), which are steps, processes or procedures that control significant hazards. A number of CCPs have been determined, based on their established relationship to effective pathogen control. CCPs can include a range of treatment (e.g., disinfection) and non-treatment (e.g., catchment management) barriers. Continuous monitoring of CCPs is preferred where possible.

The reliance upon CCPs is a departure from a traditional ‘endpoint monitoring’ approach to water quality management and represents a crucial component of the overall ‘risk management’ approach. It is widely supported within the Australian water industry and by public health regulators.

**Multiple-barrier water supply systems**
The multiple-barrier concept is based on the principle of establishing a series of barriers to preclude the passage of harmful constituents into the water system, to reduce risk to appropriate levels. This

concept is embedded in Australian water quality guidelines including the Australian Drinking Water Guidelines and the Australian Guidelines for Water Recycling. The advantage of the multiple barrier approach is that the probability that multiple processes will fail simultaneously is small, and the public would be provided a degree of protection even in the event that one of the barriers fails.

## Whole water toxicity testing / bioanalytical techniques

Chemicals rarely occur alone in environmental water samples. Rather, they occur as complex mixtures. This leads to two significant problems for environmental scientists: a vast list of individual chemicals to analyse and their potential mixture effects. In some instances, a few well-known chemicals can explain the majority of the toxic effect, but often the identified chemicals only explain a small fraction of an observed effect. This is frequently the case with municipal wastewaters (Chapman *et al.*, 2011). Also, while the concentrations of individual chemicals can often be below any critical levels (such as single-chemical guidelines), the interaction between individual chemicals and the resulting mixture effects may give rise to concern (Escher & Leusch, 2011). The chemical components of a mixture can have variable impacts on the effective toxicity of other components. These so-called 'mixture interactions' can lead to synergistic (greater than the sum of the parts) or antagonistic (less than the sum of the parts) effects on the overall toxicity.

The application of bioanalytical techniques is well established for the assessment of a number of ecotoxicological endpoints and some of the most important techniques have been applied to the assessment of CSG produced waters in Queensland (Shaw, 2010; Takahashi *et al.*, 2012b). However, there are no standardised procedures for incorporating potential effects of mixtures into the process of identifying safe levels for human exposure.

There are established methods for aggregating estimates of risk when the composition of a chemical mixture is known or can be inferred using relevant data. Such methods usually aggregate risk by assuming that risks are additive, but this assumption implies that chemicals producing the same adverse health outcome act in the same way, which may not be the case. For example, endocrine disruption can operate through different receptors, pathways and signalling webs, and it is difficult to establish whether mixtures of endocrine disrupting chemicals will produce additive effects (with or without synergistic or antagonistic interactions), particularly at the low levels typically associated with environmental exposure.

The use of bioanalytical tools is a rapidly emerging approach that may provide a measure of the overall mixture effect of a water sample (Escher & Leusch, 2011). By using the toxic equivalency concept and by comparing the toxic equivalent concentrations ($TEQ_{bio}$) derived from bioassays with the calculated toxic equivalent concentrations from the chemicals identified and quantified by chemical analysis ($TEQ_{chem}$), it is possible to obtain an estimate of the fraction of known and unknown chemicals contributing to toxicity and gain an appreciation of the total toxic potential of the complex mixture.

The standard methods to assess chemical safety of water are based either on epidemiological studies or animal testing (*e.g.*, rats, mice). Epidemiological studies are retroactive, and it would be greatly preferable to identify a problem sooner and not wait for a population response. Animal testing is widely used in single chemical risk assessment where exposure doses can be very high, but are of limited relevance for drinking water quality testing because of their relatively poor sensitivity (*i.e.*, they are not sensitive enough to detect subtle effects) and high costs (both financial and ethical). However, our understanding of chemically-mediated toxicity has greatly improved over the past decades, and we now know that the initial response of an organism to exposure to chemicals in water is at the molecular and cellular level (Escher & Leusch, 2011).

