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Discussion Paper for
Office of NSW Chief Scientist and Engineer

WATER TREATMENT AND COAL SEAM GAS

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EXECUTIVE SUMMARY

This paper examines possible treatment methods for the produced water associated with the recovery of methane from coal seams (CSG). The CSG industry is in a major development phase in Queensland with CSG facilities being established to provide gas for four export LNG plants. Within NSW the position is more subdued despite a looming crisis in the availability of gas to meet the State’s needs. CSG is produced at Camden and at several other minor sites and significant facilities are planned for Gloucester and Narrabri. There is community opposition to these developments, despite a softening of attitudes amongst the rural community in Queensland since major facilities have been established.

At the heart of CSG recovery lies the handling of the associated water. Is it a waste stream that has to be disposed of at minimum cost? Will its disposal adversely affect farmland and communities? Or should it be regarded as an asset that can provide a useful source of water to a frequently parched State? Volumes of produced water to be treated are large, but they reduce as the well ages, with the estimated life of many wells being of the order of a maximum of 20 years. Produced water is high in sodium chloride and bicarbonate and may pick up toxic organic chemicals from the coal seam. Untreated it is not suitable for stock watering. If used for agriculture without treatment it is likely to lead to salinisation and degradation of the land. The quantity of salt that it contains generally prohibits its use for stream supplementation and its use within the mining and related industries runs the risk of increasing the salt burden of the environment.

New South Wales is perhaps more fortunate than Queensland in that the bulk of coal seams of interest for CSG exploitation lie in the Sydney and Gunnedah basins which have a lower water content than the Surat basin in Queensland. Indeed, the AGL Camden operation which has been in operation for 14 years, produces comparatively little production water.

A study of the literature suggests that the treatment of production water by an integrated process involving microfiltration, ion exchange and reverse osmosis can produce water suitable for aquifer injection for future potable purposes or water suitable for irrigation. Potentially toxic substances such as heavy metals, organic compounds and radioactive species can be removed in the process with the water, after chemical adjustment, able to meet drinking water guidelines. Alternatively, with lesser treatment, it can be prepared for a variety of less demanding applications. Alternative treatment methods are described in the literature but, for the most part, they are in the pilot demonstration phase with the more promising offering application sometime in the future.

The principal problem with produced water treatment lies in the disposal of salt concentrates from the integrated process. Water recoveries in excess of 90% are possible with the concentrate needing further water removal by thermal processes if the salts present are to be recovered in the solid phase as crystals. Uncertainty exists whether there is an international market for the salt or whether a further process is needed to separate marketable components.

Because of its earlier need to deal with a burgeoning industry, Queensland is perhaps further down the track than NSW in developing regulations and guidance on treatment processes for CSG production water and the beneficial disposal of products. NSW could well adopt the Queensland protocols.

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TERMS OF REFERENCE

The Terms of Reference for the project were provided by the Office of NSW Chief Scientist and Engineer:

The paper is to identify options and approaches to managing produced water and flowback water from Coal Seam Gas extraction. This includes storage; handling and transport; water treatment recycling and purification; water disposal and concentrated brine/ salt disposal and beneficial re-use of produced water. The paper would discuss factors including how to choose the right technology, what monitoring is required, and what environmental considerations must be made in developing a produced water management plan:

a. *Characterisation - What studies are required in advance before deciding on the treatment, reuse and disposal approaches?*

b. *Water treatment - Overview of range of treatment approaches (including best practice (nationally and internationally)) used for CSG produced water and flow back water. For treatment and recycling, this could include a discussion of technologies include reverse osmosis, granular filtration, ion exchange etc, as well as emerging technologies such as membrane distillation, forward osmosis etc. In describing technologies, please discuss how the following factors guide technology selection:*

    i. *Characteristics of produced water stream to be processed or disposed of (eg chemical characteristics [organic/inorganic; pH; valency; ionic radius; concentration, presence of radioisotopes etc], physical characteristics [eg particle size; charge; concentration]), other relevant characteristics..*

    ii. *Receiving environment for waste and permeate after treatment, and required characteristics of the water, waste, brine etc.*

    iii. *Economies of scale, and cost*

c. *Re-use, handling and disposal of produced water, permeate/ purified water and concentrated waste/brine. Provide an overview of the range of handling, re-use and disposal approaches (including best practice (nationally and internationally)) used for CSG produced water and flow back water. For handling, this could include issues such as storage and transport options and other activities. For re-use, this could include irrigation, chemical extraction for products, 'mine the brine' solutions etc. For disposal, this could include reinjection, release to treatment plants and infrastructure, environmental release, disposal of concentrated salts etc. In discussing approaches to handling, disposal and beneficial reuse, please discuss:*

    i. *What environmental health and safety considerations need to be taken into account*

    ii. *What industry opportunities are available for beneficial re-use, or what market schemes can be used for disposal (eg salinity trading schemes)*

iii. *Whether economies of scale dictate options for management.*

d. *Once treatment and disposal systems are in place, what approaches are used for testing, monitoring and sampling water prior to treatment, and following treatment, this could include water sampling and soil sampling.*

e. *What notable new technologies and innovation are on the horizon or in development for treating, storing, transporting, re-using or disposing of water, and wastes from CSG?*

f. *What are the potential 'worst case scenarios' related to the water treatment and management? What are the risks (i.e. likelihood and consequences) of such scenarios occurring?*

1. INTRODUCTION

This paper is the third in the series of discussion papers on aspects of produced water derived from coal seam gas exploration and recovery commissioned by the Office of the NSW Chief Scientist and Engineer as part of the CSG review. The review as a whole is intended to draw on material in the public domain and the input of experts to develop a robust scientific basis on which the NSW Government can develop sound protocols for the orderly development of the coal seam gas industry in NSW whilst at the same time ensuring the protection of the health of citizens and the environment.

Previous studies in the review[A,B] have examined the available technical literature and reports by and for government agencies in considerable detail. They have addressed the ten terms of reference which range from a consideration of the origin and properties of coal seam gas production water through to processes and technologies available for treatment of the water and/or its disposal or beneficial use. Instances of adverse incidents related to the handling or use of production water are examined and the risk profiles of various technologies are evaluated. Knowledge gaps are identified.

A. Gore, D and Davies, P (2013) Department of Environment and Geography, Macquarie University, *Background paper on produced water and solids in relation to coal seam gas production*: Report prepared for Office of NSW Chief Scientist and Engineer

B. Khan, S and Kordek, G (2013) School of Civil and Environmental Engineering, University of New South Wales, *Coal Seam Gas: Produced Water and Solids*: Report prepared for Office of NSW Chief Scientist and Engineer

The present study draws on the two previous studies but has at its heart a more detailed look at the process aspects of handling produced and flowback water and the most promising technologies for ensuring that the water recovered is used in a way that will preserve the amenity of the land from which the coal seam gas is extracted and pose acceptable risk to community health and the environment. It has particularly drawn on the more recent information available through the internet including company newsletters, institutional reports, government advisories and fact sheets and electronic publications by environmental groups. Frequently termed “grey” literature, this material has not necessarily been peer reviewed. Drawing it together to respond to the terms of reference has been a significant challenge and the responses provided should be treated as considered expert opinions rather than conclusions based on hard scientific facts. The literature on coal seam gas is voluminous and closely linked to areas such as oil and gas recovery, groundwater, hydrogeology, water treatment, agriculture and the environment. Not surprisingly, given the scale of the industry in the USA, it is dominated by input from that country.

Across the world the recovery and use of unconventional natural gas is being heralded as a way of lowering carbon dioxide emissions whilst alternative energy options including nuclear fusion are being developed. Within the USA, both coal seam gas (8% of total natural gas produced) and shale gas industries (30% of total) are in substantial growth phases. Although similar in principle, shale degasification occurs at much greater depths than coal seam gas recovery, a point sometimes lost in the current debate over the dangers of coal seam gas recovery where problems experienced with shale gas recovery are attributed to the recovery of coal seam gas.

Community concerns over the recovery of coal seam gas in New South Wales focus on a number of issues[3,5,10,12,14,16,17,18,23,24,30,32,36,43,50,58,65,73,93,100]

i. Risk of aquifer contamination with the result that shallow aquifers drawn on for water for agricultural and human consumption will no longer be usable. The concern focuses on the migration of salts and also on the vertical migration of methane. Whilst good drilling and well completion practices would seem able to mitigate these problems, operators are now usually obliged to monitor overlying water aquifers. For the purposes of the present study, inter-aquifer transfer will not be further considered, except in so far as an evaluation will be made of deep well injection as a possible way of disposing of highly saline water from surface water treatment processes and the risk it could impose of inter-aquifer transfer of salts.

ii. Risk of salinization of soil or destruction of flora and stream habitats if untreated or partially treated produced water is used for irrigation or surface dispersal.

iii. Problem of removal of salt or saltwater concentrates from remote sites.

iv. Impact of spills or overtopping of process plant releasing concentrates to the environment.

v. Surface disturbance to farmland caused by gas-recovery and water treatment infrastructure

vi. Noise and disturbance to rural lifestyle

vii. Loss of value of rural properties with tied groundwater allocations if future groundwater availability becomes uncertain

Items i to iv will be considered in this paper.

The recovery of coal seam gas has been actively practiced in the USA since 1980. Some of the experience gained in the US can be translated into the Australian environment. However, practices do vary and a deal of produced water in the US industry is either re-injected into deeper aquifers or released after partial treatment into local rivers.

Within Australia, the coal mining industry has long practised methane removal from gassy mines, and in some instances since 1996 the methane is recovered and used as a fuel. But the widespread adoption of CSG recovery has been a feature only since the turn of the present century, with deposits of CSG in Queensland being the driving force for an on-shore unconventional LNG industry. Despite an initial approach that perhaps did not focus sufficiently on the environmental impacts given the scale of developments planned, the Queensland Government has, in recent years, initiated legislation, developed regulations and put together good-practice manuals that are now impacting favourably on the industry. A much more sophisticated approach to the treatment and beneficial use of produced water now prevails, with some excellent examples of best practice that could be readily adopted in NSW.

At the Federal level an attempt is being made to develop a coordinated policy with governing legislation and an independent advisory committee to oversee the developing industry.

It is noteworthy that Australia has developed advanced expertise in water treatment, especially in regard to technologies like membrane technology and there is the opportunity in solving the produced water problem for the coal seam gas industry for world class expertise to be developed and beneficially offered overseas where coal seam gas recovery industries are being developed.

2. PRODUCTION AND FLOWBACK WATER

Coal seam gas (CSG) is recovered from subterranean coal seams by a desorption and collection process in which the hydrostatic pressure on the seam is released by the pump-out of water. Water and gas rise separately to the surface via an annular collection pipe in the well. Depending on the porosity of the seam, the technique of fraccing may be used to increase the permeability of the seam in the neighbourhood of the base of the collection well but such fraccing is more commonly used in shale gas recovery where formations are tighter. Wells are typically spaced 400 to 1,200 m apart with interconnecting pipelines aggregating the flows from individual units. Coal seams in use or being explored in Australia for CSG recovery are typically 300 – 1,000 m below the surface. Depending on the geology of the area, fresh water aquifers may lie above the coal seam.

Because coal seams are relatively permeable and wide areas can be accessed from a small surface footprint using techniques such as horizontal drilling, fraccing is only undertaken when absolutely necessary or in the late phase of well depletion when gas release has markedly slowed. For example, the long-term Queensland based producer, Arrow Energy has fracced only 4% of its current wells[6] and fellow Queensland operator Australia-Pacific LNG proposes to fracc only 30-40% of its wells in the Talinga project[9]. Santos has indicated[105] that at the Pilliga site it does not propose to fracc any wells. AGL has successfully fracced 117 of 144 wells at its long-established Camden site[149] which has been operating since 2001, with a water-and-sand-only fraccing mixture in 60% of these wells. Fraccing a well typically requires up to 1 ML of water to which a range of chemicals have been added. 80% of this water is recovered at the surface within two days[28]. Coal seam water taken during this period is termed **flowback water** and differs from **production water** obtained once gas flow commences in that it can contain chemicals used in the fraccing process and typically has a higher TDS (e.g. 10,000 mg/L) than production water (e.g. 5,000 mg/L)[28]. Both earlier Discussion Papers consider at length the nature of these chemicals and their inherent toxicity. It is noted that BTEX chemicals (benzene, toluene, ethylbenzene and xylene) are now banned from fraccing fluids in NSW and Queensland.

The quantity of production water obtained from an individual well can vary widely. Batley and Kookana[28] report values of up to 100KL/day per well.

Key Australian players in the CSG scene are given in table 1 below:[6,9,20, 25,57,62,105]

Company	Location	State	Basin	Comment
AGL	Camden Gloucester	NSW NSW	Sydney Sydney	Mature phase Expected to Commence 2016
Metgasco	Casino	NSW	Clarence-Moreton	New developments temporarily stalled
Tower Gas	Appin Tahmoor Towers	NSW NSW NSW	Sydney Sydney Sydney	Mature phase handling colliery gas

Santos	Narrabri Fairview Roma Scotia Pony Hills Arcadia	NSW QLD QLD QLD QLD QLD	Gunnedah Bowen Bowen Bowen	Proving) All operating or under) development))))
Arrow Energy	Daadine Tipton Tara Dalby Wandoan Chinchilla Kogan/ Goondiwindi Roma Moranbah	All QLD	Surat Surat Surat Surat Surat Surat Surat Surat Surat Bowen	) All operating))))))))
Australia Pacific LNG	Rolleston Spring Gully Strathblane Talinga Taloona Yellowbank Condalbri Reedy Creek Orana	All QLD	Bowen Surat Surat Surat Surat Surat Surat Surat	) Under development)))))))
Origin Energy	Ironbank Kincora Roma PangaeBowen	All QLD	Surat Surat Surat Surat Bowen	) Gasfields operated) by Origin))
Queensland Gas Company	Condamine Kenya Wendoan Woleebee Windibri	All QLD	Surat Surat Surat Surat Surat	) Gasfields and) water treatment) plants to handle) 200 ML/d)
Westralian Gas and Power		WA		Exploration only

Data on the quantity of produced water compared with the amount of recovered gas are sparse in the public domain, but it would appear that the ratio is about 63ML/PJ in the Bowen Basin and 260 ML/PJ in the Surat Basin giving an average for the Queensland coalfields of 110 ML/PJ.

Despite fears that the quantity of water being extracted in CSG recovery around Australia is high, the Productivity Commission[79] has pointed out that it amounts to no more than 4% of the water extracted for agriculture from the Great Artesian Basin, though locally, in areas like the Walloon coal reserves in the Surat Basin in Queensland, it may have a significant impact on the groundwater availability for agriculture.

