ABSTRACT

The management of brine, generated from the desalination of saline water, is a key challenge for the mining, coal seam gas (CSG), resources and power industry in Australia and the communities of the inland towns that support these industries.

In many cases, the cost and technical challenges relating to the management of brine has a greater impact on the economic and technical feasibility of desalinating the saline brackish water than for the desalination plant itself.

This paper presents an overview of brine management relevant to the mining, CSG, resources and power sector with special emphasis on brine management for the CSG industry in Australia. With an investment of almost $70 billion in natural gas projects under construction in the Surat and Bowen Basins, the sheer capacity of the desalination plants (i.e. a cumulative capacity exceeding 400MLD), renders the CSG sector by far the largest industry investing in inland desalination technology and its associated brine management in Australia. The lessons learnt over the past decade from these project developments will be relevant to brine management for the wider mining, resources, and power industries.

Thermal evaporation technology was the dominant desalination technology applied worldwide up until the evolution and improvements in the performance of reverse osmosis (RO) membrane desalination technology during the 1980’s which resulted in the adoption of RO desalination in preference to thermal evaporation. RO is now the predominant technology applied for saline brackish water treatment in Australia. What is now evolving is RO desalination with thermal processes used in management of the resultant brine concentrate stream.

RO desalination is a separation process that generates two streams: a low salinity product water (termed permeate or RO product water) and a highly saline by-product (referred to for the purpose of this paper as the RO brine concentrate). Desalination applications for brackish water sources in remote inland locations in Australia are being increasingly required to eliminate or minimise the concentrated liquid discharges and to develop long term sustainable solutions, such as producing residual salts that can be exported from the site, that go beyond the traditional simple landfill solution. An overview of this latest trend toward zero liquid discharge (ZLD) and examples on how the lowest life cycle cost sustainable brine management solution can be achieved is featured in this paper.

The challenge for industry is to determine the best solution for brine management, given the high salinity of the brine and limited options available for acceptable disposal. This has driven the need for more sustainable options, including using innovative salt management processes to recover the salts. Other brine management options include ZLD technology to produce a semi-dry mixed salt residue that can be disposed of by on-site encapsulation or at a licensed landfill.

For example, the brine produced from the CSG industry in Queensland, Australia is typically high in alkalinity, and as such, brine management options, including acid mine waste neutralisation and recovery of salts (sodium chloride [NaCl] and sodium carbonate [Na₂CO₃]) are possible. The latter uses selective salt crystallisation, which is generally higher in capital and operating cost, but this cost maybe fully or partially offset by the revenue gained from the sale of salt(s). Where suitable geological strata can be identified, brine injection may be a low life-cycle cost solution for brine disposal.

The feasibility and life-cycle cost of any brine management option depends primarily on the location of the desalination plant site and the availability of brine management disposal/sale opportunities being in reasonably close proximity to the site.

This paper explores technical considerations, challenges and the life-cycle cost of the brine management options for the CSG industry that will achieve the most cost effective and environmentally sustainable solution. The emerging trends for desalination technology and brine management are also featured in this paper.
INTRODUCTION
A reliable and secure supply of water of appropriate quality has always been a basic need for the Australian mining, resources and power industry. In recent times, this has become a critical issue as pressure grows on the available resources, leading to increasing uncertainty over access to water resources, and to the management of excess water that may require the treatment of this water to facilitate beneficial use.

However, the impact of water security on individual operations will be determined by local factors, such as:

- Environmental stress arising from both excessive abstraction of water from the environment and discharges of inappropriately treated water to both point and diffuse sources.
- Demands of the environment creating a need to operate within sustainable yields from available surface and groundwater resources. This is a particular issue for groundwater resources where the time to replenish may take many years (or even centuries in some cases), whilst over extraction from rivers can lead to irreversible downstream environmental degradation.
- Water discharges in arid environments changing the nature of the downstream environment. This has been recognised as a critically important issue for the Australian CSG industry, where discharge of high quality water into ephemeral streams has been restricted because the continuous discharge flow of treated water to the river has the potential to change the fundamental environmental flow nature of the ephemeral stream.
- Competing demands between industry, communities, and agriculture.
- Industry creating a water demand in new regions. This is particularly relevant to the mining and oil and gas industries which are required to operate in regions determined by the location of the mineral and hydrocarbon resources.