Measuring toxicity at the cellular level (as is done using bioanalytical tools) thus provides a valuable tool for hazard assessment. It is important to recognise that not all cellular-level effects will translate into whole organism toxicity due to the presence of repair and compensation mechanisms. The cellular trigger is the necessary first step towards observable toxicity in a sequence of events called adverse outcome pathway. The adverse outcome pathway leads from the cellular response over the organ response to observable effects on the organism or population level, such as onset of disease. Therefore, the initial interaction of the chemical with its biological target or the direct cellular response to this event provides a sensitive measure of potential toxicity.

While the ultimate protection goal is human health and population health, it is possible to use *in vitro* bioassays as screening tools to quantify the cellular pathways of toxicants, which are not only indicators of the hazard potential of chemicals but can also give information on the relevant modes of toxic action. Thus bioassay responses are more than surrogate measures of the presence of micropollutants in a given water sample but can be rather used as indicators for groups of chemicals with common mode of toxic action. These indicators are potency scaled, *i.e.,* more toxic chemicals have a higher weight in a bioanalytical indicator and unknown chemicals and complex transformation products are accounted for even if they cannot be resolved from other mixture components.

### The Draft National Harmonised Regulatory Framework - Coal Seam Gas

The National Harmonised Regulatory Framework (NHRF) is being developed a guidance and reference tool for Australian federal, state and territory government regulators for the coal seam gas (CSG) industry (Standing Council on Energy and Resources (COAG), 2012). Its purpose is to provide a suite of national and global leading practices to consider and implement in the assessment and ongoing regulation of proposed projects for CSG exploration and production.

The draft NHRF identifies a series of ‘leading practices’ aimed at ensuring that CSG activities are undertaken in an acceptable manner based on environmental and social concerns. The first four leading practices are identified as being ‘overarching leading practices apply equally to each of the four core areas of well integrity, water management and monitoring, hydraulic fracturing and chemical use. These are:

1. Undertake a comprehensive environmental impact assessment, including but not limited to, rigorous chemical, health and safety and water risk assessments;
2. Develop and implement comprehensive environmental management plans which demonstrate that environmental impacts and risks will be as low as reasonably practicable (ALARP);
3. Apply a hierarchy of risk control measures to all aspects of the CSG project;
4. Verify key system elements, including well design, water management and hydraulic fracturing processes, by a suitably qualified and authorised person.

These practices are clearly well aligned with the risk assessment and risk management practices prescribed by Australian water quality guidelines. However, the specific guidance level of detail provided is small compared to what is currently referred to and used by the Australian water industry. There is no apparent cross-referencing to the existing water quality guidelines and hence no obvious attempt to ensure that the approaches adopted for CSG risk management are, in practice, consistent with established practices for water quality management in Australia.

## Baseline monitoring for produced water and salts management

A range of management strategies for produced water and salts are identified in this report. These may generally be categorised as disposal practices or beneficial use practices. Risks relating to potential environmental impacts have been identified for both types of practices. Efforts for the management of these risks should be focused primarily on the identification of safe practices and the avoidance of unacceptable impacts. Nonetheless, in many circumstances, it may be desirable to collect relevant ‘baseline’ data, prior to proceeding with a management practice, in order to undertake a retrospective assessment of environmental impacts.

## Potential measures for baseline monitoring programs

There are a range of potential measures that could be considered for baseline monitoring, depending upon the nature of the proposed produced water or salt management practice and the nature of the environment that may be impacted. Among the environments most likely to be impacted under some circumstances are surface water bodies, groundwater aquifers and soils.