The industry has shown dramatic growth in Queensland in the last decade with an aggregation of the smaller players and a greater focus on the Surat Basin. Most recently, approval has been given for the construction of a possible four world-scale liquefied natural gas (LNG) plants which will take CSG from the Queensland coal fields, primarily those in the Surat basin, and prepare it for export. $70 billion is being invested, with the scale of the operation to rival LNG developments on Australia's Northwest Shelf. Companies involved are the Queensland Gas Company (QCLNG), Santos (GLNG), Australia Pacific LNG (APLNG) (a consortium involving Origin Energy) and Arrow Energy. Media reports[C] suggest that the demand for CSG will rise dramatically, as only APLNG has sufficient current CSG production capacity to meet the new demand. The other projects will need to buy gas from other CSG producers in the market placing upward pressure on the price for natural gas in Australia which is expected to rise from its current $3-8 per GJ to $10-12 per GJ for 12 months in 2015 before settling back to $8 per GJ. The sale price of the gas will have a bearing on the funds available for produced water treatment.

One outcome of the strong growth of the industry in Queensland has been the increasing sophistication of the industry and increased overview by the regulators, both in Queensland and Federally. The economics or other-wise of a CSG venture is dependent on a number of factors:

- gas productivity of the coal seam
- difficulty in extracting the gas
- amount of co-recovered water and the extent to which it needs to be treated
- remoteness of location and availability of collection systems
- waste disposal
- peripheral activity that needs to be carried out to obtain a social licence to operate

Within the US and some decades ago, the industry evolved based on using the cheapest possible disposal method for co-recovered water (evaporation ponds, surface water augmentation and deep well injection of brines). In its initial days the Australian industry primarily used evaporation ponds or surface disposal if the salt content was sufficiently low. In Queensland and NSW the use of evaporation ponds was banned in 2010 and 2011 respectively, with the focus now being on the beneficial use of the co-produced water. In Queensland, preferred uses are (in order of preference)[103]:

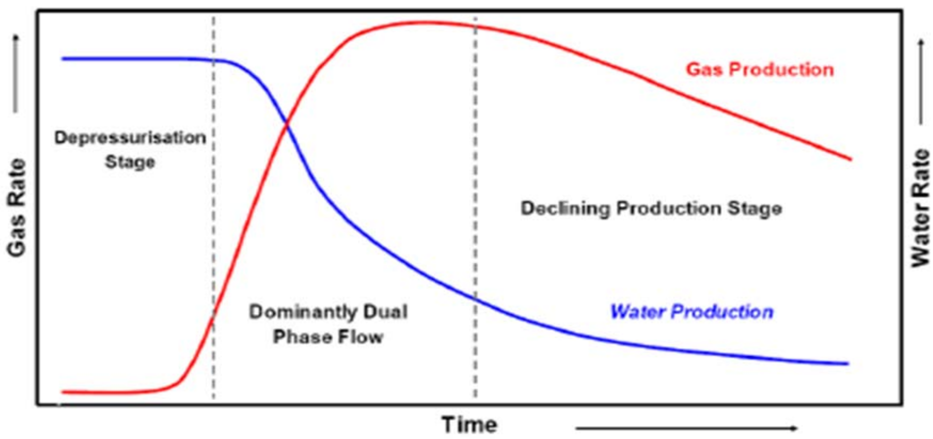
- injection into depleted aquifers for recharge purposes
- substitution for an existing water entitlement
- supplementary water for existing irrigation schemes
- new irrigation use, with a focus on sustainable irrigation projects
- livestock watering
- urban and industrial water supplies
- coal washing and dust suppression
- release to the environment in a manner that improves
- local environmental values.

These have been adopted by companies such as Australia Pacific LNG.

C *Australian Financial Review (18 March 2014).)*

In general, no significant quantities of produced water are generated during the exploration phase in the CSG industry, with the question of handling produced water coming to the fore during the proving and production phases. Queensland and NSW regulations now require the development of an approved water management plan for pilot production and full production wells. Depending on the hydrogeological circumstances, bringing a well into production may require the removal of water for a prolonged period (up to a year in some instances), during which time it must be safely stored or facilities for its acceptable management developed. Singular difficulty for the CSG industry is that the volume of produced water is high initially and then declines as gas flow increases, eventually to fall in 10-20 years as the coal bed surrounding the well becomes gas depleted. The figure below shows a typical response curves for a single well. Within a CSG field the sequence of bringing on-stream of individual wells can be scheduled to get a more even load on the water treatment plant, but this is not straightforward on a green-field site and significant on-site storage may be required.

Figure 4. Typical changes in the rates of water and gas production from a CSG well



Source: QWC2012.

Co-produced water-energy ratio for CSG production[147, various]

Basin	Co-produced water-energy ratio (ML/PJ)
Bowen Basin (Qld)	50
Surat Basin (Qld)	193
Sydney Basin (NSW)	1
Gunnedah Basin (NSW)	1-36
Gloucester (NSW)	7-23
Clarence-Moreton Basin (NSW)	2
Powder River Basin (Wyoming, USA)	245-415
Alberta Plains Basin (Alberta, Canada)	0-30
Raton Basin (USA)	202
San Juan Basin (USA)	5
Uinta Basin (USA)	63
Piceance Basin (USA)	181

In producing the above table it is noted that as flows decline over the life of a well, estimates are very approximate but do show the relative “wetness” of the relevant coal seam in so far as CSG recovery is concerned .

Section 4 discusses the characterisation of produced water, but, in general terms the salt level may vary from 200 to 10,000 mg/L total dissolved solids (TDS)[4] or even higher, with the average TDS across the Queensland CSG industry being 6,000 mg/L[4] which is about one-sixth that of seawater. Using the above water to gas ratios and, as a first assumption, with a water treatment cost is $\$2/m^3$ for a system that ensures beneficial use of the water (e.g. reverse osmosis), this represents an impost of 3-15% on the gas sale price. Further developments and increased scale of operation would be expected to bring the water treatment cost down.

3. CHARACTERISATION OF PRODUCTION AND FLOWBACK WATER

An essential feature of deciding on a treatment, re-use and disposal approaches is a thorough characterisation of the produced water during the early, plateau and decline phases of well or site operation. Whilst the exploration phase will have provided an indication of the quality of initial production water likely to be encountered, developing data for later mature stages of well operation will require projection of this information into the future based on experience of similar wells, and the extent to which multiple well operation on a CSG site can be coordinated to maintain some consistency of feed quality to a water treatment plant. Similar comments apply to where the water is of sufficiently low salinity to allow it to be used without extensive further treatment. It would be normal practice and permitted under regulatory protocols to first place production water in a holding pond, but the size of this pond will be limited for cost and environmental measures. Studies[4] have shown that there can be considerable variability in the quality of produced water across a basin and that inter-basin variability can be extreme. Coal seams in the Sydney basin are "drier" than those in the Surat and Bowen basins and this can markedly affect the economics and environmental factors associated with CSG recovery.

Essential information in designing a treatment/re-use strategy for production water on a given site would include:

Parameter	Purpose	Comment
Flow and Composition of Produced Water		
Daily output per well and site of production water	Needs to cover projected life of well and site, with estimates for the latter based on experience	Unless in established CSG field will probably have to rely on **production trial** on small number of wells with attendant handling of gas and produced water. Time scale of months.
Suspended solids in water	Will they decline with time?	Possibly not a major factor if fraccing has not been used.
Dissolved solids (TDS)	Full chemical analysis required	These are the primary determiners of treatment process that will allow beneficial re-use of production water.
Any significant organics present	Possible toxicity if not subsequently removed	Can have deleterious effect on production water treatment process
Site Geology and Hydrogeology		
A geologic map of the site and associated hydrogeological studies	Aquifers, aquitards identified and groundwater flows characterised.	Essential for predicting production water flows with time and the possibility of aquifer recharge by treated water or disposal of treatment concentrates in deep, isolated aquifers.
Baseline Groundwater Monitoring		
Water levels, pressure head and composition of locally recovered groundwater	Provides baseline for future operations	Provides basis for assessing likely impact of CSG recovery and resilience of used groundwater aquifers. /Continued

Parameter	Purpose	Comment
Soil Characteristics of Potential Re-Use Sites		
Target re-use site soil characterisation	Details of soil structure and permeability and chemical components present.	Need to confirm the ability of soil to handle residual salt in treated water and the optimum irrigation protocol to avoid salinization or degradation of land.
Surrounding Environment		
Detailed description of local environment including flora, fauna, surface water flows	Provides basis for decision on possible surface disposal of treated water	Essential if it is decided that surface disposal is preferable to aquifer recharge or other beneficial reuse.

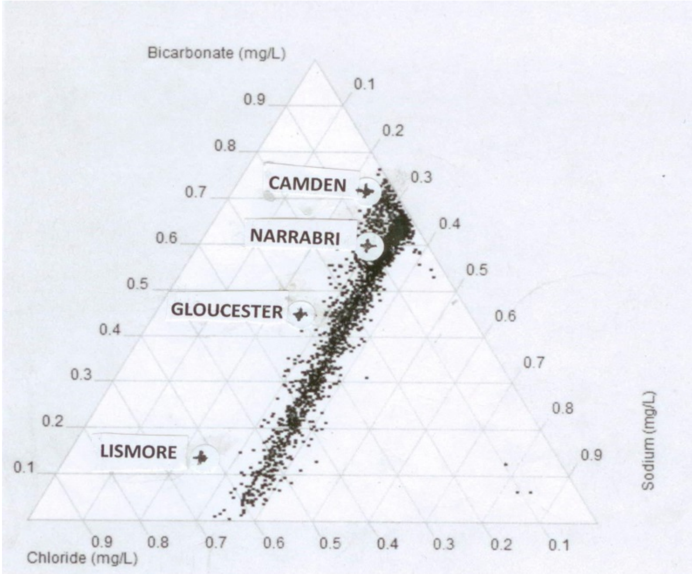
The two previous studies[A,B] have examined the chemical analysis of produced water from a number of CSG recovery sites and, in one instance, have compared them with overseas figures. Whilst parameters like pH, suspended and dissolved solids are important, a more detailed chemical analysis that includes all likely salts, organic substances and potential process foulants is important. Fraccing, if practised, can introduce a range of foreign substances, some having questionable toxicity.

The table overleaf comments on the components that are typically analysed for and compares the results obtained at several CSG recovery sites.

Parameter	Camden[A]	Metgasco[A] Lismore	Santos Narrabri PEL 238[144]	Surat Basin[A] (range)	USA (range)[A]	USA Dahm[B] 2011	USA Powder River[15]	USA San Juan[40]	AGL Gloucester CR06[26]
pH	7-8.5	8.81	8.3	8-9	8.2-8.5	5.4-9.3	7.5	8.0	9.6
TDS	7790	3,070	21,000	4,500-6,000	370-3,460	150-39,000	1,750	7,789	4,385
TSS			30			0-580		52	276
SAR				107-116	25	0.2-452	26		
Boron	0.06	313	0.87		0.20-0.26	BDL-4.7	100	107	0.3
Fluoride	1.3	0.78	5.8		1.0	1.2-20	1	2.2	1.4
Sodium	3030	557	6,200	300-1,700	130-880	12-5,260	619	2,352	1,710
Magnesium	4	11	4		0.01-14.6	0.1-511	12	16	4
Silica	9.6		23		12	3.6-37		13	13.7
Sulfate	<1	15	4	5-10	0-12	BDL-1,800		8	<1
Chloride	287	1,430	2,000	590-1,900	6.3-64.0	BDL-2,190		18	1,270
Potassium	10	777	45		35	1.7-970	7	16	12
Calcium	4	13	7			1.5-5,530	25	43	9
Manganese	0.007	0.9	0.009			BDL-2.0	20	0.2	0.5
Iron	0.13	7	0.28			BDL-258	2.8	5	
Bicarbonate (as $CaCO_3$)	6540	236	10,100	580-950	290-2,416	117-13,900	1,920		2,020
Strontium			1.3						3.1
Barium			13	8-9					<0.001

Values are in mg/L - BDL Below detection limit - Range indicates range of values for multiple sites –Absence of figure denotes no information available - Superscripts refer to references cited.

Water Quality Characteristics for US Produced Water from Coal Seams[40]



The table and figure show that produced water from coal seams in Australia has (with one exception) significantly higher total dissolved solids than produced water in the USA. Produced water from the San Juan Basin (the USA's oldest methane producing area) lies closest to that in Australia, but Australian produced waters are proportionately higher in bicarbonate and generally plot to the left of US waters on a triangular diagram. This means that Australian waters are buffered and technologies (such as reverse osmosis) trialled in the US may not map directly to Australian conditions. Also, the high bicarbonate (unless removed) poses difficulties for the use of untreated production water for irrigation or surface discharge.

Within NSW, AGL is conducting a series of irrigation trials using Coal seam gas production water from its development wells in Gloucester blended (1:3) with water from a local river for the production of forage crops. Initial results[131] are promising with minor build-up in the salinity level of the soil in the trial area. It has also established 45 groundwater monitoring wells to establish baseline data for the CSG recovery site which is planned to accommodate 110 wells in the proposed stage 1 development in 2016. AGL is also collecting extensive hydrogeological data to allow it to build an effective model of aquifers and associated groundwater flow.

At its Narrabri site, Santos is conducting production trials on 8 wells and monitoring groundwater at 300 wells. It has relocated its water treatment plant to Leewood, outside the Pilliga forest and is developing hydrological models of the Narrabri site. It has submitted a preliminary Environmental Impact Statement to the NSW Government which includes characterisation of the likely produced water. Through its Produced Water Management Plan[144] for proving production well PEL238 at Narrabri, an indication of the full produced water characterisation parameters used by Santos can be gained. The Santos results are reproduced overleaf. These would seem an adequate set of parameters for produced water characterisation, provided they were supplemented occasionally by analysis for dissolved organics and radionuclides, neither of which Santos found at levels likely to be of environmental or health concern.