Whilst the demand for water continues to grow, the availability of water supply and the ability to discharge water to the receiving environment is subject to increasing uncertainty and scrutiny. This uncertainty arises from many factors, though the issues relevant to the mining, resources, CSG and power industries may include:

- **Legislative uncertainty**: There are examples, such as in the Australian CSG sector, where the rapid growth and scale of activity has forced regulators to consider not just individual projects but larger scale cumulative effects. This has led to changes to the regulatory environment, for the example of the Australian CSG industry, this included the banning of

evaporation ponds as a primary treatment mechanism. The challenge for industry in this situation is not just compliance, but the fact that new regulations and guidelines are being created as the industry develops.

- **Climate change uncertainty**: In particular the impact of greater frequency and intensity of storm events and prolonged droughts.
- **Social license to operate**: This is increasing becoming a front page issue around the world as the mining industry moves into new regions. The Tia Maria project in Peru is an example where the industry faced significant issues related to specific community groups. The Tia Maria project was reportedly cancelled after violent clashes between the police and protestors (BBC website, 9 April 2011)

DE Salination Plant Brine Management Overview
Desalination processes produce low salinity product water plus a high salinity brine concentrate solution. The main issue to be managed is the effect of the hyper-saline RO brine concentrate stream on the receiving environment.

For inland RO desalination plants, the issue of RO brine concentrate management is becoming an increasingly important issue that needs careful consideration. Inland RO desalination applications (typically treating brackish water) became common in the 1980’s often associated with remote mining and power station projects.

These RO desalination plants applied in the Australian mining industry typically had capacities measured from a few MLD. The relatively small RO brine concentrate flows generated from these desalination plants were perceived as manageable using evaporation ponds.

More recently, the CSG and mining industries have installed larger RO desalination plants. This has coincided with a greater focus on the regulation of RO brine concentrate discharges.

The RO brine concentrate generated from a desalination plant consists predominantly of water with a significant level of dissolved salts. A key decision in considering RO brine management is whether to seek to manage the brine “as is” or to undertake further treatment. The former may be an option when desalinating low salinity brackish waters where the brine TDS may be as low as 1000mg/l and may be usable for specific agricultural applications.

There may be options for disposal of brine into saline aquifers, where this does not have a detrimental effect on the background aquifer water quality and an environmental consent can be obtained.

The option of reinjection to an aquifer will be dependent on the availability of suitable sites and
on local environmental regulations. It is however, due to environmental constraints and technical challenges, unlikely to be a universal solution.

Piping to the ocean or use of brine for industrial processes may be theoretically possible but is unlikely to be commercially viable or environmentally acceptable in most cases.

The alternative is further treatment of the RO brine concentrate. This can be implemented with one or more of the following objectives:

- Recovering additional desalinated water for beneficial use for applications such as irrigation of crops and/or forests, industrial use, and discharge to rivers for potable use by the neighboring communities.
- Reducing the volume of the RO brine concentrate and chemical waste water streams generated from the RO pre-treatment and UF/RO membrane cleaning systems (potentially producing a solid material depending on degree of treatment).
- Recovering a salt or mixture of salts that have commercial value and can be removed from the site and transported by road or rail as a saleable crystallised salt product.

It is worth noting that the recovery of salts to produce a saleable product may not be financially viable in its own right but simply be a least cost way to manage the highly saline material.

When attempting to create a saleable product the following criteria must be considered:

- Location and transport cost to market
- Capacity of the market to absorb additional large volumes of usable salt both locally and internationally
- Purity of salt product produced and how this compares with the purity of similar commercial salt products from other sources
- Technical capability to produce the highest value salts
- Cost of production which may involve either:
  - brine concentrators and crystallisers that are capital intensive due to use of exotic materials of construction and often energy intensive to run or
  - large scale evaporation pond systems that will need to be lined (possibly double lined) and subject to stringent long term monitoring requirements.