### Surface water bodies

Surface water bodies may include natural rivers, streams and lakes, as well as artificial structures including farm dams and larger reservoirs. Relevant water quality measures, commonly used for assessing the condition of surface water bodies include total organic carbon (TOC), total dissolved solids (TDS) or electrical conductivity (EC), turbidity, colour, dissolved oxygen (DO), alkalinity and pH. The concentrations of specific ions such as sodium ($Na^+$), calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), ammonium ($NH_4^+$), nitrate ($NO_3^-$), sulphate ($SO_4^{2-}$), carbonate ($CO_3^{2-}$), bicarbonate ($HCO_3^-$) and chloride ($Cl^-$) may also assist in source tracking future water quality impacts.

More direct assessments of ecological health of waterways can be achieved by surveys of biota within the waterway. These may include an assessment of the numbers and diversity of zooplankton (primarily small insects such as water fleas), phytoplankton (eg, algae), fish and other large organisms such as snails. Attached aquatic plants including as grasses and moss also provide an indication of ecosystem type and health. Vegetation diversity and density on waterway banks may be surveyed as future trends may indicate changes to flow patterns, scouring and erosion.

A biological monitoring framework designed to identify sensitive indicators of the response of aquatic ecosystems to the disposal of CSG produced was recently developed for the Queensland Government and could be expected to be largely applicable to most regions of NSW (Takahashi *et al.*, 2012a).

### Groundwater aquifers

Water quality of groundwater aquifers is most commonly characterised by salinity measures such as TDS or EC, as well as by the concentrations of some specific ions including $Na^+$, $Ca^{2+}$, $Mg^{2+}$, $CO_3^{2-}$, $HCO_3^-$ and $Cl^-$ since these commonly determine the suitability of the aquifer for various applications such as for irrigation, livestock or human consumption. For shallow ('water table') aquifers, bacterial contamination may also be assessed by measures of E. coli or total coliforms. Measures of pH and redox conditions (Eh) facilitate an understanding of aquifer condition, but are prone to change when extracted waters are exposed to the atmosphere.

### Soils

Relevant soils for baseline assessment may include those which are proposed to be irrigated with produced water, or those which may be unintentionally exposed to produced water, concentrated brines or disposed salts. Important measures for soils include salinity and sodicity. Salinity, which represents the total ionic composition, may be determined by a number of means, including the measurement of EC. Sodicity represents the amount of exchangeable $Na^+$ in the soil and has a strong influence on the soil structure. Dispersion occurs when clay particles swell strongly and separate from each other on wetting. On drying, sodic soil becomes dense, cloddy, and without structure. Other key soil compositional characteristics include pH, organic carbon, and nutrients including nitrogen (N) and phosphorous (P). The presence of some potentially toxic elements (such as boron (B)) may also be monitored.

Direct measures of soil permeability may also provide useful supplemental information to ionic composition. Other common physical soil health assessment indicators include aggregate stability (the extent to which soil aggregates resist falling apart when wetted), available water capacity (the quantity of water that a soil can store for plant use), surface hardness (soil surface penetration resistance), and subsurface hardness (penetration resistance encountered at depths below the surface).

Standard biological soil characterisation tests include measures of ‘active carbon’ (the fraction of soil organic matter that is readily available as a carbon and energy source for the soil microbial community) and ‘potentially mineralisable nitrogen’ (the amount of nitrogen converted from an organic form to inorganic form by the soil microbial community over a set incubation time).

### Temporal and spatial aspects of baseline monitoring programs

Many environmental systems naturally exhibit high degrees of spatial heterogeneity and temporal variability. Surface water systems in particular can be highly dynamic, exhibiting considerable physical, chemical and ecological change over seasonal, annual and longer timeframes. This natural variability may present significant challenges for the collection of ‘representative’ data, both prior to and subsequent to any potential impacts from produced water and salts.