Santos Energy NSW – Produced Water Management Plan: PEL238, PAL2 and PPL3

Parameter	Units	Produced Water *Average concentration*
Total Dissolved Solids (TDS)	mg/L	21,000
Temperature	°C	15 - 30
pH		8.33
Total Suspended Solids (TSS)	mg/L	30
Turbidity	NTU	50
Carbonate (CO3)	mg/L as CaCO3	670
Bicarbonate (HCO3)	mg/L as CaCO3	10,100
Chloride (Cl)	mg/L	2,000
Sodium (Na)	mg/L	6,200
Sulphate (SO4)	mg/L	4
Calcium (Ca)	mg/L	7
Magnesium (Mg)	mg/L	4.0
Potassium (K)	mg/L	45
Strontium (Sr)	mg/L	1.3
Barium (Ba)	mg/L	13
Fluoride (F)	mg/L	5.8
Silica (SiO2)	mg/L	23
Boron (B)	mg/L	0.87
Iron (Fe, dissolved)	mg/L	0.28
Cyanide (Total)	mg/L	0.004
Manganese (Total)	mg/L	0.009
Aluminium (Total)	mg/L	0.10
Phosphorus (Total)	mg/L	0.14
Ammonia	mg/L as N	13
Nitrate	mg/L as N	0.10
Nitrogen (Total)	mg/L	14
Copper (Total)	mg/L	0.022
Zinc (Total)	mg/L	0.023
Arsenic (Total)	mg/L	0.010
Chromium (Total)	mg/L	0.006
Hexavalent Chromium	mg/L	<0.05
Cadmium (Total)	mg/L	0.0053
Mercury (Total)	mg/L	0.00071
Molybdenum (Total)	mg/L	0.00064
Nickel (Total)	mg/L	0.0013
Antimony (Total)	mg/L	0.00012
Selenium (Total)	mg/L	0.0150
Uranium (Total)	mg/L	0.0001
Lead (Total)	mg/L	0.0037

4. WATER TREATMENT PROCESSES

A wide range of water treatment processes has been developed over the last century both to prepare naturally available water for potable and agricultural use and clean up waste water such as urban sewage and aqueous effluents from industry. These processes can remove suspended solids, salts and dissolved organic and biological species and adjust the properties of the final water so that it is fit for purpose, being the provision of fresh or recycled urban water or water fit for agricultural or industrial re-use or release to waterways. The principal determiner in the choice of a process is reliability and cost. A massive international industry has grown in providing process design advice, plant construction and operation and equipment. Most of the major international players are represented in Australia and there is a wealth of local expertise.

An improved knowledge of water chemistry underpins the newest developments. Traditional technologies such as sedimentation, flocculation and biological treatment still have an important role to play, but the emphasis has possibly changed to the additional removal of salts, dissolved organic species and hazardous substances. With its pioneering work on low pressure microfiltration, Australia has played its part in producing membrane solutions which complement hitherto cost-inaccessible technologies like reverse osmosis. The overall cost of some of the more complex water treatment processes has dropped substantially making them available to tasks like the treatment of CSG production wastewater.

Most water treatment processes are designed to handle a steady flow of water over a period of many years. They are designed to handle feed water of a relatively consistent quality, albeit with the occasional spike in the concentration of an inlet component. The industry as a whole is tightly focused on steady and safe operation and the monitoring of all aspects of plant performance. It is also experienced in the safe handling of the potentially hazardous chemicals used in conventional water treatment.

Applying current water treatment technologies to the treatment of CSG production water faces the following challenges:

- The flow from individual production wells changes with time, being high initially and then declining
- The chemical composition of the feed may change over the life of the well
- It can be difficult to quickly turn down the flow of water from a producing well in the event of treatment plant upset
- The life of a CSG facility is 10-30 years compared with a much longer life expectation in municipal water and industrial waste treatment
- The need for water plant operational skills at the water treatment site

By CSG field management which stages the life cycle of individual wells and the provision of detention ponds the problem of ensuring a relatively constant feed flow can be addressed, but at the cost on site of an inventory of untreated produced water. Alternatively, where a single extensive field or a number of separate fields in relatively close proximity exist, the may be the opportunity of combining all produced water at a single treatment facility, thus also gaining the advantages of economies of scale. Significant storage of water will still be required.

For the purposes of this paper, no differentiation is made between flowback and produced CSG water as far as treatment processes go. Flowback water is associated with fraccing of a well. Since this is done (if at all) at the development stage of the project or when a new well is added to an existing operation, the handling of the water produced falls under the aegis of (for example) the NSW EPA and must be appropriately handled in the same way as production water in the proving stage. With the NSW and Queensland ban on the use of BTEX in fraccing fluids and a requirement that any fraccing fluid additives be disclosed it is possible to combine flowback water with produced water in the detention pond and consider the treatment of both together, knowingly monitoring for any introduced chemicals as part of the produced water treatment process.

The next section overviews the range of water treatment technologies appropriate to production water. The principal determiners of a particular treatment process are the level of salinity of the produced water, its volume and its most beneficial use.

Reverse Osmosis

A brief outline of reverse osmosis has been given in the two earlier reports[A,B]. It is a pressure driven process in which a semipermeable membrane rejects salts and other species in the feed water to give a permeate of water suitable for potable use.

Reverse osmosis had its origins in a post-Second World War program at the Oak Ridge National Laboratory in the US which initially saw the development of the Dow B9 hollow fibre desalination module prior to 1960. The cellulose acetate RO asymmetric membrane first appeared in 1960, along with the development of spiral-wound cartridge design. Since that time membrane design and cartridge development have led to reverse osmosis being the preferred technology for the desalination of seawater and the deionisation of brackish and waste waters. Transport of water through a reverse osmosis membrane occurs by a solution-diffusion mechanism within the active surface layer. More recent developments have led to nanofiltration in which a membrane with definable pores can partially reject monovalent salts and totally reject divalent salts and operate at a much lower transmembrane pressure than classical reverse osmosis membranes. A further development (originated in Australia) has been the use of looser membranes (microfiltration and ultrafiltration membranes) at low transmembrane pressures for the purification of water prior to reverse osmosis, thus obviating the need for and cost of extensive pre-RO water treatment. Reverse osmosis treatment to produce potable water from seawater is now a mature technology with substantial plants established in Australia as indicated in the Table below.

An important feature of membrane processes such as reverse osmosis is the need to minimise the build-up of the rejected species at the membrane surface. This is accomplished by cross flow and by including spacers that encourage feed re-mixing close to the membrane surface. Buildup of rejected salts at the membrane surface increases the osmotic back pressure and requires higher transmembrane pressures and the risk of salt crystallisation and deposition at the membrane surface. This is why the percentage recovery of the feed water is limited in seawater reverse osmosis plants.

Australian Experience in Seawater Desalination

These plants are of world scale and handle inlet sea water where the total dissolved solids (TDS) is of the order of 35,000mg/L. One-third of the seawater is recovered as permeate having a salt content of less than 500 mg/L with the two-thirds remaining having a salt content of 52,000 mg/L and being returned to the sea. Australia's six large scale desalination plants have had a capital cost of $12 billion. Some rely on renewable energy sources (principally wind turbines). The cost of the drinking water produced is $2-3/KL with the Kwinana plant having a low of $1.2/KL. These costs are 3-5 times more expensive than those at Israel's five largest plants, reflecting the need for higher associated construction and infrastructure costs in Australia and the economies of scale. Although only some of the plants are in full scale operation because of abundant rain after their construction, Australia has developed a high level of expertise in the design and operation of large desalination plants and this technology, though expensive, should be placed firmly on the technological agenda for the treatment of produced water from coal seam gas operations for beneficial applications. Disposal of the salty concentrate from reverse osmosis plants remains a significant problem in non-coastal areas.

Australia seawater desalination plants

Location	Capacity GL/annum	Capacity ML/day	Expertise	Established
Kwinana, WA	45	121	Degremont	2006
Binningup, WA	100	270	Valoriza Agua	2011
Adelaide	100	270	Acciona Agua/Trility	2012
Gold Coast	48	125	Veolia	2009
Sydney	91	246	Veolia	2010
Melbourne	150	405	Degremont	2011

Reverse Osmosis for the Treatment of Produced Water

With the advent of NSW and Queensland Government regulations (2011 and 2010) no longer allowing the use of evaporation ponds for the disposal of production water, the use of reverse osmosis to beneficiate the water for further use has become an important feature of the CSG scene in Australia. Australia's recent uptake of reverse osmosis technology for this purpose is dramatic.

Since produced water typically has a much lower salt content than seawater (it is closer to brackish water) the percentage recovery of the feed water can be very much higher than in seawater plants. Plants are designed for multistage operation and overall percentage recoveries of 90% are routinely called for. Dow[55] has indicated a planned recovery of produced water of up to 97% for its integrated design. The intended use of the permeate (potable, aquifer replenishment, irrigation) and percentage recovery sets the design parameters for plant design and membrane choice. The concentrate from the process is salty water which can be placed in evaporation ponds for further concentration (not permissible in NSW) or fed to a thermal device such as a falling film evaporator to produce a concentrate from which salt can be crystallised.

Successful design and operation of reverse osmosis facility for the recovery of treated water from produced water requires particular care and a knowledge of the chemistry of the system. Problems are associated with[C]:

- Divalent salts (e.g. Ca^{2+} and Mg^{2+}) can crystallise and deposit at the membrane surface because of the high level of carbonate ion present
- Because the feedwater is held in a feed pond for some time, there is the risk of algal growth and any such algae must be removed before the feed water is presented to the membrane system
- Any dissolved organic components derived from the fraccing process or from the coal seam need to be removed before the RO stage because of risk of damage to the membrane
- Risk of silica induced precipitation at the membrane surface if the overall recovery is set too high

These problems can be successfully overcome by:

- Sufficient residence time in feed pond to allow settling of suspended solids
- Feed pretreatment to remove algae
- Incorporation of a microfiltration unit to clarify feed prior to further treatment
- Placing a deionisation unit to remove Calcium and Magnesium ions before the reverse osmosis unit and an adsorption bed (if necessary) to remove organics
- Carefully monitoring silica levels and using pH increase prior to the reverse osmosis stage to avoid precipitation of silica species at the membrane surface
- Choosing the most appropriate end membrane system (tight nanofiltration or reverse osmosis) for the permeate and final concentrating stages[1].

A list of current and possible future desalination plants in Australia has been provided by Global Waterworld (Vol 13, Issue 7, July 2012)[99] and is reproduced overleaf.

C The author acknowledges a helpful discussion with Professor Greg Leslie of the University of New South Wales who, through IWES, runs a series of training workshops in Australia in the membrane treatment of produced water from coal seam gas recovery

Recently contracted CSG water treatment capacity in Australia

Location	Client	Capacity (m^3/d)	Equipment supplier	Year online
Roma	Santos	1,500	Osmoflo	2011
Roma	Santos	10,000	Veolia	
Fairview	Santos	20,000	Veolia	
Pony Hills	Santos	6,000	Osmoflo	
Windibri (Surat Basin)	QGC	6,000	Osmoflo	2011
Kenya	QGC	100,000	GE	2011
Kenya (mobile)	QGC	12,000	GE	2011
Northern WTP (Wandoan)	QGC	100,000	GE	2013
Roma	Origin Energy	2,400	Nirosoft	2004
Spring Gully	Origin Energy	12,000	Pall Corporation	2007
Moranbah	Arrow Energy/ AGL Energy	2,000	Aquatec-Maxcon	
Darling Downs	Arrow Energy	2,500	Aquatec-Maxcon	
Condamine	QGC	6,000	Veolia	
Bibblewindi	Eastern Star	1,000	Impulse Hydro	2009
Daandine	Arrow Energy	12,000	Pall Corporation	2009
Condamine Power Station (plant 1)	QGC	2,000	Clean Teq	2012
Condamine Power Station (plant 2)	QGC	2,000	Clean Teq	2012
Talinga	APLNG	20,000	Pall Corporation	
Talinga expansion	APLNG	20,000	Unknown	2013
Condabri Central	APLNG	40,000	Unknown	2013
Reedy Creek	APLNG	40,000	Unknown	2013
Total		**415,000**		

Source: Global Waterworld 2012[99]

Upcoming opportunities in Australian CSG water treatment

Location	Project name	Client	Capacity (m^3/d)	Notes
Dalby (plant 1)	Surat Gas Project	Arrow Energy	60,000	Max. plant capacity
Dalby (plant 2)	Surat Gas Project	Arrow Energy	60,000	Max. plant capacity
Wandoan	Surat Gas Project	Arrow Energy	60,000	Max. plant capacity
Chinchilla	Surat Gas Project	Arrow Energy	60,000	Max. plant capacity
Millmerran/Kogan	Surat Gas Project	Arrow Energy	60,000	Max. plant capacity
Goondiwindi	Surat Gas Project	Arrow Energy	60,000	Max. plant capacity
Fairview	Gladstone LNG	Santos	Undecided	RO plant
Roma	Gladstone LNG	Santos	Undecided	RO plant
Arcadia Valley	Gladstone LNG	Santos	Undecided	RO plant
Roma/Fairview	Gladstone LNG	Santos	Undecided	Mobile RO plant
Roma/Fairview	Gladstone LNG	Santos	Undecided	Mobile RO plant
Bowen Basin	Bowen Gas Project	Arrow Energy	50,000	Higher end of range
Ironbark	Ironbark	Origin Energy	6,000	Possible plant
Central-southern Queensland	Future Gas Supply Area Project	Santos	Undecided	4,100 wells max.
Southern Queensland	Galilee Gas Project	Galilee Energy/ AGL Energy	Undecided	
Total			**416,000**	

The largest of these is small by seawater desalination standards and will suffer from the poorer economy of scale. But reverse osmosis is a modular technology which, if needs be, can be skid mounted for relocation during the production proving phases of CSG fields. Moreover, the Australian operators of these plants are gaining first-hand experience of handling CSG production water which will prove invaluable in in later very large scale plants where the production water from multiple fields is combined.

Two features of recent plant installations are the inclusion of advanced instrumentation to allow the plant to be operated remotely and the contracting to an experienced designer/operator to take on a contracted treatment service. This would appear to overcome some of the risks associated in introducing complex water treatment technology into a petroleum-based industry.

Three considerations for the successful operation of integrated reverse osmosis facilities are:

- The removal of any hydrocarbons present prior to the reverse osmosis step. Whilst BTEX is banned from the fraccing step, some hydrocarbons may be picked up from the coal seam. If such hydrocarbons are present (and it is generally unlikely), they need to be removed by an adsorbent bed prior to ion exchange and reverse osmosis. Treatment facilities for produced water from petroleum recovery plants have experience in this.
- Removal of any naturally occurring radioactive materials (NORM). US reports cite some produced waters with radioactive species at 0.2 – 14.7 Bq/L. Ion exchange and reverse osmosis will successfully capture radioactive species in the treatment process concentrate.
- Removal of boron which can be damaging to some flora. Choosing the correct reverse osmosis membrane can solve this problem.

Web sites are available for organisations offering plant and component design (e.g. Evoqua (formerly Siemens)[107], Dow[55], Arup[31], ABR[101], Veolia[108] etc. GoldSim[97], for example, offers a process flowsheeting package and gives an illustration of a typical plant design for the treatment of CSG water.

The level of activity in the use of reverse osmosis for the treatment of CSG production water in Australia suggests that it is a viable option for pursuing the beneficial use of produced water. The principal drawbacks are possible lack of economies of scale, energy costs and disposal of concentrates. Companies in the Surat Basin see it as a possible means of rehabilitating the holdings in current evaporation ponds and, through guaranteeing the supply of treated water to townships and farms, of strengthening their case for a social licence to operate CSG facilities.

A photograph of a Siemens portable reverse osmosis plant is reproduced overleaf[115].

FlexRO reverse osmosis units are installed in mobile water treatment trailers from Siemens Water Technologies.