The maximisation of water recovery and reduction of waste to a solid material is known as ZLD. ZLD has been applied in the power industry since the 1980’s when it was introduced for inland coal fired power plants. The brine at these power stations was disposed of in the ash dams, where the brine salts typically comprised only a small portion of the overall power station waste produced. Environmental drivers are now encouraging the industry to consider and implement ZLD for inland desalination sites.

**Trends**

The mining, CSG, resources and power industry is seeing the emergence of new high recovery RO systems using unique approaches that can deliver lower energy solutions compared to the traditional stand alone thermal evaporative processes whilst achieving significantly high recoveries.

An approach incorporating a unique chemical precipitation process has been employed for treating water in the mining industry in South Africa with recoveries of > 97% reported.

An Australian desalination company has developed a patented innovative high recovery RO technology termed ‘Brine Squeezer™’ which is designed to achieve recoveries > 95%. This technology is based on the use of available RO membrane elements with larger feed spacers that facilitate high cross flow velocities and maximise effectiveness of membrane cleaning. Innovative cleaning strategies have been developed to effectively clean foulants and scalants. This brine squeezer can be operated at high salinities with high cross flow velocities to increase the saturation levels to reduce the scaling potential. The process incorporates controls for monitoring and adjusting plant operating parameters for fouling/scaling. The potential benefits of the brine squeezer™ technology are:

- Lower Capex when combined with brine concentrator/ crystalliser with the potential to halve the size of the conventional thermal evaporation process.
- Lower Opex when combined with brine concentrator/ crystalliser with the potential to halve the energy requirement of the conventional thermal evaporation process.

Forward RO is currently being commercialised and if proven to be technically and economically viable for these applications it offers a low cost high recovery solution that has the potential to reduce the energy requirement compared with conventional desalination technologies.

The incorporation of nanotechnology into membrane desalination is a growing area of development, both commercially with companies including NanoH2O and by University Research Centres. The National Centre of Excellence in Desalination Australia (NCEDA), based in the Murdoch University Rockingham Campus in Perth has undertaken R&D on emerging brine concentration technologies (e.g. ceramic membrane distillation).
CHALLENGES OF BRINE MANAGEMENT FOR THE AUSTRALIAN CSG INDUSTRY

The development of a brine management solution for a given CSG project depends on the total volume of salt expected, which ultimately depends on the water production profile of the specific development. In the CSG industry each development is different as it relates to the location of production wells, volumes/ratio of gas/water produced, and CSG produced water quality; however, one constant in all CSG developments is the level of uncertainty of these variables. Since CSG production occurs over a long period of time (up to 30 years), change within a given coal seam gas field can occur and this can affect water quality and quality. One of the key challenges for the CSG producer is providing the most adaptable and flexible water and brine management solution.

The illustration provided in Figure 1 is a broad outline of a conceptual CSG water management strategy.

![Conceptual CSG Water Management Strategy](Image)

As shown in Figure 1, the decision to use desalination is driven by the quality of CSG water. There are extensive technology options for desalination; however, RO membrane desalination is the industry benchmark technology, now widely adopted for CSG water desalination in NSW and Queensland. The emerging trend in the CSG industry in Australia is the adoption of high recovery RO and hybrid systems, primarily driven by the need to optimise recoveries to minimise the brine volumes generated.

Regardless of the mechanism used to desalinate the water, the brine concentrate after desalination of CSG water carries the salts present in the CSG water, but at significantly elevated levels. Brine is generally defined as a saline stream with at least 40,000mg/L total dissolved solids (TDS).

Management of this saline stream is a critical consideration.

Technical Considerations

Whilst the primary goal is to select a brine management option, some of the following technical considerations can influence the selection of a particular option and ultimately the overall brine management concept used.

Some of the key technical considerations include:

- Number and location of brine treatment facilities. Determining the location of brine treatment facilities depends heavily of the development gathering network architecture and the number of water treatment facilities used. Options include centralised or decentralised brine treatment locations and whether to co-locate with other facilities such as gas compression facilities.
- Transport costs are a significant consideration for most brine management options, from transport of chemicals used in some of the options to transport of salts for disposal or to the salt market.
- Land access. For options requiring brine transport (trunklines) land access through some areas may potentially be difficult.
- Energy source. Energy options include electricity supply, waste heat, solar and self-generation via a combined cycle gas turbine.
- Equipment capacity. Given the uncertainty of production profile of CSG water the installation of higher capacity water treatment plant may be required early in the project life for options with process units such as selective crystallisation. Pipeline sizing may require overdesign for peak flows or high flow scenarios, which increases capital costs and where the pipeline is under-utilised for the long term low flow requirement.
- Storage requirements for options with process units may be considered to enable a reduction in plant capacity.