It will commonly not be possible to collect data directly pertaining to the full range of natural variability for many relevant environments. However, baseline monitoring programs should be designed to encompass sufficient variability in environmental conditions so as to facilitate an assessment of likely overall variability in parameter measurement. This may be achieved by first characterising the variability in relevant environmental conditions (eg, temperatures, river flow rates, local rainfall, etc). In many cases, the relevant information may be available from existing historic or current monitoring programs. These variability’s may then be presented ‘probability density functions’ (PDFs) and key aspects of these PDFs (eg, 10th percentile, median and 90th percentile) estimated. Parameter monitoring data may then be targeted to coincide with these points on the PDFs. This approach would facilitate an estimation of the overall likely variability of most parameters with limited monitoring capability.

### The use of control or reference sites

It some cases, it may be possible to identify suitable ‘control’ or ‘reference’ sites, which are unlikely to be (intentionally or unintentionally) impacted by produced water or salts. This would facilitate direct comparison between an impacted and non-impacted site. Since some (spatial and temporal) variability will always be inherent for environmental systems, the use of multiple reference sites would be appropriate in order to characterise the inherent natural variability prior to comparison with an impacted site. Suitable reference sites should be carefully selected with the aim of identifying sites subject to comparable environmental (and other) variability.

## Remediation of impacts related to produced water and solids

Remediation of contaminated groundwater is complex and costly. Effective bioremediation of groundwaters highly contaminated with biodegradable organic chemicals has been demonstrated (Sedran *et al.*, 2004; Zein *et al.*, 2006). However, remediation of waters impacted by inorganic salts can only be treated by physical processes such as reverse osmosis (see discussion on page 37). In all cases, these remediation processes involve extraction of the groundwater, followed by treatment at a suitable treatment facility. The treated water could then be disposed of or beneficially used. Alternatively, it is possible to recharge many groundwater aquifers by managed aquifer recharge (Kazner *et al.*, 2012; Ward & Dillon, 2012).

Remediation of soils can be undertaken by a variety of approaches. The simplest approach is by amendment, by which additional chemicals (such as calcium and magnesium) or organic matter (usually from composted material) may be added to improve physical structure and biochemical properties. While this approach may improve soil drainage and growing conditions, it does not directly remove the salt from the system. Salt removal may be gradually achieved by carefully planned drainage and removal of drainage water from the site. An alternative (or complimentary) approach is known as phytoremediation, involving the use of salt-tolerant crops to bioaccumulate salts into the plant material. The plant material can then be harvested and removed. For example, recent research has demonstrated effective phytoremediation of salinity affected soil with soybean (*Glycine max (L.)*

*Merr.*), narrow leaf cat-tail (*Typha angustifolia L.*) and sea holly (*Acanthus ebracteatus Vahl*) (Boonsaner & Hawker, 2012).

In NSW, there is a duty to report pollution incidents causing or threatening material harm to the environment (See Protection of the Environment Operations Act 1997 ss 147–153). A pollution incident includes a leak, spill, or escape of a substance, or circumstances in which this is likely to occur. Material harm includes on-site harm as well as harm to the environment beyond the premises where the pollution incident occurred. Sufficient detail of the incident must be reported to enable appropriate follow-up action. Failing to report a pollution incident posing material harm to the environment is an offence that carries a maximum $2,000,000 penalty for corporations.

Furthermore, two NSW Codes of Practice have been developed for CSG activities, for Well Integrity and for Fracture Stimulation Activities. These codes identify ‘leading practices’ around risk management and these include a range of incident and emergency response plans, and notification processes.

# Knowledge gaps

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

There are a number of important knowledge gaps related to the management of produced water and solids. All of these knowledge gaps could be addressed by additional research effort. Key knowledge gaps are summarised below.

## Variability of produced water qualities in NSW basins

Produced water composition can be highly variable, both in terms of total dissolved solids concentration and specific inorganic and organic chemical composition. Australia (and NSW) currently lack sufficient detail on the variability between basins and between individual wells within basins. This information is required to inform decisions about the nature of appropriate potential beneficial reuse applications and necessary treatment requirements. Much of the relevant data may be collected during pilot testing for proposed specific CSG operations. However, there would also be significant value in understanding water quality variability more broadly across individual basins, since this knowledge would assist in regional planning of produced water management. Understanding these requirements and opportunities on a broad scale would enhance the ability for optimised beneficial reuse and environmental outcomes.