Microfiltration[107]

Microfiltration is a pressure driven membrane process like reverse osmosis except that it uses membranes with large pores and low transmembrane pressures (<100 Kpa) to remove macrosolutes, microbial species and suspended solids from water. It is frequently used in water treatment systems and as a pre-treatment to reverse osmosis. The technology is now well established commercially and is appropriate as a component of processes for production water treatment.

Membrane Distillation[111]

Membrane distillation is a membrane-based process that effects separation by using heat to bring about the transfer of water vapour across the pores of a hydrophobic microfiltration membrane. It is a superficially attractive technology for the purification of CSG production water because the energy requirement is very much less than in reverse osmosis and a very high (98%) recovery of water can be obtained. It has been demonstrated on the pilot scale on CSG production water but has only just found commercial application for small-scale seawater desalination (10 ML/day)[151], primarily because of the need to have available waste heat and the need to prevent “wetting out” (filling of the membranes pores with water) of the membrane after a prolonged period of operation. Although an interesting technology it could not, at this stage, be considered a reasonable contender for a large scale CSG produced water treatment plants in Australia. It should be flagged for possible attention in the longer term.

Forward Osmosis[111, 113]

In comparison to reverse osmosis that relies on hydraulic pressure, forward osmosis utilises osmotic pressure, which is induced by a concentrated drawing solution located on the permeate side of the membrane. The draw solution contains the purified water passing through the membrane and is later treated to recover this. The process is claimed to be able to treat dirty feed waters and potentially uses less energy than reverse osmosis and minimises membrane fouling. However, downstream separation capacity is needed to recover the permeate and the membrane itself may allow the passage of some of the chemical in the drawing solution into the concentrate. Though the process has been demonstrated on the pilot scale for the recovery of water from CSG production water, it also is not at present a reasonable contender for full scale application in this duty.

Electrodialysis

Electrodialysis has emerged as a strong competitor for reverse osmosis and nanofiltration in the treatment of brackish waters for potable purposes. Electrodialysis uses an electric field to separate ions through ion-selective membranes. It has been demonstrated as effective for desalting 5,000 mg/L groundwater[111] and is preferable to reverse osmosis where the silica content is high. It has the advantage that it can produce water with a low sodium adsorption ratio (SAR). It lacks commercial demonstration in the field on the large scale and a study[118] suggests that it is less economically attractive than reverse osmosis for the treatment of CSG produced water if the feed concentration lies beyond 2,000 mg/L of total dissolved solids (TDS).

Variations on conventional electrodialysis include electrodialysis methathesis (EDM) which uses a special arrangement in the membrane stack to overcome the problem of treating waters having high contents of soluble calcium sulphate[120]. This leads to a Zero Discharge Desalination (ZDD) regime in which calcium sulphate can be recovered as a commercial product. Sodium chloride recovered is reused in the process. However, the process is only of use where the sodium chloride content of the feed water is very low, which is not the case in Australia.

Deionisation

Deionisation (Ion Exchange) is a well travelled technology for the removal of ionic components from brackish water. It relies on using ion exchange resins to exchange unwanted ionic species for more acceptable ionic species and is particularly effective in operations like the softening of water. A variant on conventional fixed bed ion exchange is offered by the Dow company[55, 120] in which CSG produced water having a sodium content of 500 mg/L and a poor SAR is transformed into high quality water suitable for irrigation by the Higgins Loop process which uses a circulating resin technology to maximise deionisation effectiveness. Dow estimates that the cost of such treatment is \$US 0.3-1.2/m^3 depending on the TDS of the feedwater. Dow also offers a range of other resins and adsorbents for the removal of hydrocarbon components from water. The technology for CSG production water is a derivative of Dow's specialised technology for the treatment of produced water from petroleum operations.

Deionisation has an upper ceiling of TDS beyond which it becomes uneconomical and the disadvantage that its operation requires the use of regeneration chemicals and gives rise to liquid wastes. When used in combination with other treatment processes, deionisation offers a way to optimise the operation of membrane technologies to enable high recoveries of processed water. In this regard, for example, Siemens[115] offers a trailer based technology that combines aspects of deionisation with microfiltration and reverse osmosis. The mobility of the plant enables the treatment of CSG production water during the proving stages of CSG fields.

Capacitive Deionisation

Capacitative deionisation is a variant of electrodialysis where an electric field is used to move ions into a collection region in the vicinity of carbon aerogel electrodes.[111] Periodically the polarity of the electrodes is reversed and the captured ions are freed and form a concentrated reject solution.

Reports by the United States Department of Energy (US DOE) of a 2007 study[121] suggest that the technology is good for treating TDS concentrations of 2,000-5,000 mg/L. Beyond 5,000 mg/L reverse osmosis is more economic. Capacitative deionisation leads to removal of 75-90% of the incoming salt, making it interesting for situations where the produced water is destined for irrigation. Capacitative deionisation is said to be particularly resistant to fouling, thus mitigating the need for stringent feed water pretreatment.

The technology still has not been demonstrated on the large commercial scale and is not thus considered as appropriate at this stage for implementation on the Australian scene although a pilot scale unit is available for purchase.

Electrodeionisation[122]

Eltron technology is claimed to reduce the cost of salt removal from produced water by 60-70% compared with conventional ion-exchange deionisation, while eliminating the use of mineral acids for resin regeneration. It yields a caustic soda product. It has not yet been tested on CSG production water but is being evaluated in a US DOE program[111]. It cannot at this stage be regarded as of potential interest for application in Australia.

Thermal Processes

Thermal processes like multi-stage flash evaporation are established processes for the production of potable water overseas and, at the large scale and where cheap energy is abundant, offer a means of producing cheap water of high quality. They will handle relatively dirty feed streams and can operate at high recoveries, producing a concentrated effluent. On the downside, their footprint is large, they are energy intensive and the mix of salts in produced water can pose materials problems. For these reasons and overall cost per ML of water treated the technology is not regarded as a realistic contender for the treatment of produced water from CSG recovery.

Granular Activated Carbon

Granular activated carbon (GAC) can be used to remove the following contaminants from produced water: mercury, cadmium, natural organic matter, BTEX compounds, synthetic organic chemicals—specifically benzo(a)pyrene, di(2-ethylhexyl)adipate, di(2-ethylhexyl)phthalate, hexachlorobenzene, dioxin, and radionuclides. [125] It relies on adsorption of the species on the surface of carbon particles which have surface pores having a large surface area. The bed is regularly backwashed and replaced when it nears its adsorptive capacity. The suppliers of activated carbon typically take spent carbon off-site for re-activation. GAC filtration can be an important step in an integrated CSG production water treatment system or ensuring that water used for irrigation or stock watering meets water quality specifications.

Veolia Opus[112, 124]

The Veolia OPUS system is an integrated water treatment system able to fit on a cargo trailer and capable of handling CSG produced water to deliver a potable water product with 90% recovery. The processing scheme is much as described under reverse osmosis.

Comparisons of Treatment Technologies

From the above discussion it is evident that no one treatment technology alone is likely to meet the needs of treating production water from CSG recovery, but a combination of technologies (as, for example, described in the section on reverse osmosis) will do this. The technical challenge is considerable – the reduction of salt content, balancing of the SAR, and removal of any hydrocarbons, radioactive species and specific species like boron, with the aim of meeting either drinking water standards or standards for stock use or irrigation. In 2009 the University of Colorado[111] provided a guide to the costs of various forms of water treatment (USA figures). Costs for modularised intensive processes like reverse osmosis have fallen significantly since that time, dependent on scale of operation.

Costs for Treatment of Production Water[111]

Management Option	Estimated Cost ($US/m^3)[111]
Surface discharge	0.1 - 5
Secondary recovery	0.3 - 8
Shallow re-injection	0.6 - 8
Evaporation pits	0.1 - 5
Commercial water hauling	6 - 35
Disposal wells	0.3 - 17
Freeze-thaw evaporation	17 - 31
Evaporation pits and flowlines	6 - 11
Constructed wetlands	0.01 - 12
Electrodialysis	0.1 - 4
Higgins loop	0.3 - 1,3
Cartridge filter - RO	0.3 - 0.4
Softening-filtration-IX-RO	0.4 - 1.7
Induced air flotation for de-oiling	0.3
Anoxic/aerobic granular activated C	0.5

In 2008 the US Government Department of Energy launched a R&D support program entitled *Research Partnership to Secure Energy for America* (RPSEA)[111] which made significant government grants for forward-looking university-industry co-operative programs aimed at increasing US access to indigenous energy sources. Support for unconventional gas recovery featured largely in the early support provided, with a number of grants being given for the study of treatment alternatives for the production water from the winning of gas from coal seams and shale deposits in 2009 and beyond. Pilot scale programs exploring different treatment technologies were initiated. The results of these programs are only just beginning to come to hand and it is likely that a much clearer picture of the strengths and weaknesses of the various technologies will emerge over the next couple of years and US companies will establish commercial-scale plants based on the most promising of these. However, it is fair to note that the accent presently in the US is on the recovery of shale gas rather than coal seam gas, with shale gas production generally leading to less produced water and a quite different cost structure. Notably, treatment of production water from CSG recovery did not feature significantly in the latest round of RPSEA grants awarded.

Water treatment companies do have the expertise and experience to design and operate plants that will achieve the desired level of treatment. Cost of treatment is the most important feature and it is closely tied to quantity of production water, the concentration of salts and other contaminants and the ease or otherwise with which concentrates from the treatment process can be handled to avoid environmental risk. Scale of operation will be an important factor in eventual cost. Perhaps the following extract from the Veolia website[123] is indicative of the future approach that will be taken by the larger Australian CSG players:

QGC Water Treatment Plants

QGC Pty Limited has awarded a contract worth up to A$800 million to Veolia Water Australia Pty Ltd to operate and maintain QGC's three water treatment plants in the Surat Basin.

Under the 20-year contract Veolia Water will operate and maintain the plants, which will treat groundwater produced alongside natural gas. QGC is investing more than A$1 billion in infrastructure to treat this generally unused salty water for use by agriculture, industry and towns. From June 2013 Veolia Water electricians, instrument technicians, plant operators and water engineers will operate and maintain ultrafiltration, ion exchange, reverse osmosis and brine concentration equipment in addition to pump stations and electrical substations.

The two main water treatment plants to be maintained and operated are under construction at sites known as Kenya and Woleebee Creek, about 35 km from Chinchilla and Wandoan respectively. These facilities will have a combined capacity to treat about 200 megalitres a day - or about 80 Olympic-sized swimming pools - during peak production. A smaller, 6-megalitre treatment plant is already operating at QGC's Windibri site near Chinchilla, providing water to Cameby Downs coal mine and Condamine Power Station.

For more information visit:

QGC website. www.veoliawater.com.au/veoliawater/contracts-projects/48266.htm

5. RE-USE, HANDLING AND DISPOSAL OF PRODUCED WATER

The CSG industry in the USA grew as an outreach of the on-shore conventional gas industry where produced water was re-injected into the gas well to increase recovery. Having to deal with produced water that could not be re-injected directly was regarded by the industry as a significant nuisance and one that could be resolved in the first instance by evaporation ponds, surface disposal or injection into a deeper geological structure not hydraulically connected with the coal seam from which CSG was being recovered. However, with the passage of time the loss of potentially valuable water around mine sites in the western USA became a community and government issue and government support to conduct R&D to develop beneficial applications developed. USA experience highlighted the dangers of using the produced water directly for irrigation because of its high sodium content. In coming later to the CSG industry, Australia has the benefit of the US experience and perhaps a more enlightened approach to beneficial re-use. At the heart of the issue, of course, is the cost of beneficiation. For those CSG fields where the water to gas ratio is low, treatment costs are low in proportion to the sale price of CSG. In the more northerly fields (e.g. the Surat Basin) volumes of produced water per unit of gas produced are high, but not as high as in the majority of US fields. With the higher flow of produced water, frequently the total dissolved solids in the produced water are down and extensive treatment is more straightforward.

Within Australia most attention has been paid to the matter of beneficial re-use by the Queensland Government. Given the fast development of the industry in that state and the volumes of water involved, this is not surprising. Important legislative and regulatory outputs from that state are: *Queensland National Resources and Other Legislation Amendment Act* (2010)[102] [banning BTEX in fraccing], *Coal seam gas water management policy (2012)*[103] , *Approval of coal seam gas water for beneficial use (2013)*[105], *General Beneficial Use Approval— Irrigation of Associated Water (including coal seam gas water)(2013)*[104], *and Coal Seam Gas Recycled Water Management Plan Guideline(2013)*[102]. Companies seeking approval for a CSG recovery operation are required to provide a coal seam gas recycled water management plan along with the customary environmental impact statement. Some companies that are currently operating evaporation ponds under existing permits are examining how these ponds can be drained and replaced by beneficial use of the water.

Within NSW the Regulatory Framework comprises:

Environmental Planning and Assessment Act 1979 (Planning)
Coal Seam Gas Exclusion Zones
Mining and Petroleum Gateway Process
Administered by the new Office of Coal Seam Gas
Code of Practice for Coal Seam Gas Well Integrity
Code of Practice for Coal Seam Gas Fracture Stimulation
Petroleum Onshore Act 1991
Water Management Act 2000
Aquifer Interference Policy
Protection of the Environment Operations Act 1997
The Environment Protection Authority
Support to Landholders
Land and Water Commissioner

An Office of Coal Seam Gas has been established and the Chief Scientist and Engineer has completed a report on the industry.

At the Commonwealth level under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (**EPBC Act**) an amendment came into force in 2013 bringing any CSG development likely to have a significant impact on a water resource under Federal oversight[129]. Both NSW and Queensland have endorsed the liaison with the Commonwealth.

In evaluating different approaches to the handling of CSG produced water in the Australian environment, regard must be had to the stage of development of the local CSG industry. At the exploration and early development stage, produced water is minimal and can, if required be handled by tankering to a site where it is treated. Because any such water is likely to be highly saline, disposal of tankered material must be to a facility that can protect the environment from high salt levels. A licensed waste management facility can do this by placing the water in a storage monocell. It is in the production or proving stage where a few wells are being worked to determine their productive potential that significant problems first arise. Depending on the CSG field the volume of produced water may become significant and a decision has to be taken to commence to store this water in an approved holding pond pending later construction of a treatment plant or the water may be tankered away to an existing treatment plant elsewhere. Much depends on whether the CSG recovery operation is at a green field site. Once full scale production of CSG is entered into, appropriate and approved provision for produced water treatment is necessary and the provision for this will normally be initiated through a produced water management plan. What follows is an evaluation of the different treatment alternatives that might be considered in the Australian environment.

By way of illustration the discussion of a typical produced water specification has been used. This is taken from the Santos Produced Water Management Plan for PEL238, PAL2 and PPL3[144] as previously included in this paper.