Uncertainties and Risks

The following issues represent some of the significant industry concerns:

- **Brine production** - Given the long life span of gas project's (up to 30 years) the production of CSG water can vary. Any unforeseen performance issues of water desalination plants could have the potential to cause fluctuations in brine production.
- **Salt Purity** - Whilst it is technically possible to obtain the required level of purity, there is some uncertainty on the level of treatment required to obtain purity of the final salt and what effect that would have on the NPV of the option of salt recovery, which requires further evaluation. Boron, fluoride, potassium, silica, sulphate, and organics are contaminants known to be problematic for food and industrial (chloralkali) grade salt and could cause scaling of the brine concentrator heat exchanger.
- **Salt Markets** – The key prerequisite to implementing brine treatment to recover salt for market sale, is establishing a viable commercial route. There is significant uncertainty surrounding the market sale of recovered salt given that the Australian salt market is limited to a few vendors and the significant potential entry barriers to overseas...
markets, which require further evaluation. There is also some uncertainty on prices of salts as they may fluctuate depending on market conditions. Future risk of the local salt market becoming saturated and overseas markets will also need to be considered.

Transport of salt (for disposal or market sale) and chemical consumables - may also be a potential issue given the remote location of treatment facilities. In some cases, it is estimated that multiple truck movements will be required on a daily basis, increasing the traffic along the local transport routes. This is regarded as a significant social/public perception risk. The transport costs of each option will require evaluation on a case by case basis.

Injection Targets - Uncertainty is associated with the feasibility of suitable injection targets for brine injection. Investigations are required to determine feasibility of brine injection, which require a long lead time to develop. Hence brine injection is generally considered as a low cost opportunity that could be implemented if/when suitable injection targets are found. If this option is actively pursued due to the low feasibility issues of other options, an alternate brine management solution or increased storage capacity should be considered as a “stop gap” technology in the interim.

Salt Disposal - Disposal directly to landfill is not a regulator preferred option and is subject to availability of 3rd party landfill operators and licensing of the salt disposal. Whilst the landfill levy (potentially as high as $150/tonne) currently does not apply in some areas, changes in legislation in the future may introduce the levy and impact on the overall salt disposal cost and economic viability. This is a key consideration for the implementation of any of the salt disposal options.

Solar Evaporation Site Remediation Costs – There is uncertainty associated with cost for decommissioning and remediation of the ponds. The solar evaporation ponds require salt removal, typically via manually operated equipment. Due to the lack of large scale examples of this practice in the CSG industry, there is some uncertainty relating to the costs associated with the removal of salts from lined ponds.

Opportunities for Salt Disposal

The following opportunities may be considered on a case by case basis for a given development:

- Joint Venture Solution (aggregated treatment on behalf of multiple brine producers)/3rd party processing. High level assessment of this option indicated a 30% better NPV for joint venture between 2-3 parties when compared with a dedicated single facility.
- Use of cogeneration as an alternative to grid supply for power and energy intensive concepts such as ZLD, enhanced salt recovery and/or water treatment.
- Owing to the high alkalinity found in CSG waters, there is potential use of CSG water or brine for acid mine water neutralisation.
- Market sale of salt, sold as brine (Kostick, 2009). Although salt in brine is the least valuable this option reduces processing costs
- Owing to the energy requirements of brine treatment technologies, there is potential use of waste heat from neighbouring industries.
- Recovery of heat from solar evaporation ponds
- Onsite encapsulation or purpose built landfill facilities for disposal of salt. The elimination of salt transport cost can reduce the overall salt disposal cost significantly; however, this option requires further development and feasibility analysis on a case by case basis.

Analysis of Brine Management Options

The selection of an appropriate brine management solution for a particular CSG development requires thorough consideration of a range of factors that affect the particular development. For a given development it may be the case of eliminating certain options which are clearly unviable, and allow options with potential to be further progressed and analysed.