## Treatment processes for concentration (and ZLD) of produced waters

Reverse osmosis is a relatively well established process for produced water desalination. However, water recoveries by reverse osmosis are generally limited to 70-80%, producing a concentrated waste stream as a by-product. A number of emerging technologies (such as forward osmosis and membrane distillation) offer potential opportunities for further concentration of brines (towards zero liquid discharge) at acceptable energy and financial costs. However, these technologies are yet to be fully developed or proven at full scale operation. Further developments in this area will provide opportunities for improved water recovery and more financially viable sustainable management of dissolved salts.

## Commercial opportunities for salt recovery and beneficial salt use

Commercial opportunities for salt recovery and beneficial use of those salts would provide a major driver for the improved management of produced water and associated dissolved salts. While some promising opportunities have been considered in recent years, commercial applications have failed to fully develop. The cost effective recovery of high or medium value salt products from concentrated brines remains as an elusive knowledge gap. Serious consideration should be given to the establishment of a ‘co-operative’ of CSG companies operating in Australia to fund the commercial production of appropriate salt products. Even if it was anticipated that this operation would run at an ongoing commercial loss, this could be considered as a viable solution for managing large quantities of waste salts.

## Satisfactory disposal opportunities for concentrated produced water brines

In the absence of commercial opportunities for salt recovery from concentrated produced water brines, satisfactory disposal opportunities will need to be identified. Disposal by landfill or land application poses environmental risks unlikely to be manageable over the long term. This is because the hazardous substances (salts) in produced water are non-degradable and their ongoing effective containment may only be achieved for a finite period. Long term land application will result in everincreasing risks to soil and water. Marine disposal, potentially via existing outfall infrastructure, is one opportunity that appears not to have been comprehensively assessed.

## Trace chemical composition of highly treated produced water for potable use

The use of highly treated produced waters to supplement drinking water supplies is of increasing interest in Australia and internationally. With careful membrane selection and optimised operational conditions, it is known that reverse osmosis (possibly with additional treatment processes) can produce very high quality water. However, under less ideal conditions, various small molecules (particularly low molecular weight, uncharged organic chemicals) may be poorly rejected by RO membrane and persist at measurable concentrations in the membrane permeate. Since treated produced water is not a well-established drinking water source, there is scant information available regarding which chemicals may persist, or even which chemicals to look for. The use of bioanalytical assays may provide an effective means of verifying safe drinking water quality in such cases.

## Harmonisation of CSG risk management practice with Australian water industry risk management practice

Risk assessment and risk management already play an important role in the assessment and regulation of all CSG projects in Australia. However, there may many, fundamentally different, approaches to undertaking risk assessment and risk management. Throughout the last decade, the Australian water industry has made significant developments to applying a carefully conceived, comprehensive approach to risk management, as articulated in numerous important national guideline documents including the Australian Drinking Water Guidelines (NHMRC & NRMMC 2011) and the Australian Water Recycling Guidelines (NRMMC, EPHC & AHMC 2006). It is apparent that current risk management of produced water is not aligned with the Australian water industry approach and there are no corresponding national guidelines detailing how that may be achieved by the CSG industry. Harmonisation of the two approaches/industries should be undertaken to ensure a consistent approach to water resource (and public health) risk management. This is particularly important in cases where CSG activities may impact upon current or potential future drinking water supplies.

## Best practices for deep-well injection of produced water or brine

Deep-well injection of produced water and brine is not currently a common practice in Australia (unlike some parts of the USA). However, it is apparent that there is considerable interest in this process as a future means of waste disposal. In NSW, the practice would be regulated under the Aquifer Interference Policy. However, there is currently no broadly accepted national guidance document for how deep-well injection could be undertaken in order to best manage the inherent risks, such as risks to groundwater quality. Such a document should be developed with the involvement of the CSG industry, the Australian water industry, environmental regulators and other stakeholders, and be subject to formal endorsement by relevant Australian regulatory authorities.