U.S. Practice

Produced water disposal practices at the major US coal bed methane sites are given in the table below. Approximately 40% of produced water is injected into deep wells. Federal law does not permit injection into aquifers with a TDS< 10,000 mg/L.

Production Water Disposal Practices in USA 2010[150]

Basin	Management and Disposal Practices	Factors Affecting Management Option	Treatment Technologies Observed During Site Visit
Appalachian (Central)	• Injection • Land application with no crop production • Surface discharge	• Availability of large receiving water bodies • Land application is permitted under West Virginia general permit	• Sedimentation /Continued

Basin	Management and Disposal Practices	Factors Affecting Management Option	Treatment Technologies Observed During Site Visit
Appalachian (Northern)	• Injection • Surface discharge	• Availability of large water receiving bodies	• Aeration • Sedimentation (coagulants use not permitted in Pennsylvania)
Black Warrior	• Surface discharge	• Availability of large receiving water bodies • Geological formation cannot handle the volumes of produced water	• Operators typically use a combination of storage ponds, sedimentation, and aeration
Powder River	• Injection • Surface discharge • Evaporation/infiltration ponds	• High volumes of water with low salinity	• Aeration • Sedimentation • Ion exchange
Raton	• Injection • Surface discharge • Dust suppression • Livestock watering		• Aerated storage ponds
San Juan	• Injection • One operator is an indirect discharger	• Availability of formations for injection • High salinity of produced water • State regulations	• Altel a thermal distillation system is used by indirect discharger

Injection into Suitable Aquifers

One of the principal concerns of the rural community is that CSG production will lead to a lowering in the water levels in surface bores used for town water supply, irrigation and stock watering. US practice has seen CSG production water injected directly into aquifers, with the guiding principle being that the injection should occur into an aquifer containing water of a similar or higher salinity. What happens to this water once injected depends on the regional hydrology and the successful use of this approach depends on an intimate knowledge of sub-surface geology. The approach does nothing to assist the availability of good quality water in shallow aquifers, though osmotic and flow gradients would appear to protect the upper aquifers from salt contamination if the geology is correct. The consensus of US experience suggests that this is so. A variant of this approach is to re-inject the production water into the coal seam once the gas has been removed. Santos[133] has examined this possibility for its Gladstone LNG project but, because of water storage problem, has concluded that it will not be feasible until the site has been in operation for at least ten years. Produced water for injection or re-injection is always filtered to remove suspended solids and is disinfected, usually by chlorine, to prevent the introduction of viable biological species into the target aquifer.

One development that has been pioneered in the US by the company Big Cat Energy[60] is to avoid bringing the production water to the surface at all by constructing the recovery well so that it directs produced water into a suitable aquifer lying above the coal seam. The company claims quick permitting by US environmental authorities of CSG recovery systems based on this technology. Its use in Australia would very much depend on whether the local geology and hydrogeology were right and the risk of contamination of aquifers still closer to the surface was acceptably small.

A perhaps more acceptable practice for regulators and the community is to treat the produced water by the processes discussed above up to a standard where it is compatible with water in the aquifers used to supply towns and/or water for stock watering and irrigation. Depending on the quality of the produced water and the level of its chemical contaminants, this will require more or less extensive treatment. Santos[133] is trialling aquifer injection to a surface aquifer at its Roma gas field, with the intention of long term supply of treated water to the town of Roma by recharging its supply aquifer. The long term aim is to place 9 ML/day into the Gubberamana sandstone aquifer supplying the town.

Rather than recharging the water supply aquifer, the approach taken by the Queensland Gas Company is to sell its treated water to agricultural customers on the understanding that they will reduce their demand on the communal water supply aquifer.

The standards for water for potable use are clearly specified in the Australian Drinking Water Guidelines, which have been recently updated[126]. The produced water treatment process used by the CSG producer would clearly have to ensure the removal of unwanted species down to the guideline level if these species will not be removed in the municipal water treatment plant.

Provision of Water to Existing Agricultural and Industrial Users

Treated production water would be a valuable resource for industrial users in inland Australia where the supply of water from rivers is uncertain. For example, a chemical plant or a small power station could use up to 2.4 GL per year for makeup and blow-down of cooling towers[D]. Treated water has also been successfully supplied to Australian cattle feedlots. Use of semi-treated production water to grow algae for biofuel has been suggested[52].

The provision of treated or untreated CSG production water to external parties for irrigation provides potential if the benefits/costs are attractive. Both earlier studies[A,B] have written on the problems associated with irrigation water containing high levels of sodium ions and low levels of calcium and magnesium ions because this can lead to soil degradation. The extent of the problem is quantified by determining the Sodium Adsorption Ratio (SAR) of the irrigating water defined as:

$$SAR = Na^{+}/(0.5\ Ca^{++} + 0.5\ Mg^{++})^{0.5}$$

Soils with SAR> 15 are strongly sodic and will be harmed by the application of sodic irrigation water containing high levels of sodium as will non sodic soils subjected to prolonged application of sodic irrigation water . It is important in irrigating to keep the level of applied water sufficiently low so that it does not progress beyond the root zone and mobilise salt in underlying soil.

D P Puckorius, *Consider Recycled Water for your Cooling Tower Makeup*, Chemical Engineering Progress, February 2013, 24-29

The Queensland Government has specified requirements for irrigation water. These requirements meet ANZECC[127] specifications.

> ***Minimum standards***
> The following criteria apply to the general approval for beneficial use of CSG water for irrigation purposes:
> • Irrigation shall not be applied to Good Quality Agricultural Land;
> • 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; and
> • Irrigation shall not be undertaken at a rate that results in water run-off to permanent water courses.

For the produced water in the Santos case study, the sodium level is 6,200 mg/L and the bicarbonate level is 10,100 mg/L. Without further treatment it would not be a candidate for direct irrigation, but could be used for irrigation if sodium was removed and the balance of the water improved. Santos is conducting successful agricultural trials using treated water.[133]
A similar comment would apply to produced water likely to come from the proposed AGL facility at Gloucester where the sodium level is 1,100 mg/L, calcium 7 mg/L and magnesium 2 mg/L with a TDS of 2,900 mg/L. As earlier indicated, AGL is conducting an irrigation trial at Gloucester in which one part of minimally treated produced water is added to three parts of river water to get the blend within a reasonable chemical specification for irrigation. Salt present in the produced water is not removed by this procedure, but careful irrigation practice and rotation of the fields irrigated ensures that the additional burden of salt becomes contained in the soil below the root zone. AGL sees this blending approach as possibly having application when the produced water output significantly declines after the first few years of well operation. Key to the successful use of treated CSG produced water for irrigation lies in ensuring that it will not adversely affect the quality of the soil or lead to an unacceptable build-up of salt within the soil.

As an example of the water requirement for irrigation, Lucerne requires 7-10 ML/ha over the full irrigation season[134]. For Stage 1 of the proposed Santos Narrabri project, this would equate to providing the irrigation water requirement for 150-200 ha.

In some instances in the USA and to a limited extent in Australia, produced water has been used for stock watering. However, the requirements in Queensland of the use of treated produced water for this purpose are quite strict. The total acceptable levels of salts in water for different livestock are given in the table below.

Livestock Allowable Total dissolved solids

All Livestock	**Acceptable level (mg/L)**
Pregnant and lactating	<5,000
Beef cattle	<5,000
Dairy cattle	<4,000
Sheep/goats	<6,000
Horses	<6,000
Pigs	<6,000
Poultry	<3,000

Stringent limits are also placed on the nature of these dissolved solids

Lightly treated process water from CSG recovery may also be used in nearby mine sites. Queensland Gas Corporation reports the use of 15% of the produced water in the early stage of its operations as being used for coal washing on a nearby mine site. However, such use does not guarantee the remove of salts in this water from the associated rural environment.

Re-use in CSG Project Construction or Operation

CSG produced water may be used during project construction and operation for the following:

- Dust suppression
- In the fraccing of wells - up to 1 ML water is required to fracc a single well
- Construction site reticulated water (after treatment)

Whilst dust suppression unpaved roads is regarded as a valid use of raw produced water by environmental authorities, its use does increase the salt burden within the CSG recovery site and limits are placed on its use to prevent run-off into nearby streams.

Irrigation of Company Owned Crops

As earlier indicated, trials of irrigation by treated produced water are being conducted by Santos[137] and AGL[131]. QGC[136] provides treated water to the town of Chinchilla and to properties along the way for irrigation. The overall results are positive as are the press reports. Trials of irrigation of company-owned sites and those of co-operating landowners are seen to be a stalking horse for more widespread adoption of the use of treated CSG production water for agriculture.

Supplementary Flow in Watercourses

Increasing the flow in watercourses, both ephemeral and permanent is seen by the Queensland Government as less attractive than the immediate beneficial use of CSG recovery produced water[103]. To meet stream disposal requirements under ANZECC[127], production water in NSW and Queensland (for example that from the Santos and AGL proposed operations) would have to undergo treatment. Matching the TDS of the treated production water to that of the watercourse (typically a maximum of 500 mg/L) would require deionisation and/or reverse osmosis plus chemical adjustment. The capacity to do this exists with current technology and the release of treated water to the Condamine River is already practised with no apparent adverse effects on the ecology of the river. There has been the suggestion that reverse osmosis treated water may, because of the absence of suspended matter, be too 'pure' for direct disposal into inland waterways. High bicarbonate ion loadings have been found to exert a detrimental effect on aquatic life.

Aquaculture[79]

Pilot trials have shown that produced water subject to minor treatment can be suitable for aquaculture if potassium is added. This application still requires the disposal of saline waste and the building of containment structures that are leak-proof.

Disposal of Treated Produced Water in Queensland[147]

The disposal options for treated produced water adopted by three of the principal CSG producers in Queensland are given in the table below. The volumes associated with Surat Basin operations justify large-scale treatment plants drawing from multiple gas fields. In this way some consistency of supply is guaranteed. However, the maximum project life is anticipated as 20-30 years and this contrasts with the project life usually assumed in the conventional water treatment industry where a life of 50-70 years is not uncommon. The result is that capital equipment cannot be amortised over a long period.

Table 16: Summary of management strategies preferred by project proponents

CSG–LNG project	Beneficial use	Disposal	Treatment
Queensland Curtis LNG	• Irrigation of tree crops with blended water (a mix of treated and untreated water) • Supply of treated or untreated water to mines (includes coal wash water) • Reinjection of treated or untreated water	• Disposal of water to evaporation ponds (short- to medium-term solution)	• Reverse osmosis with evaporation ponds for brine stream
Australia Pacific LNG	• Treated water for agricultural use, crop and plantation irrigation • Opportunistic discharge of treated water to surface water		• Reverse osmosis with evaporation ponds for brine stream
Gladstone LNG	• Treated and untreated water irrigation of food, fodder and tree crops • Treated water provided to supplement potable water supply • Treated water supplied for industrial use		• Reverse osmosis with injection wells and evaporation ponds for brine stream

Source: adapted from Environmental Resources Management 2009; URS 2009; Worley Parsons 2010.

Disposal of Concentrates

Best practice integrated two stage reverse osmosis plants operating on CSG produced water have been shown to achieve 90% recovery meaning that the volume of concentrate is 1/10th of the feed. For a feed of 21,000 mg/L this amounts to a concentrate stream of 1.8 g/L which is still well short the saturation concentration for sodium chloride in water (36 g/100 ml at 20^{o}C). In practice the limit on concentration in reverse osmosis is determined by the osmotic pressure of the concentrated solution at the membrane surface and the tendency of other species present to crystallise before sodium chloride. In practice the concentrate stream can be further concentrated by falling film evaporation and, if desired subsequently crystallised to give a solid product. Tankering and disposal of a liquid concentrate in a specially constructed well at a licensed waste disposal site is possible. Alternatively a solar pond can be used for the final concentration and crystallisation stage. Disposal of solid crystals equally requires a specially constructed enclosure.

For the Santos Narrabri project the TDS is 20,000 mg/L ("half that of seawater") and for a produced water average volume of 1.5GL/year this represents a dry salt disposal requirement of approximately 30,000 tonnes per year , equivalent in volume to a 24m cube. Ensuring that such a volume of salt is placed in secure landfill is a technical, but not insurmountable, challenge. The alternative is to hold the concentrate as a concentrated salt solution. Handling as a close-to-saturated solution would increase the volume required roughly threefold. A secure landfill would be one where there was no possibility of leakage long-term into surface waters in the event of adverse weather events or into groundwater systems.

It is therefore not surprising that CSG companies in Australia (primarily in Queensland) are exploring the possibility of deep well injection of production water treatment concentrates into secure aquifers of similar concentration. This approach is widely practised in the USA but does require a detailed geological and hydrogeological knowledge of the site. The challenge is to ensure that there will be no leakage of stored salt into surface freshwater aquifers. The approach is being trialed in the Surat basin.

The disposal of produced water or produced water concentrates to the ocean or estuaries is also feasible for CSG facilities appropriately located. The liquid so disposed of would have to meet ANZECC[127] guidelines in terms of quality and pretreatment would be required and, in the case of concentrate, suitable dispersion at point of entry to the ocean or estuary. It is noted that the Dart Energy CSG facility in Scotland[145] discharges partially treated produced water into the Firth of Forth under environmental licence. Waste water from mines in the Hunter Valley is permitted to be discharged into the Hunter River under a scheme whereby salt disposal permits are traded[146]. Mine waste waters (200L per tonne of coal mined) are retained in holding ponds and are released under instructions when the flow in the river is sufficient to ensure that the addition of wastewaters will not cause environmental damage. Such a scheme is only feasible for estuaries close to the coast where the salt added will be quickly flushed out to sea. In this regard it is instructive to reflect on the reason that Dart Energy has ceased its plans for a CSG facility at Fern Bay, north of Newcastle[20]. From a production water disposal viewpoint the site would have been ideal. The proposed site was bounded by the Hunter River on one side and the Pacific Ocean on the other but fell foul of the NSW regulation not permitting CSG operations within 2 km of a residential community[152].

Beneficial Uses of Concentrated Brines and Recovered Salts

Salt is a significant raw material for the chemical industry and the world production approximates 300 million tonnes per year[137]. Approximately 10% of this is traded internationally with the lowest quality salt demanding a price of $42/tonne for de-icing of roads in temperate countries[138]. Considerable quantities of higher quality salt are used in the chlor-alkali industries. There is a possible market for specific chemicals extracted from salt (valuable metals, heavy metals, rare earths) but the extraction costs are high and alternative sources exist. It is possible that an export market could be developed based on the salt recovered from the treatment of CSG produced water. However, the cost of transporting the raw salt to a seaport is a negative factor and a careful appraisal of total transport and shipping costs would be required.