For further analysis a spread of several potential brine management concepts using well-defined options should be considered to fully explore the solution space for brine management. These may include:

- Salt recovery 1 (concentrator, selective crystalliser) + market sale of salts;
- Salt Recovery 2 (concentrator, multiple selective crystalliser’s) + market sale of salts;
- Salt Disposal 1 (solar evaporation ponds) + disposal of salts;
- Salt Disposal 2 (concentrator, mixed salt crystalliser) + disposal of salts;
- Salt Disposal Hybrid (concentrator + solar evaporation ponds) + disposal of salts;
- Brine Disposal 1 (aquifer injection);
- Brine Disposal 2 (pipeline to ocean outfall);
- Joint Venture (aggregated salt processing facility)
Financial Analysis of Brine Management Options

WorleyParsons have undertaken extensive studies for CSG developments for brine management concepts.

Capital, operating and remediation costs have been developed using high level process design & mass balances to obtain reagent/product/waste flows to establish the overall operating costs. The net present value (NPV) of several concepts was also determined.

Figure 2 shows the normalised NPV of some of the concepts considered, normalised against the selected baseline case (Salt Disposal 1 – Ponds) to show the comparison in the normalised NPV.

Figure 2: Normalised NPV of Brine Management Concepts for Development 1

The study found all options had a negative NPV. Brine injection performed best, with the least negative NPV; however this option had the highest level of uncertainty given injection targets were not yet confirmed. Interestingly, the salt recovery of 2 salts did not perform well, indicating the revenue from the second salt does not appear to justify the additional process requirements and complexity to recover the second salt. In contrast, salt recovery of the predominant salt in this case, NaCl appeared more viable, and achieved the next best NPV. In another study for Australia Pacific LNG, brine injection also performed well with the best NPV and low sensitivity, closely followed by sale of salts (Brannock et al).

In the event that there is not a commercial route for market sale, the fallback option is to dispose of the salts at an appropriately licensed landfill facility. The combination of technology and traditional ponds of the hybrid option performed better than the other salt disposal concepts 1 and 2.

It’s noted that numerous inputs specific to the given development were used to determine the NPV of the concepts and therefore the ranking of options may not necessarily apply in another development. In another study by WorleyParsons, the outcomes were markedly different with some differences in the ranking of concepts found with the exception of brine injection, which also proved the best in NPV.

Figure 3: Normalised NPV of Brine Management Concepts for Development 2.

As shown in Figure 3, the normalised NPV of the same concepts were analysed for a larger development in a different location. For this development, evaporation ponds performed poorly, whilst the salt recovery options for 1 and 2 salts performed well. Given the larger size of the development, the difference between the salt recovery 1 and 2 was reduced owing to the economics of scale and larger quantities of the more valuable soda ash salt product that could be recovered.

Sensitivity Analysis

Each CSG development is staged differently, produces varying amounts of water/gas and the characteristics of CSG water quality also fluctuates. It is therefore important to assess not only the entire life cycle and cost requirements for the entire system but also the response of different brine concepts to a number of key levers in order to determine the most robust, adaptable and flexible brine management concept.

The key levers affecting the brine concepts include:
- Brine production;
- Water Quality;
- Salt revenue;
- Salt disposal costs;
- Chemical cost;
- Transport cost; and
- Energy costs.

The sensitivity analysis indicated that the brine pipeline and salt recovery of two salts has the greatest sensitivity. Brine injection was also an outlier due to feasibility, despite having the lowest NPV and is resilient against changes in flow. The remaining concepts were quite comparable.
Non-Cost Considerations

The consideration of non-cost factors added further rigour to the evaluation of options. In pre-feasibility studies completed by WorleyParsons non-cost factors unique to each development were considered in addition to the financial considerations (i.e. NPV analysis). The criteria considered include:

- **Environmental Impact** – The extent of beneficial use of resources for each option was considered. Concepts using salt recovery processes were considered to have higher beneficial use, given the salts are produced for the purpose of market sale. Greenhouse gas (GHG) burden was also considered and in some cases offset the benefit from of market sale of salts.