## Assessment of social impacts from the transient nature of produced water availability for some activities or locations

Produced water may provide significant quantities of water in some locations for some time. However, at any location, the period for which produced water will be available is finite. This period may be less than a decade for individual wells, or as long as a few decades in gas fields where it planned to drill numerous wells over time. In any case, it will be necessary to ensure that the short-term increase in water availability does not lead to the development of industries and communities that come to rely on the ongoing availability of unsustainable water resources. Failure to prevent this would have significant social, environmental and economic impacts. There appears to be little current experience or expertise for the careful consideration of these possible consequences when determining appropriate uses for available produced water.

## Public acceptance of some potential produced water disposal and beneficial reuse practices

There are a number of potential produced water and brine disposal methods that have not been developed on a large scale in Australia. These include deep-well injection and (possibly) marine discharge. In addition to any technical issues requiring to be addressed, these disposal methods may possibly have low levels of public acceptability. The likely public acceptance of these methods, as well as ways to manage public acceptance appear not to have been comprehensively researched. Similarly, some beneficial use applications, such as potable use of highly treated produced water have not been closely examined in Australia.

# Other comments

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

Three key issues that were not specifically solicited for discussion in this report, but are of considerable importance are identified below.

## Produced water treatment and management costs can impact the viability of a CSG project

The costs associated with managing produced water may be a significant factor in the overall profitability of CSG production. The total costs commonly include (Aqwatec, 2013):

- Construction of treatment and disposal facilities, including equipment acquisitions;
- Operation of those facilities, including power, chemical additives and personnel;
- Management of residuals or by-products resulting from the treatment of produced water;
- Permitting, monitoring, and reporting;
- Transportation.

If an operation cannot reduce water production rates or sufficiently minimise water management costs, the cost of managing produced water may impact the viability of the whole operation. Once the cost of managing produced water exceeds the value of the hydrocarbon produced from the well, the well is usually shut down (Aqwatec, 2013).

The costs of produced water management vary extensively depending on the location, disposal method, the type of waste (quality and quantity), and the extent of competition in the local or regional area. Direct discharge and impoundment/evaporation are the least expensive management options, while commercial tankering of water or concentrate are the most expensive options for management of produced water.

## Produced water treatment and management carbon footprint

There is an apparent general trend in produced water management away from low-technology solutions (e.g., evaporation basins and direct discharge) towards higher levels of treatment (e.g., reverse osmosis and even ZLD). While there may be some clear environmental (and social) advantages of high-technology treatment, this approach also tends to come with an additional carbon footprint. This increase in carbon footprint should be accounted for when considering optimum management options for produced water.

An appropriate approach to the consideration of environmental impacts of produced water management options would be to undertake a Lifecycle Assessment (LCA) analysis of the options considering a diverse range of established mid-point or end-point LCA indicators.

## Produced water beneficial reuse and disposal: Social concerns

There are numerous social issues regarding the management of produced water that should be considered alongside the technical and economic issues.

One important social issue is ‘public acceptance’ of various practices, including disposal practices (e.g., deep-well injection, marine discharge) and beneficial use practices (e.g., supplementation of drinking water supplies). In order to address such public acceptance issues, it will be important to have a better understanding of the factors that increase or decrease public acceptance of various practices in relation to produced water management.

A second social concern relates to the temporary or transient nature of produced water availability. High levels of water availability may encourage the development of various water-intensive activities. However, there is a risk that, without careful planning, industries or communities could become reliant upon a water supply without fully appreciating that it is not sustainable in the long-term. In such circumstances, there are risks of major social, environmental and economic impacts when large quantities of produced water cease to become available.

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