An alternative approach might be to consider the use of salt in the production of sodium carbonate[140], as has been up to recently practiced in South Australia at the Penrice Soda[139] plant where salt recovered from the ocean by evaporation ponds was used. This plant ceased operation in 2013 citing international competition. However the Penrice report notes a strong international market for sodium carbonate which may be able to be recovered from CSG water treatment concentrates. There is possibly room for one soda plant in Australia based on CSG salt if the economics were right. However, given scale advantages it would most likely be preferentially located in Queensland using the significant amounts of salt that could be recovered from Surat basin fields. Transport of salt feed to this plant from NSW CSG operations might be feasible.

Storage, Handling and Transport Options

As has been indicated earlier, the variability of flow of CSG production water over the life of a well necessitates the storage of produced water so that feed flow to a treatment plant can be somewhat leveled. The use of open holding ponds is acceptable for this purpose and permitting authorities now have strict rules on how these ponds should be constructed so that walls are impervious and will endure. Similarly, it is necessary to provide storage for treated water and saline concentrates. Storage for the latter should be designed to hold a waste which, because of its concentration, is particularly hazardous to the environment should it leak. Design requirements call for reservoirs to be able to withstand a 100-year rainfall event without over-topping. The technology and controls used in sewage treatment plants provide a good basis for design, though attention will need to be paid to the potentially corrosive nature of production water and concentrates in the choice of materials of construction and aspects of plant safety.

Transport of raw production water and concentrates in specially designed tankers should only be considered as a last resort or when a project is in its very early phases as the volumes required to be transported can become high and the impact of tankers on roads and rural populations severe. Larger scale, well-integrated CSG developments have the opportunity to build buried piping networks for fluid transportation purposes.

A positive trend that is occurring is for water treatment companies to now supply integrated systems for CSG production water that can be trailer mounted and shifted as needs change. This has the benefit in the development phase of a project that produced water can be site-treated with the concentrate being sufficiently small in volume for it to be tankered for further use or disposal.

6. TESTING, MONITORING AND SAMPLING WATER AND IMPACTED ENVIRONMENT

The Queensland Government has developed a guideline for the analyses that must be done at the outset of treatment of CSG production water. It appears overleaf.

The Queensland beneficial use guide (2013)[104,105] gives the minimum standards required for treated production water to be used for beneficial purposes in such applications as:

Aquaculture and human consumption of aquatic foods Coal washing Dust suppression Industrial and manufacturing operations Irrigation Livestock watering

Where appropriate, these are consonant with national guidelines and would seem a sensible basis for setting minimum standards by the NSW Government after a discussion with stakeholders. They have not been repeated in this paper as they are readily accessed.

As far as releasing treated production water into aquifers for potential future potable use, it will be important to ensure that the water meets NHMRC drinking water guidelines[126]. Whilst the local water treatment plant will be designed to remove turbidity and microorganisms, particular care needs to be taken that the injection in to the aquifer does not introduce toxic substances. Hence a full water monitoring as called for by NHMRC is appropriate. Should treated production water be supplied directly for potable uses, testing against the NHMRC guidelines again applies as it would for landowners who draw their supplies for bores entering the aquifer.

As normal control measure, a CSG field should contain a number of groundwater monitoring wells and these should surround the field to monitor the level of the groundwater and, through sampling, be used to detect any abnormal appearance of chemicals in the groundwater. Depending on the local hydrogeology, regulating authorities usually choose to place draw limits on the amount of water that CSG recovery operators can extract over a period. For example the AGL CSG operation at Gloucester is allowed to extract 730 ML per year. In other jurisdictions a limit is placed on the extent to which the level of groundwater can drop before corrective action is taken.

Fodder King[142] produces a regular report for the regulatory body and the community on the results of soil analyses taken on Tiedman property (AGL Gloucester operation) where irrigation using CSG production water blended with aquifer fresh water is being trialled. The range of parameters reported provide a good basis for monitoring the ongoing health of the soil. The list of parameters used is readily accessible and will not be reported here.

CSG Water Quality Requirements

This 'CSG water quality requirements' document must be read in conjunction with the *Coal Seam Gas Recycled Water Management Plan Guideline including Exclusion Decision Application Guideline.*

The pre-supply water quality data collection program, aquifer baseline, source water, operational and ongoing final water quality monitoring programs should be developed in accordance with the parameters listed below. In feed ponds where there is no potential for the introduction of disinfection by-products (DBs) through the recirculation of water, testing for DBs in feed water is not required.

Any additional monitoring requirements have been specified in the relevant sections of the *Coal Seam Gas Recycled Water Management Plan Guideline including Exclusion Decision Application Guideline.* The parameters outlined below are likely to change once a robust water quality dataset has been developed by industry.

Samples must be presented as total. Filtered results are only relevant for the protection of aquatic organisms, and give no indication of risks to public health.

CSG Water Quality Parameters

Chloroform (DB)	Bromodichloroacetic acid (DB)
Bromodichloromethane (DB)	Chlorodibromoacetic acid (DB)
Dibromochloromethane (DB)	Trichloroacetic acid (DB)
Bromoform (DB)	Tribromoacetic acid (DB)
2,2-Dichloropropionic acid (DB)	HAA6 (DB)
Monochloroacetic acid (DB)	Monochloroacetonitrile (DB)
Monobromoacetic acid (DB)	Dichloroacetonitrile (DB)
Dichloroacetic acid (DB)	Trichloro-acetonitrile (DB)
Dibromoacetic acid (DB)	Bromochloro-acetonitrile (DB)
Bromochloroacetic acid (DB)	Total organic halogen (TOX) (DB)
Chlorite (DB)	Caesium
Chlorate (DB)	Chromium
Chlorine dioxide (DB)	Cobalt
Bromate (DB)	Tungsten
N-Nitrosodimethylamine (NDMA) (DB)	Vanadium
Total Petroleum Hydrocarbons	Uranium
Dibenz[a,h]anthracene	Copper
Indeno[1,2,3-cd]pyrene	Gold
Benzo[a]pyrene	Iodide
Benzo[b+k]fluoranthene	Iron
	Naphthalene
Chrysene	PAH (as B(a)P PEF)
Benz[a]anthracene	Lead
Thallium	Lithium
Thorium	Magnesium
Tin	Manganese
Benzene	Mercury
Toluene	Molybdenum
Ethylbenzene	Nickel
Xylenes (all isomers)	Niobium
Nonylphenol	Palladium
Bisphenol A	Platinum
Phenol	Potassium
Cyanide	Rubidium
Chloride	Boron
Fluoride	Bromide
Nitrate	Ruthenium
Sulphate	Selenium
Aluminium	Silver
Antimony	Sodium
Arsenic	Strontium
Barium	Tellurium
Beryllium	Zinc
Bismuth	
Monobromoacetonitrile (DB)	Lead-210
Dibromoacetonitrile (DB)	Polonium-210
Cadmium	Radium-226
Calcium	Radium-228

(DB) indicates the parameter is a disinfection by-product

Queensland Government

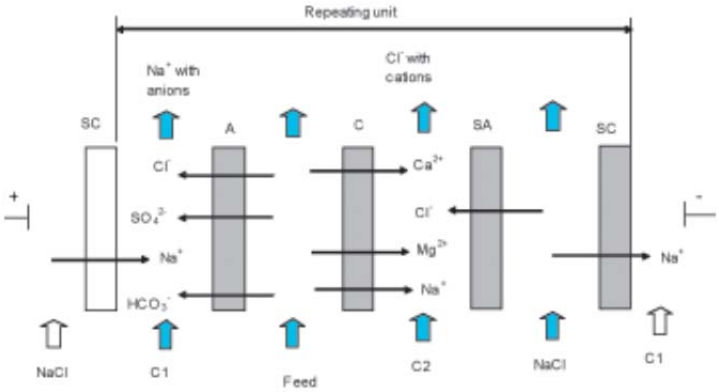
7. NOTABLE NEW TECHNOLOGIES AND INNOVATION FOR TREATING, STORING, RE-USING AND DISPOSING OF WATER AND WASTES FROM CSG

Through its Department of Energy, the US Government is funding the pilot appraisal of a number of CSG production water treatment processes that offer potentially better energy economics than processes now in use. None to date has emerged as a significant newcomer, but there are several developments that are worthy of continuing observation.

Zero Liquid Discharge (ZLD) by Electrodialysis Metathesis (EDM)[119]

In this technology the concentrate from a reverse osmosis unit is sent to a modified electrodialysis unit which has repeating units of four compartments and four membranes instead of the usual two as shown. This configuration (called EDM) splits the concentrate into two streams of highly soluble salts: one containing sodium with anions and the other containing chloride with cations. The highly concentrated stream can then be recovered as a solid by a mechanical vapour compression crystalliser. ZLD is achieved by blending reverse osmosis permeate with EDM product and the condensed vapour from the crystalliser. The advantage of this process is that it can boost water recovery to close to 100%.

Schema for EDM unit



ABR Technologies[101]

This company has developed a novel sorbent powder which can remove heavy metals from production water from CSG recovery and innovative processes for regeneration of acids and alkalis used in the ion exchange process used for preparation of this water for beneficial use.

KNew Process[D]

Developed for the processing of acid mine wastes, this technology turns the regeneration mixes from ion exchange into useful and relatively valuable exit products as opposed to valueless brines. KNew uses nitric acid in the regeneration step to produce potassium nitrate whilst sodium chloride is recovered in a relatively pure state.

D D J Bewsey (2014) *AMD Back to the Land*, The Chemical Engineer, April 2014, pp32-36

The process will need adjustment to treat CSG production water but its attraction is the reduction of the solids present into a concentrated waste stream of heavy metals and useful products. It is being developed at the pilot scale in South Africa.

National Centre of Excellence in Desalination[141]

This Centre is conducting a wide range of R&D on aspects of desalination of brackish water, including alternative lower cost technologies and disposal of concentrates. At the University of Wollongong, Professor Nghiem has a large project (investment in excess of $1 million) on the extraction of water and minerals from CSG production water for beneficial use. To quote:

> "A major issue associated with the production of coal seam gas (CSG) is the management of co-produced water. This project will develop a holistic approach to the management and beneficial utilisation of CSG water as well as its mineral content. A specific focus is on the development of low maintenance membrane distillation and multi effect distillation systems using on-site low grade heat to increase water recovery. The project will also evaluate the production of sodium hydroxide from the supersaturated concentrate using a chlor-alkali membrane electrolysis process".

The project, which is collaborative with CSG producers and separation equipment companies, could well lead to exciting outcomes, able to be adopted by the industry.

Mintek Electrocoagulation[143]

Mintek, an Australian company offer a front-end process claimed to halve the load on reverse osmosis plant by use of electrocoagulation.

Industry Knowledge of Deep Well Injection of Concentrates[2A]

With greater exploration by industry of possible sites for CSG recovery has come much improved knowledge of basin characteristics and aquifers. This knowledge is frequently held within company files. Progress in utilising deep well injection of concentrates into isolated aquifers containing highly saline water depends on this information. The practice is common in the USA. Whilst it is not considered likely that suitable aquifers will be found in the Sydney basin because of the relative impermeability of the Permian structures of which the deeper parts are comprised and the apparent absence of high permeability deeper isolated aquifers, it is likely that northern NSW and certainly the Surat basin in Queensland will present opportunities for deep well injection. To be confident of taking up such opportunities a deep knowledge of the geology and hydrogeology of the site will be required. Cooperation between government and corporate bodies should occur.

[2A] Helpful discussions with Mr John Ross, Manager Hydrogeology Upstream Gas of AGL Energy Limited are gratefully acknowledged

8. 'WORST CASE SCENARIOS' AND THEIR RISK OF OCCURRENCE

The two previous papers[A,B] have discussed US experience in environmental incidents that have occurred at CSG facilities. Incidents have been dominated by spillages.

'Worst case scenarios' imply significant human health issues or serious environmental damage. The table below identifies possible serious scenarios associated with the holding and treatment of production water. It does not consider the possibility of a surface drinking water aquifer becoming contaminated by poor well drilling and completion leading to a leakage of highly saline material upwards. This aspect has been covered by the code for drilling developed by the NSW Government.

Worst case scenarios

Scenario	Potential Outcome	Risk	Comment
Inadequately treated production water	Aquifer supplying potable water becomes contaminated due to injection of this water	Low	Decision to reinject into an aquifer being used for human or stock water should only be taken after a comprehensive appraisal of the risk and a standard of treatment plant design, operation and monitoring similar to that of a municipal potable water supply facility.
Significant surface leak of untreated production water due to treatment plant failure.	Infiltration into shallow aquifers used for water supply. Off site environmental damage.	Moderate	Good design practice would call for containment with monitoring to detect any leaks or signs of potential failure. Treatment plant subjected to Hazop. Staff well trained. Leaked material diverted to holding pond.
Overtopping of containment ponds by severe rain event causing offsite flow	Untreated production water or treatment concentrates flow off site causing environmental damage	Low	Good design practice calls for holding ponds to be run to cope with a 100-year flood event. In an extreme situation e.g. major flood, the level of dilution would mitigate environmental damage.
Failure of walls of containment ponds	Possible infiltration of sub-surface aquifers	Low	Since the Pilliga incident the design criteria for the walls of containment ponds have been tightened with monitoring devices under containment walls to detect signs of imminent failure or any significant leakage
Spillage of treatment chemicals	Off-site environmental damage	Low	Hazardous chemicals used in membrane plant cleaning adequately bunded and monitored
Poor disposal practices for solid wastes	Site contamination and risk of heavy metals and radioactive species escaping off- site	Low	Possible solids comprise crystallised salts and adsorbent materials including ion exchange beads. Proper protocols for disposal of the relatively minor volumes should ensure compliance with environmental guidelines

If the skill sets required for treatment plant operation model, for example, those in a sewage treatment plant, it is highly likely that safe and secure operation can be achieved. If, as seems now to be the standard protocol, the plant is to be operated remotely, adequate local manpower must be available for an expeditious response to maintenance problems and plant upsets. There is a clear advantage to be had in economies of scale where the costs of skilled overview of plant operation can be shared.

9. CONCLUSIONS

A review of the available literature and discussion with experts suggests that produced water from CSG recovery can be treated to achieve the beneficial goals espoused by bodies like the Queensland Government. Because of the very high levels of production water associated with CSG recovery operations in the Surat basin and the scale to which the industry has grown in Queensland, the Queensland Government is perhaps further down the path than the NSW Government in developing regulatory profiles for the handling of produced water. With present prices for methane from CSG, there appears to be sufficient flexibility for operators to implement a processing regime where beneficial use is made of the produced water recovered.

Treatment processes vary. On the one hand there is the least expensive option of using the produced water in the industry or in coal mines. But the volumes in the Surat clearly exceed this sink. Produced water appears generally too saline to be applied for irrigation without further treatment. Also, it contains chemicals that are at unacceptable levels for uses such as stock watering. The consensus, in Queensland at least, is that it makes sense to subject the water to substantial further treatment so that it is suitable for aquifer injection or irrigation.