- **Timeline Schedule Impact** – The ability of a concept to deliver in a timely manner.

- **Regulatory compliance** – The level of preference of each option considered.

- **Social/ Community Impact** – The degree to which landholders are impacted, impact on community health wellbeing and the impact on the physical surroundings is considered.

- **Technical Integrity and Personal Risk Exposure** – Process and Technical Integrity of the processes used was considered. Concepts using process units were considered more complex relative to ponds, pipeline or injection and considered to be more susceptible to design flaws. Personal exposure and resilience to 3rd party damage during the operations phase was also considered.

- **Development & Execution Robustness** – The adaptability and flexibility of each option was considered in the sensitivity analysis and level of technical maturity within the CSG industry.

- The complexity and variability of the solutions and impacts requires a robust (ideally accredited) process of analysis with powerful sensitive capabilities beyond simple weighted factor multi-criteria analysis or spreadsheet based approaches.
CONCLUSION

Given the expected increase in the gap between demand and availability of traditional water resources, desalination will continue to be an important water management technology for communities and industries. Brine management will become an increasingly important component for any desalination project. The brine management technology providers have over the past decade invested in the development of innovative and cost effective brine management solutions to meet the significant challenges that will be faced in the future. There is continuing technology development within the global industry focused on making brine management both more technically robust, reliable and economically viable.

**CSG Brine Management**

Where suitable geological strata can be identified, brine injection may be considered as a low life cycle cost brine management solution. CSG brine in the Surat Basin is particularly high in sodium, chlorides and carbonates and as such is favourable for the recovery of salts: NaCl and Na₂CO₃. Selective salt crystallisers are the benchmark technology, which is generally high in capital and operating costs, but is offset by the revenue gained from the sale of salt(s).

Other brine management options that need to be considered include solar evaporation ponds or ZLD technology to produce a mixed salt residue that can be disposed via onsite encapsulation or at a suitable licensed landfill.

Evaluation and selection of a robust, adaptable brine management solution requires a thorough assessment of all factors for a given development.

From studies performed by WorleyParsons, the following options were found to be robust and adaptable:

- **Solar evaporation ponds** – simple, well defined, with scope for optimisation including footprint reduction (via brine volume reduction) and low grade salt recovery; however best suited to small scale developments where footprint and waste salt generation/disposal is not prohibitively large.

- **Brine Concentrator/Crystallisers for Salt recovery** – enables beneficial use of recovered salt(s), salt purity can be controlled and suitable for large scale developments allowing the salt generated to be managed sustainably. Applicable for small scale applications (i.e., ranging from 1MLD to up to 10 MLD) with opportunities to incorporate novel technologies. However economies of scale are more favourable for large capacities (>10MLD) with more opportunities for market sale of salt. A range of vendors are available enabling competitive tenders.

The study outcomes described in this paper provide an indication of the ranking of options. However, the order of ranking has the potential to change significantly depending on the individual CSG development and the unique challenges of that development. It is recommended that options be evaluated on a case by case basis.

Due to the level of uncertainty, CSG producers may consider a number of solutions that can be used as fallback options in a certain order of preference for a specific development.

Rapid growth of the CSG industry has forced regulators to consider not only the individual projects but the cumulative effects of several large scale projects. The challenge for industry in this situation is not just compliance, but the fact that new regulations and guidelines are being created as the industry evolves. Similarly, treatment technology and approaches in brine management is continually evolving. It is recommended that regulatory changes and the progress of cutting edge technologies be continually monitored and it is anticipated that from lessons learnt and as solutions for brine management mature over the next few years, some of the uncertainty and risks in will be mitigated and holistic solutions for brine management will become better defined and established.

The huge investment, over the past few years, by the CSG industry in Australia for CSG produced water projects, located in remote inland locations, has resulted in a cumulative desalination capacity exceeding 400MLD. The large number and sheer magnitude of these projects, their technical and logistics complexity, coupled with the extensive experience and lessons learnt by the CSG industry on the implementation of these desalination plants, incorporating unique ‘state of the art’ world class high recovery desalination & brine management technologies, will be of critical importance and relevance to the successful implementation of future brine management projects for the mining, resources, and power industries in Australia.
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