The preferred technologies are settling as a combination of microfiltration, ion exchange and reverse osmosis. In this way heavy metals and radioactive substances can be removed in the early section of the treatment plant and a high recovery of quality potable water obtained. Whilst alternative technologies using less energy are on the horizon, to date they have not been demonstrated at sufficient scale to warrant full scale implementation. However, this might come and technologies are sufficiently modular to incorporate future technology advances. Scale of operation is important in determining the final cost of treatment of produced water, with a figure of $\$2/m^3$ being representative.

Surprisingly, not a lot of new thinking can be obtained from the US scene as deep well injection of unprocessed production water is still practiced and disposal of untreated water to rivers is considered acceptable, despite observed environmental problems.

The problem of disposal of treatment concentrates remains the elephant in the room. For the large plants envisaged in northern NSW and Queensland the quantity of salts to be disposed of is substantial. Whether to handle these as a solid by crystallisation or as a highly concentrated solution is moot. Currently they are being stored in brine ponds awaiting resolution of the disposal issue. While there is an international market for salt and processes available to win valuable components from the concentrated saline liquor, operators have been reluctant to commit to further treatment, choosing as a last resort to store the concentrate or solid salt in landfill cells. However, the quantities involved are substantial and the storage potentially environmentally hazardous.

ABOUT THE CONSULTANT

Emeritus Professor Chris Fell AM FTSE CPEng is a chemical engineer, listed on the National Professional Engineers Register. As an academic at the University of New South Wales he was Foundation Director of a Commonwealth Special Research Centre for Membrane and Separation Technology and Foundation Chair of the CRC for Waste Management and Pollution Control. He was co-inventor of the technology that led to the Australian membrane company Memtec Limited (see www.10innovations.unsw.edu.au). Since retirement from UNSW he has run a boutique consulting practice providing advice to government and industry and serves as a company director.

REFERENCE MATERIAL

Some of the reference material has been referred to individually in the paper, but other material has been drawn on for general background. The table below categorises the references that have been drawn on for general background and information checking.

General reviews of the industry and coal seam gas produced water	**Australian producers of coal seam gas**	**Specific studies yielding comparative data on coal seam gas production water**	**Reports relating to US and overseas**	**Produced water treatment processes**
2, 21, 22, 34, 35, 39, 42, 47, 63, 64, 67, 68,76, 81, 87	19, 33, 37, 75	28, 45, 49, 66, 71, 72, 74, 98, 132	27, 29, 29, 41, 44, 46, 48, 53, 54, 61, 69, 77, 78, 80, 83, 84, 85, 88, 89, 91, 92, 96, 110, 114	70, 94, 95, 106, 110, 128, 130

Web sites listed have all been accessed in the period 7 – 21 April, 2014.

Number	Web Address	Title	Content
1	http://www.australianminesatlas.gov.au/education/fact_sheets/coal_seam_gas.htm l	Coal seam gas fact sheet	Geoscience Australia data 2012
2	http://en.wikipedia.org/wiki/Coal_bed_methane_extraction	Coal bed methane extraction	General overview
3	http://www.lockthegate.org.au	About coal seam gas	Comment on problems with technology
4	http://www.csiro.au/Outcomes/Energy/Energy-from-oil-and-gas/What-is-coal-seam-gas.aspx	What is coal seam gas	2012 factsheets
5	http://www.gisera.org.au/publications/faq/faq-csg-general.pdf	General coal seam gas frequently asked questions	2011 information Gas Industry Social and Environmental Research Alliance
6	http://www.arrowenergy.com.au/our-company/what-is-coal-seam-gas	What is coal seam gas – Arrow Energy	2014 Produces 20% of Qld's gas primarily for power stations.
7	http://www.csiro.au/news/~/media/28458902B7DD460AA6BDDAEF02B28145.ashx	Coal seam gas – Produced water and site management	2012 Options for site management
8	www.ehp.qld.gov.au/management/non-mining/documents/beneficial-use-guideline.pdf	Approval of coal seam gas water for beneficial use	2013 Approval protocols
9	http://www.aplng.com.au/home/what-coal-seam-gashttp://www.aplng.com.au/home/what-coal-seam-gas	What is coal seam gas	Overview of Qld project

10	http://vimeo.com/53629052	Air, water and CSG	SCU methane measurements, Talinga
11	http://pubs.usgs.gov/fs/fs-0156-00/fs-0156-00.pdf	Water produced with coal bed methane	2000 USGS report
12	http://www.fogmirboonorth.org.au/coal-seam-gas/	Coal seam gas fact sheet	Mirboo North, Victoria Lock the Gate
13	http://www.originenergy.com.au/1143/Coal-seam-gas	Coal seam gas – Origin Energy	Information on activities
14	http://www.nrc.nsw.gov.au/content/documents/Submission%20-%20ST%20-%20Australian%20Gas%20Alliance.pdf	Coal bed methane hazards in NSW	2005 Atkinson report on hazards
15	http://www.all-llc.com/publicdownloads/CBM_BU_Screen.pdf	Handbook on CBM produced water – ALL Consulting	2003 handbook produced for USA CBM recovery
16	http://greenleft.org.au/node/48936	Green Left Weekly	Methane in drinking water
17	www.energyandresources.vic.gov.au/earth-resources/victorias-earth-resources/minerals/coal-seam-gas	Coal Seam Gas – Energy and Earth Resources	2014 The Victorian position should production be proposed
18	www.sixdegrees.org.au/content/our-position-coal-seam-gas-csg	Our position on coal seam gas	Highlights problems.
19	https://www.csg.nsw.gov.au/	Coal Seam Gas	2013 NSW Government CSG website showing activity
20	http://www.dartgas.com/page/Our_Business/What_is_Coal_Bed_Methane/	What is coal seam gas?	Dart has now abandoned operations in Australia
21	http://www.globalskm.com/Insights/Achieve-Magazine/Issue1-2013/Managing-the-risk-of-coal-seam-gas-CSG-water.aspx	Managing the risks of coal seam gas water	2013 Summary of current status
22	http://www.aph.gov.au/About_Parliament/Parliamentary_Departments/Parliamentary_Library/pubs...	The development of Australia's coal seam gas resources	2012 Review by Parliamentary Library
23	http://www.abc.net.au/news/specials/coal-seam-gas-by-the-numbers/waste/	By the Numbers – salt and chemical waste	2014 Report of program on this topic
24	http://www.keepthescenicrimscenic.com/coal-seam-gas-information.php	Keep the Scenic Rim scenic	Opposition to Arrow Energy exploration in Scenic Rim region
25	http://www.energyaustralia.com.au/servlet/search?query=Santos+Gunnedah+Basin+CSG+overview&=	Santos Gunnedah Basin CSG overview	2009 Brief description of activities
26	http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/Gloucester%20Document%20Repository/Community%20Updates/20140821_Extracted%20Water%20Management%20Strategy%20%20%20Consultation%20Draft.pdf	Gloucester Project – Extracted water management policy	Data on AGL Gloucester operation 21 August 2014

27	http://waterquality.montana.edu/docs/methane/cbmfaq.shtml	Frequently asked Question – Coal bed methane	2003 Montana- deals with disposal
28	http://www.publish.CSIRO.au/paper/EN12136.htm	Environmental issues associated with coal seam gas recovery: Managing the fracking boom	G Batley and R Kookana Environmental Chemistry 2012 9(5) 425-428 Geogenic species released during fracking
29	https://crawford.anu.edu.au/pdf/inthenews/12186-unconventional-gas-document-web-fa.PDF	Unconventional gas processing and water resources	2012 Lessons from US on better governance – Workshop for Australian regulators
30	http://www.ssec.org.au/resources/FactSheets/CSG%20Impacts%20-%20Summaryv4.pdf	Coal seam gas as threat to water resources – Sutherland Shire	Information on problems From Stop CSG Illawarra
31	http://at4mag.arup.com.au/issue4/6.htm	It's Gas Gas Gas – except for the "fracking" issues	2013 Arup Consulting summary of technology
32	http://csgfreenorthernrivers.org/csg-risks	Learn about CSG	Details possible problems
33	http://peakenergy.blogspot.com.au/2008/10/coal-seam-gas-producers-new-masters-of.html	Coal seam gas producers – the new masters of the universe	2008 Overviews Australia's CSG industry
34	https://www.ipa.org.au/library/.svn/text-base/Energy34.pdf.svn-base	More than Davy lamps and canaries – Coal seam methane in the 21st century	2004 Paints benign picture of production water disposal
35	https://www.kateausburn.com/faq-coal-seam-gas	Frequently Asked Questions – Coal Seam Gas	2014 Journalist Kate Ausburn
36	http://www.stoppilligacoalseamgas.com.au/%3Fpage_id%3D61	Coal seam gas threat – Stop Pilliga Coal Seam Gas	Comments on spill that contaminated aquifer
37	http://www.otfordeco.com/CoalSeamGasExploration.html	Coal seam gas mining - Otfordeco	2010 report on approval for exploration in Illawarra
38	http://www.beneterra.com.au/Sound-science-pg21914.html	Tracking solutes and water from subsurface drip irrigation application of coalbed methane produced water	2011 Study on Powder River Basin, Wyoming
39	http://wentworthgroup.org/wp-content/uploads/2013/12/BREE_Coal-seam-gas-production_WILLIAMS-etal-.pdf	Coal seam gas production – Wentworth Group of Concerned Scientists	2013 Useful overview of challenges faced by the industry

40	http://aqwatec.mines.edu/produced_water/new/IPEC2010/2.IPEC2010_WaterQuality.pdf	Coalbed methane produced water: Usability through characterization	2010 Colorado School of Mines
41	http://www.worldcoal.org/coal/coal-seam-methane	What is coal seam gas?	2013. Provides world resources. Nothing on produced water
42	http://www.basinsustainabilityalliance.org/links/coal-seam-gas-water-discussion-paper.pdf	Management of water from coal seam gas production	2009 Queensland Government Prefers aquifer injection of treated water
43	http://ccag.org.au/coal-seam-gas-csg/	Caroona Coal Action Group and SOS Liverpool Plains	2013 Statistics on wells and produced water. Highlights spills.
44	http://serc.carleton.edu/research_education/cretaceous/coalbed.htm	All Things Cretaceous Coalbed methane - SERC	University of Montana take on Powder River CSG operation
45	http://www.groundwater2010.com/documents/McLeanWendy.pdf	Isotopic tools for assessing aquifer connectivity during coal seam gas exploration	2010 study of aquifer connectivity in Broke NSW
46	http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/1317/report/0	Treatment of Produced Water from Coal-Bed Methane Production Using Carbon Aerogel Technology	1996-97 US EPA SBIR supported trial of capacitive deionisation
47	http://naturalcsg.com.au/coal-seam-gas/the-myths	Natural Coal Seam Gas	2013 APPEA
48	https://geoinfo.nmt.edu/publications/periodicals/nmg/downloads/25/n4/nmg_v25_n4_p95.pdf	New Mexico's Raton Basin Coalbed Methane Play	2003 gives gas and produced water volumes
49	http://large.stanford.edu/courses/2013/ph240/iskhakov1/	Coalbed methane course	2013 Discusses Australian fraccing technique.
50	http://huntervalleyprotectionalliance.com/hvpa_concerns.html	Why are we concerned about coal seam gas – Hunter Valley	Concerns are fraccing and disposal of salt water. Quotes Bohena pilot 6 wells as each yielding 100ML daily.
51	http://www.pir.sa.gov.au/petroleum/prospectivity/basin_and_province_information/unconventional_gas/frequently_asked_questions?SQ_DESIGN_NAME=printer_friendly	FAQ: Un-conventional gas in SA	Primarily on coal seams
52	http://eprints.usq.edu.au/24107/	Coal seam gas water as a medium to grow Dunalliella Tertiolecta for lipid extraction	2013 Treated production water for algal growth

53	http://www.oilandgasbmps.org/viewpub.php?id=47	Intermountain Oil and Gas BMP project	2006 Handbook
54	www.netl.doe.gov/KMD/Cds/disk2/SanJuanandRatonBasins.pdf	Managing Coal Bed Methane Produced Water for Beneficial Uses, Initially Using The San Juan and Raton Basins as a Model	2004-5 Exposition of alternative technologies with costs
55	http://www.dowwaterandprocess.com/en/industries-and%20applications/oil_field_water	Oil Field Water	2014 Dow Higgins loop ion exchange technology
56	http://www.sbs.com.au/news/article/2013/03/12/factbox-csg-australia	Factbox: CSG in Australia	2013 SBS overview
57	http://www.westraliangasandpower.com.au/whatisCSG.htm	What is coal seam gas	2009 Overview of WA activity
58	http://gallery.mailchimp.com/d7505c99d17f8deba775cfcea/files/Aust_CSM_report_by_Caroona_Group.pdf	Environmental, Social and Economic Issues Associated with Coal Seam Gas	2009 Good overview
59	http://www.deakin.edu.au/research/stories/2012/05/08/the-coal-seam-gas-industry-in-australia	The Coal Seam Gas Industry in Australia	2012 Review
60	http://www.bigcatenergy.com/Evolution-CBM-Water-Management.aspx	History of CBM water management	2013 Re-injection expertise
61	http://digitool.library.colostate.edu/dtl_publish/35/182726.html	Coalbed Methane Produced Water Organic Matter Characterization: Contribution, Origin, and Potential Impact on Membrane Treatment Technologies	2014 Powder River Basin
62	http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/CSG%20Community%20News/Gloucester/Factsheets/2013/Exploration%20and%20Production%20CSG%20Fact%20Sheet%202.pdf	Coal Seam Gas – Fact Sheet 2	2013 AGL
63	http://www.slideshare.net/3pillarsnetwork/iah-symposium-2009-groundwater-in-the-sydney-basin	Groundwater in the Sydney Basin Symposium	2009 Symposium slides

64	http://aie.org.au/AIE/Documents/Oil_Gas_121114.pdf	An analysis of coal seam gas production and natural resource management in Australia	2012 Report prepared for Environmental Deans
65	http://www.communityovermining.org/CSG.html	Coal seam gas	2014 Describes problems
66	http://www.sciencedirect.com/science/article/pii/S0166516209001797	Stable isotope and water quality analysis of coal bed methane	2010 article
67	https://www.tresscox.com.au/resources/resource.asp?id=405#.U0ZXOE3NuUk	Coal seam gas water – Part 1: Solution to Queensland's water	2008 Overview
68	http://environmentvictoria.org.au/content/coal-seam-gas	What is coal seam gas?	2013 Summary
69	http://www.fws.gov/mountain-prairie/contaminants/papers/documents/r6721c05.pdf	Assessment of Contaminants Associated with Coal Bed Methane-Produced Water and Its Suitability for Wetland Creation or Enhancement Projects	2005 Wyoming study in Powder River Basin
70	http://www.waterworld.com/articles/iww/print/volume-8/issue-5/features/ion-exchange-amp-deionization-treating-coal-bed-methane-produced-water.html	Ion Exchange & Deionization: Treating Coal Bed Methane Produced Water	2014 Waterworld report
71	http://ro.uow.edu.au/cgi/viewcontent.cgi?article=1038&context=thsci	Coal Seam Gas: Issues for Consideration in the Illawarra Region, NSW, Australia	2012 Thesis
72	http://www.secarbon.org/files/black-warrior-basin.pdf	Summary of field test site and operations	2010 CO_2 Sequestration in drained coal bed
73	http://www.ntn.org.au/wp/wp-content/uploads/2013/04/UCgas_report-April-2013.pdf	Toxic Chemicals in the Exploration and Production of Gas from Unconventional Sources	2013 article
74	http://irrigear.com.au/content/case-studies/mining	Coal seam gas-water treatment and re-use	2014 AGL Gloucester
75	http://www.yoursayagl.com.au/welcome-to-agls-online-community?tool=qanda	Your say	2014 Interactive website

76	http://archive.nwc.gov.au/library/waterlines/54	Onshore co-produced water: extent and management	2011 Detailed treatment
77	http://www.ceri-mines.org/coalbedmethane.htm	Coal Bed Methane Co-produced Water Treatment	2007 US experience
78	http://www.riversimulator.org/Resources/Purveyors/AugmPapers/CoalbedMethaneProducedWater.pdf	Coal bed methane produced water	2007 Augmentation of Colorado River
79	http://www.pc.gov.au/__data/assets/pdf_file/0014/122531/sub018-attachment4-resource-exploration.pdf	Is there a drop to drink?	2012 Productivity Commission report on CSG produced water
80	http://www.nap.edu/catalog.php?record_id=12915	Mangement and effects of coal bed methane produced water in the Western United States	2010 Paperback
81	https://www.engineersaustralia.org.au/sites/default/files/shado/Divisions/Western%20Australia%20Division/Groups/Oil_Gas/cbm_presentation.pdf	Australian Coal Bed Methane: Principles and Development Challenges	2012 Prepared by T K Soh. Slides
83	https://www.novascotia.ca/nse/dept/docs.policy/BMP.for.Formation.Water.from.Exploration.Production.pdf	Environmental Best Management Practices for Formation Water from Coal Bed Methane Exploration and Production Activities	2008 Report
84	http://www.usbr.gov/research/projects/detail.cfm?id=3259	Treatment and Beneficial Use of Produced Water in the western U.S.	2012 Links GIS information to production to explore beneficial uses.
85	http://www.ems.psu.edu/~elsworth/courses/egee580/2010/Final%20Reports/CBM_Report.pdf	Coalbed methane: Utilization and treatment in North Western San Juan, Colorado	2010 Detailed student report at Penn State – examines costs
86	http://ceda.com.au/media/263565/cedaunconventionalenergyfinal.pdf	Australia's Unconventional Energy Options	2012 report
87	http://www.nswfarmers.org.au/__data/assets/pdf_file/0007/31687/Key-Terms-CSG-v2_1.pdf	Mining and Coal Seam Gas in NSW – Information for landholders:	2013 Terms explained

88	http://peakoil.com/forums/viewtopic.php?f=6&t=69408	Questions about coal seam gas	2014 Communications site. US to post new disposal regulations in 2014
89	http://tsop.org/refs/cbmaw.htm	Coalbed-Methane Associated Water Selected References - revised November, 2013	2013 List of US focused references
90	http://caha.org.au/wp-content/uploads/2012/03/submission-to-the-NSW-Chief-Scientist-and-Engineer		
91	http://www.swhydro.arizona.edu/archive/V4_N6/feature1.pdf	Coalbed Natural Gas and Water Management in the Powder River Basin	2006 Gives water to gas ratios for US operations
92	http://billingsgazette.com/news/state-and-regional/wyoming/water-wells-recover-amid-coal-bed-methane-bust/article_854f3913-4fb8-5c39-a1ef-f84e468de822.html	Water wells recover amid coal-bed methane bust	2014
93	http://miningaustralia.com.au/features/coal-seam-gas-the-explosive-debate	Coal seam gas: The explosive debate	2013
94	http://www.greencarcongress.com/2006/06/windpowered_ele.html	Wind-Powered Electrolysis of Coal Bed Methane Water for Hydrogen Production	2006 SBIR grant US
95	http://www.ags.gov.ab.ca/energy/cbm/	Coalbed methane	2013 Disposal of produced water by deep well injection
96	http://www.circleofblue.org/waternews/wp-content/uploads/2010/08/prodwaterpaper1.pdf	A white paper describing produced water from production of crude oil, natural gas and coal bed methane	2004
97	http://www.goldsim.com/Web/Solutions/Showcase/EnvironmentalExamples/CSGBrine/	Coal seam gas brine management	2011 Flowsheeting program gives design
98	http://www.metts.com.au/Desalination_and_Power_Gen.html	Desalination for the Power Industry (Applications, Efficiencies and Costs)	2014 Consultants and suppliers

99	http://www.globalwaterintel.com/archive/13/7/general/sizing-coal-seam-gas-water-market.html	Sizing up the coal seam gas water market	2012 Market in Australia
100	http://www.couriermail.com.au/news/opinion/opinion-hey-greenies-youre-not-gonna-like-this-news-but-coal-seam-gas-water-is-a-godsend-for-farmers/story-fnihsr9v-1226747187508	OPINION: Hey Greenies you're not gonna like this news, but coal seam gas water is a godsend for farmers	2013 Courier Mail
101	http://www.abrprocess.com/latest-news.html	Combating the salt menace from coal seam gas	2012
102	http://www.dews.qld.gov.au/__data/assets/pdf_file/0005/45158/csg-recycled-wmp.pdf	Coal Seam Gas Recycled Water Management Plan Guideline	2013 Department of Energy and Water Supply
103	http://www.ehp.qld.gov.au/management/non-mining/documents/csg-water-management-policy.pdf	Coal seam gas water management policy	2012 DEWR, Queensland
104	http://www.ehp.qld.gov.au/management/non-mining/documents/general-bua-irrigation-of-associated-water.pdf	General Beneficial Use Approval— Irrigation of Associated Water (including coal seam gas water)	2013 DEHP, Queensland
105	http://www.santos.com/library/Narrabri%20Gas%20Projects%20request%20for%20DGRs.pdf	Narrabri Gas Project Preliminary Environmental Assessment	2014 Santos document
106	http://desalination.edu.au/2013/07/cheap-seawater-desalination/#.Uz1Sco3NuUk	Cheaper seawater desalination	2013
107	http://www.evoqua.com/en/applications/case-studies/Pages/default.aspx	Evoqua Water Technologies	2014 Formerly Siemens
108	http://www.veoliawater.com.au/	Veolia Water Australia and New Zealand	2014
109	http://nexusgroupsolutions.com/TechnicalBrief_Produced%20Waters.pdf	Oil and gas produced water treatment technologies	2014 The Nexus Group
110	http://aqwatec.mines.edu/publications/CathPub/ER1_Treatment_of_CBM_PW.pdf	Treatment of coalbed methane produced water	2011 AQWATEC Colorado School of Mines
111	http://www.rpsea.org/files/1841/	An integrated framework for the treatment and assessment of production water	2009 RPSEA
112	http://cdn.intechopen.com/pdfs-wm/41954.pdf	State of the Art Treatment of Produced Water	2013

113	http://www.usbr.gov/research/AWT/reportpdfs/report133.pdf	Multibeneficial use of produced water through high-pressure membrane treatment and capacitive deionization technology	2009 Colorado School of Mines study
114	http://inside.mines.edu/Cath	Tzahi Cath/Forward osmosis	2014 Describes research at Colorado School of Mines
115	http://www.waterworld.com/articles/iww/print/volume-8/issue-5/features/ion-exchange-amp-deionization-treating-coal-bed-methane-produced-water.html	Ion Exchange & Deionization: Treating Coal Bed Methane Produced Water	2014 Siemens trailer technology
116	http://ipec.utulsa.edu/Conf2006/Abstracts/Hayes_67.pdf	Electrodialysis treatment of coal bed methane produced water: Engineering issues and cost projections	Argonne Laboratory Cost estimate $US0.9/m^3
117	http://www.deswater.com/DWT_abstracts/vol_2/2_2009_278.pdf	Electrodialysis reversal: Process and cost approximations for treating coal bed methane waters	2009 Cost estimate $US0.4-6/m^3
118	http://www.riversimulator.org/Resources/Purveyors/AugmPapers/CoalbedMethaneProducedWater.pdf	Coal bed methane produced water	ED not economic beyond feed of 2,000 mg/L
119	http://www.fwrj.com/techarticles/0711%20tech1.pdf	Zero Liquid Discharge Desalination of Brackish Water with an Innovative Form of Electrodialysis: Electrodialysis Metathesis	2011 University of Texas

120	http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_0032/0901b803800325f0.pdf?filepath=liquidseps/pdfs/noreg/177-02016.pdf&fromPage=GetDoc	A low cost Option to Reduce Sodium Levels in Coal Bed Methane Coproduced Wastewater using DOWEX G-26 Resin	2014 Dow ion exchange
121	http://www.netl.doe.gov/research/coal/crosscutting/pwmis/tech-desc/deion	Fact Sheet – Capacitative Deionisation	DOE reporting 2007 study
122	http://www.gewater.com/search.html?searchTxt=coal bed methane production water	Water and process technologies	2014 GE Electrodeionisation
123	www.veoliawater.com.au/veoliawater/contracts-projects/48266.htm	QGC major treatment plant	2014 Award to Veolia of major treatment project
124	http://www.veoliawaterst.com/opus/en/	Optimised pretreatment and unique separation	2014 Veolia integrated system
125	http://www.usbr.gov/research/AWT/reportpdfs/report157.pdf	Oil and Gas Produced Water Management and Beneficial Use in the Western United States	2011 Describes treatment technologies. Excellent exposition.
126	https://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/eh52_aust_drinking_water_guidelines_update_131216.pdf	Australian Drinking Water Guidelines	Up to date 2013
127	http://www.environment.nsw.gov.au/water/usinganzeccandwqos.htm	Using the ANZECC Guidelines and Water Quality Objectives in NSW	2013 Guidance on ANZECC Document
128	http://www.csg.nsw.gov.au/features/what-you-need-to-know-about-coal-seam-gas-csg#.U0o2YE3NuUk	What you need to know about coal seam gas	2013 Legislative and regulatory
129	http://www.mondaq.com/australia/x/274750/Water/Coal+Seam+Gas+National+regulatory+update	Coal seam gas – national regulatory update	2013 Report on Commonwealth developments
130	http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0005/433643/Irrigation-water-quality.pdf	Irrigation water quality	2011 Advice to farmers from NSW Department of Primary industries
131	http://www.agl.com.au/about-agl/how-we-source-energy/natural-coal-seam-gas/gloucester-gas-project/irrigation-trial	Irrigation trial	2014 AGL irrigation trial report

132	http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/CSG%20and%20the%20Environment/Gloucester/Assessments%20and%20Reports/2014/20140213_2013%20Flow%20Testing%20of%20Craven%2006%20and%20Waukivory%2003%20Gas%20Wells.pdf	2013 Flow testing of gas wells	2014AGL Gloucester Parsons Brinkerhoff
133	http://www.santoswaterportal.com.au/media/pdf1833/131009_santos_glng_stage_2_cwmmp_revision_2_summary_plan.pdf	CSG water management and monitoring plan	2013 Santos Gladstone LNG plant
134	http://www.depi.vic.gov.au/agriculture-and-food/dairy/pastures-management/managing-dryland-lucerne/irrigation-of-lucerne-for-hay	Irrigation of Lucerne for hay	1998
135	http://www.metgasco.com.au/industry-news/coal-seam-gas-water-godsend-farmers	Coal seam gas is a Godsend for farmers	2014 QGC plant treated water used for agriculture
136	http://www.couriermail.com.au/news/queensland/santos-wins-farmers-and-graziers-to-csg-and-queensland-reaps-benefits/story-fnihsrf2-1226788114485	Santos wins farmers and graziers to CSG and Queensland reaps benefits	2013 Courier Mail
137	http://www.ihs.com/products/chemical/planning/ceh/sodium-chloride.aspx	Sodium chloride	2014 World market
138	http://www.adkaction.org/files/public/Full_Study_Salt.pdf	Review of costs and effects of road de-icing	2010 US practice
139	http://www.penrice.com.au/company.htm	Company overview	2014 Penrice Soda
140	http://www.wy.blm.gov/prbgroup/research_mtg/bicarbonate.pdf	Sodium Bicarbonate and Coal Bed Methane Production: Standards Development	About 2009 Montana Excellent chemistry overview
141	http://desalination.edu.au/research/projects/novel-desalting/	National Centre of Excellence in Desalination	2014 Gives list of projects currently underway
142	http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/CSG%20Community%20News/Gloucester/Community%20Updates/2013/September/FK%20AGL%20DRE%20Rpt%202_Final_LowRes.pdf	Soil quality testing and management	2014 Fodder King

143	http://www.minetek.com/services/water-management/evaporation.html	Innovative mining solutions	2012 Evaporators, electro-coagulation
144	http://www.santos.com/library/PEL238_PAL2_and_PPL3_Produced_Water_Management_Plan.pdf	Produced water management plan	2014 Santos Narrabri proving well data
145	http://www.dartenergyscotland.co.uk/	Welcome to Dart Energy in Scotland	2014 Describes Dart Energy CSG facility in Scotland

146	http://waterinfo.nsw.gov.au/hunter/trading.shtml	Hunter salinity trading scheme	2014 Describes trading scheme allowing mine waste water discharge into Hunter River
147	http://nwc.gov.au/__data/assets/pdf_file/0007/18619/Onshore-co-produced-water-extent-and-management_final-for-web.pdf	On-shore co-produced water and management	2011 RPS report for National Water Commission
148	http://www.environment.gov.au/node/24354	Development of the Dalby water supply through the integrated use of coal seam methane water, recycling and demand management	2013 Major Commonwealth grant for new initiative on treated CSG produced water
149	http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/CSG%20Community%20News/Camden/Factsheets/2013/January/130122_FracturingFactSheet.pdf	AGL's New South Wales hydraulic fracturing fact sheet and frequently asked questions.	2013 114 out of 144 Camden wells fracced. 60% by water and sand only.
150	http://water.epa.gov/scitech/wastetech/guide/304m/upload/cbm_report_2011.pdf	Coalbed methane extraction: Detailed study report	2010 US EPA study of current production water disposal practices
151	http://www.aquaver.com/company-profile/aquaver.html	Membrane Distillation Systems	2014 Maldives seawater desalination plant
152	http://www.planning.nsw.gov.au/Portals/0/PlanningYourRegion/CSG_exclusion_zones_residential_CICs.pdf	Coal Seam Gas Exclusion Zones	2013 Provides policy and a map